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Prospective Applications of Cold Plasma for Processing Poultry Products: Benefits, Effects on Quality Attributes, and Limitations

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Abstract: Eliminating the pathogens from the chicken egg and meat is of supreme value for food scientists. In this regard, researchers have explored the potential applications of cold plasma, as a promising technique, to increase the profitability of poultry farming and safety of the poultry products. In the present study, an overview of the conducted research on plasma treatment of poultry products is presented to highlight the potential benefits of this emerging technology for the food and poultry industries. The potential negative effects of plasma treatment on the quality attributes of the product are also discussed. Moreover, the limitations of this technology and considerations for its commercial applications are illustrated. Furthermore, the needs for future research in this area of science are pointed out. Several studies have confirmed the applicability of cold plasma for egg and chicken decontamination. Considering the number of the recently conducted research and on-going advances in plasma science, this technique may assist food producers in enhancing the poultry product safety in the near future.

Keywords: chicken, cold plasma, egg, microbial decontamination, poultry

Introduction

The poultry industry is one of the most important fairs of the agri-food industry. The poultry products, such as chicken meat and egg, provide a significant portion of the human diet. The poultry meat is currently the most consumed meat in many regions of the world (OECD, 2018). The production and consumption of poultry meat are predicted to increase in the next decades (OECD, 2018) due to the affordable price, high nutritional quality, and limited cultural and religious restrictions on the consumption of these products. In addition, avian eggs are valuable sources of proteins and nutritional components. Recently, avian eggs have been recognized as a source of several valuable bioactive compounds for the biotechnology, medical, pharmaceutical, and food industries (Lesnierowski & Stangierski, 2018). Therefore, the poultry industry plays a crucial role in the provision of a sustainable food supply.

However, poultry products have limited shelf-life and are potential sources of concerning pathogens (for example, *Salmonella*). Therefore, the food industry employed several approaches to enhance the safety and shelf-life of these products. Conventional preservation techniques for poultry products include freezing, refrigeration, dehydration, thermal treatments, food additives incorporation, packaging, and combinations of these methods, that is, hurdle technology (Barbosa-Cánovas, Medina-Meza, Candoğan, & Bermúdez-Aguirre, 2014). However, several drawbacks are associated with these approaches including limited shelf-life extension and quality deterioration (for example, lipid oxidation and undesirable changes in color and texture). It is generally believed that synthetic food additives (for example, antimicrobial agents) may inversely affect consumer health (Casani, Rouhany, & Knøchel, 2005). Besides, the chemical preservation of poultry products is limited in many regions of the world. Therefore, the poultry industry has assessed the emerging techniques that can enhance the safety of products to meet the consumer demands for the safe, high quality, and sustainable food supply. Although several emerging technologies have greatly improved the safety of poultry products (Pattison, McMullin, Bradbury, & Alexander, 2008), cold plasma is still in its infancy and researchers are trying to explore its potential benefits for the poultry industry.

Cold plasma, as the fourth state of the matter, consists of charged particles, reactive chemicals, and light energy. It was first used in electronics and polymer industries (Cheng et al., 2014; Chizoba Ekezie, Sun, & Cheng, 2017) for structural modifications. The packaging industry has also used plasma for modification of polymer structure to achieve desirable properties of packaging materials (Pankaj et al., 2014). Recently, the findings of many studies imply that nonthermal plasma technology can be considered a profitable tool in agri-food industries such as the poultry industry. Researchers around the world showed that this emerging technology can be used for enhancing the microbiological safety of various

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products (Aly, 2013; Apostol, Georgescu, Vatuiu, & Gaceu, 2015; Dirks et al., 2012; Georgescu, Nicolae, Apostol, & Gherendi, 2017; Lee et al., 2011, 2012, 2016; Ragni et al., 2010; Rossow, Ludewig, & Braun, 2018; Wang, Zhuang, Lawrence, & Zhang., 2018; Yong et al., 2014) and increasing the production rates in the farm (Wang et al., 2016; Zhang et al., 2017; Zhang, Do, et al., 2018; Zhang, Huynh, et al., 2018; Zhang, Wang, et al., 2018).

The decontamination of poultry products is one of the most important applications of cold plasma. Poultry products are usually contaminated with several foodborne pathogens including *Salmonella* and *Campylobacter* species (Galiş et al., 2013). These pathogens are usually carried asymptomatically in the gastrointestinal tract of birds that can be transferred to their meat in the slaughtering process. Similarly, avian eggs can be contaminated with these microorganisms as they shed in the feces in large quantities. It was estimated that, just in the United States, more than 70 million people experienced food poisoning that, many of them, were probably related to the consumption of poultry products (Doyle & Erickson, 2006). Unfortunately, recognizing foodborne pathogens is challenging for the farmers as infected chickens possess slight or no symptom regarding their appearance and their production rate. It was reported that the consumption of chickens (Kimura et al., 2004) and eggs (Glynn et al., 2004) are the principal risk factors for sporadic *S. enterica* and *S.* Typhimurium infections, respectively. An epidemiologic survey in the United Kingdom revealed that poultry products are the main risk factor for *Campylobacter* infection (Rodrigues et al., 2001). Therefore, it is important to reduce the risk of these outbreaks by disinfecting poultry products. The conventional disinfection methods suffer from a number of drawbacks (Doyle & Erickson, 2006). For example, chemical preservatives introduce harmful compounds into the food products that are associated with health problems (Carocho, Morales, & Ferreira, 2015). It was reported that consumers are reluctant to use the food products that are prepared with chemical preservatives (Lorenzo et al., 2018). Natural preservatives may negatively affect the sensory properties of products (Gavahian, Hashemi, Mousavi Khaneghah, & Mazaheri Tehrani, 2013; Lorenzo et al., 2018). Therefore, the decontamination effects of emerging technologies on poultry products have recently attracted the attention of researchers all over the world.

The microbicidal effects of nonthermal plasma on several food products have been already confirmed through previously conducted studies (Coutinho et al., 2018; Dasan, Yildirim, & Boyaci, 2018; Gavahian & Mousavi Khaneghah, 2019; Lopes et al., 2018; Misra & Jo, 2017; Olatunde & Benjakul, 2018; Zhang et al., 2019). Researchers showed that this process can inactivate a wide range of troublesome microorganisms, including biofilms (Jahid, Han, & Ha, 2014; Niemira, Boyd, & Sites, 2014), spores (Lopes, Mota, Gomes, Delgadillo, & Saraiva, 2018; Patil et al., 2014), and viruses (Bae, Park, Choe, & Ha., 2015; Puligundla & Mok, 2016). However, the efficacy of cold plasma for treatment of various poultry products should be discussed to promote its industrial application. This review, for the first time, provides an overview on the potential applications of nonthermal plasma technology in the poultry industry, highlights its stunning benefits for farm production and product safety enhancement, discusses the limitations of this technique, and suggests the considerations for its industrial adoption.

To collect the appropriate references for the present study, a comprehensive literature search was performed on previously published data through scientific databases (for example, "Scopus," "Web of Science," "PubMed," "SciELO," and "ScienceDirect"). No restriction was applied with regard to the research period. In this regard, combinations of relevant terms, including "cold plasma" AND "nonthermal plasma" AND "plasma" AND "arc plasma" AND "dielectric barrier discharge" AND "corona" AND "glow" AND "poultry" AND "avian" AND "chicken" AND "rooster" AND "duck" AND "geese" AND "poultry farming" AND "egg" AND "cooked egg" AND "yolk" AND "egg white" AND "albumen" AND "glair" AND "eggshell" AND "chicken" AND "chicken meat" AND "chicken skin" AND "egg decontamination" AND "meat decontamination" AND "egg quality" AND "meat quality" were used to collect the potential appropriate references. The first author of the present work reviewed the title and the summary of the resulted materials to exclude the documents that did not comply with the inclusion criteria. The elimination process was then continued through reading the full text of the chosen articles from the previous step to verify the suitability of these documents based on the inclusion criteria. The second author of the present study double checked this process. In case of discrepancy, the authors asked the opinion of the last author of the present work. Besides, the references of the retrieved studies were analyzed to find further relevant sources. Moreover, the articles that cited the retrieved surveys (according to search engines such as "Google Scholar") were reviewed to find potential appropriate references. Afterward, Mendeley reference manager software (Elsevier, the Netherlands) was used to organize and to de-duplicate the selected papers. In the present study, the inclusion criteria were original research/scientific studies that were published in English with an accessible full-text that investigated the applicability of cold plasma in the poultry industry.

Nonthermal Plasma and Its Generation

The term "plasma" generally refers to macroscopically neutral mixtures of reactive species, including charged molecules, ions, free electrons, radicals, photons, and ionized molecules or atoms, which exhibit collective behavior due to the long-range Coulomb forces (Bittencourt, 2013). The detailed information about the fundamentals of plasma and the mechanisms involved in plasma generation can be found in the literature (Bárdos & Baránková, 2010; Bittencourt, 2013; Fridman, 2004; Tendero, Tixier, Tristant, Desmaison, & Leprince, 2006). As plasma mixtures can be available at a wide range of temperatures, scientists categorized plasma mixtures into two groups, namely thermal and nonthermal (cold) plasma (Niemira & Gutsol, 2011). While the term "nonthermal plasma" is defined by physicists as a plasma that has a clearly nonuniform (nonequilibrium) distribution of energy among its components and the electrons may transfer energy through collisions with heavier particles and change their status into the reactivity state (Niemira & Gutsol, 2011), food scientists describe this term as plasma gases that neither induce thermal damage to the product nor rely on high temperatures for food processing such as food decontamination (Bhat et al., 2002; Gavahian & Mousavi Khaneghah, 2019). The direct application of the thermal plasma in the food industry is probably not feasible as it operates at extremely high temperatures that may deteriorate many food components. On the other hand, the nonthermal plasma was claimed to be a potential alternative to many traditional processes in the food industry (Gavahian, Chu, Mousavi Khaneghah, Barba, & Misra, 2018; Misra & Jo, 2017). Cold plasma can affect microorganisms and food components through ultraviolet (UV) radiations and chemical interactions (for example, between reactive species and food components). All of these mechanisms are usually involved in the nonthermal plasma process at the same time, resulting in a great

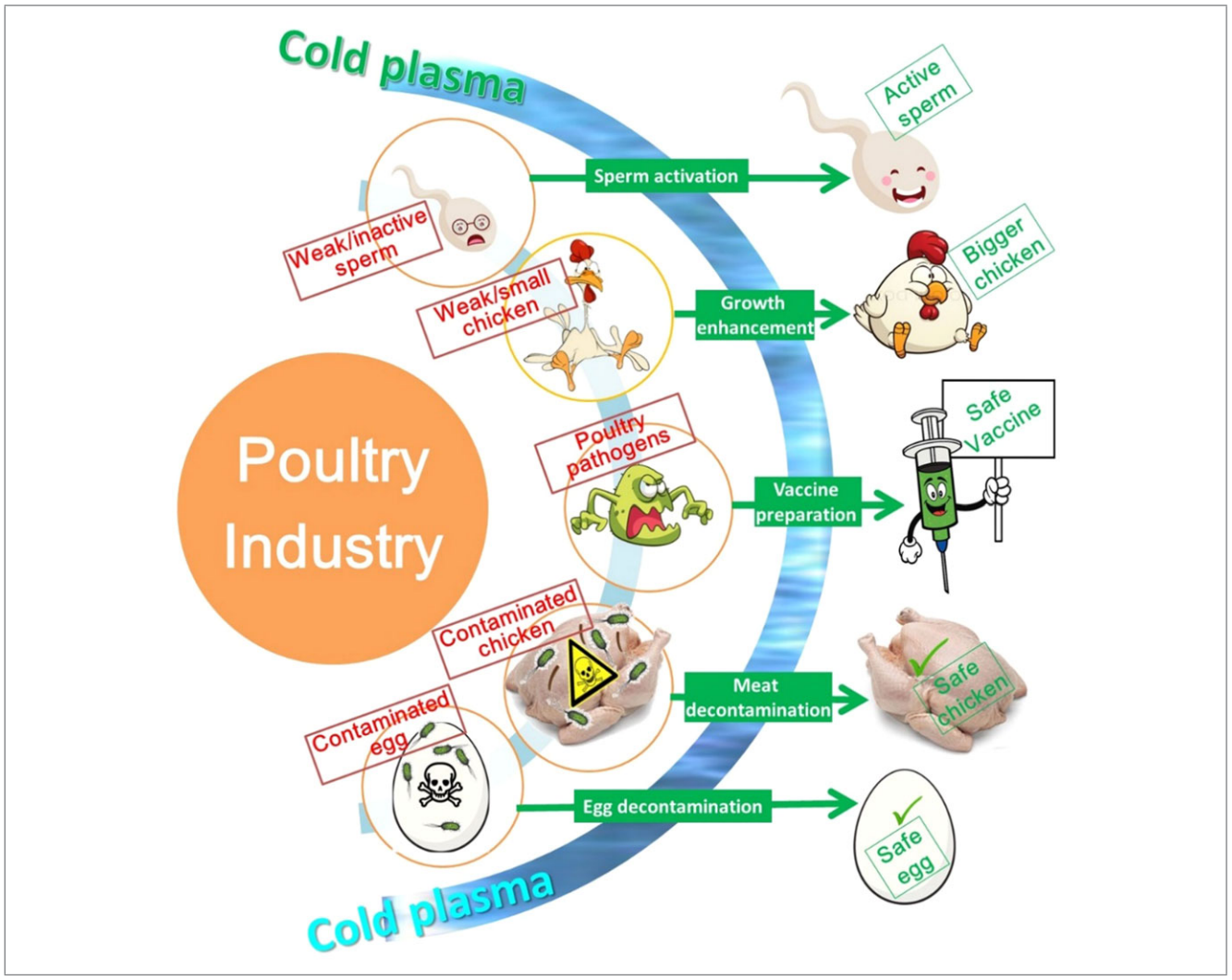

Figure 1–A summary of prospective applications of cold plasma in the poultry industry.

impact on food and cell components (Bhat, Lee, VanVollenhoven, Teng, & Bieber 2002).

Nonthermal plasma can be generated using several energy sources and under different conditions. Electricity, microwaves, and laser are among the common energy sources for plasma generation (Szabó & Schlabach, 2014). The plasma energy can also be generated under atmospheric or negative pressure (Niemira & Gutsol, 2011). Besides, cold plasma can be generated through various discharging systems including radio-frequency (which uses pulsed electrical current to produce plasma inside an electrical coil), glow (which has two electrodes at both sides of a separating area that contains a special gas composition), and barrier (which produces the plasma energy by distributing the electrical current through dielectric material) (Szabó & Schlabach, 2014). Detailed discussions on the designs of plasma systems can be found in the literature (Szabó & Schlabach, 2014; Thirumdas et al., 2018). To this date, a number of plasma-generating systems, including plasma jets (Kim et al., 2013; Lee et al., 2011), corona discharges (Dobrynin, Friedman, Fridman, & Starikovskiy, 2011), and dielectric barrier discharges (DBD) (Georgescu, 2015; Lee et al., 2016), have been used for treatment of food materials such as poultry products (Thirumdas et al., 2018). Furthermore, the application of plasma activated water, that is, plasma-treated water that contains a number of reactive species, has been explored for inactivation of pathogens associated with chicken (Thirumdas et al., 2018).

Nonthermal Plasma and Poultry Industry

Recent studies have proposed cold plasma as a tool to enhance the production yield in chicken farms, through vaccine production, growth and reproduction enhancement (Wang; et al., 2016; Zhang et al., 2017; Zhang, Do, et al., 2018; Zhang, Huynh, et al., 2018; Zhang, Wang, et al., 2018), and to assure the safety of the poultry products (Aly, 2013; Apostol et al., 2015; Dirks et al., 2012; Georgescu et al., 2017; Lee et al., 2011, 2012, 2016; Ragni et al., 2010; Rossow et al., 2018; Wang et al., 2018; Yong et al., 2014; Figure 1). This wide range of potential application is because of the presence of reactive species and photons and the consequent chemical reactions that these components may induce in the treated product.

A previously conducted microbiological study confirmed the decontamination effects of DBD plasma against common poultry product-associated pathogenic (*S. enterica*, *S.* Typhimurium, and *C. jejuni*) and spoilage (*Pseudomonas fluorescens*) bacteria (Rothrock et al., 2017). This study also revealed that different bacteria have different survival rates under the same plasma treatments. For example, 0.5 and 2 min of nonthermal plasma treatment resulted

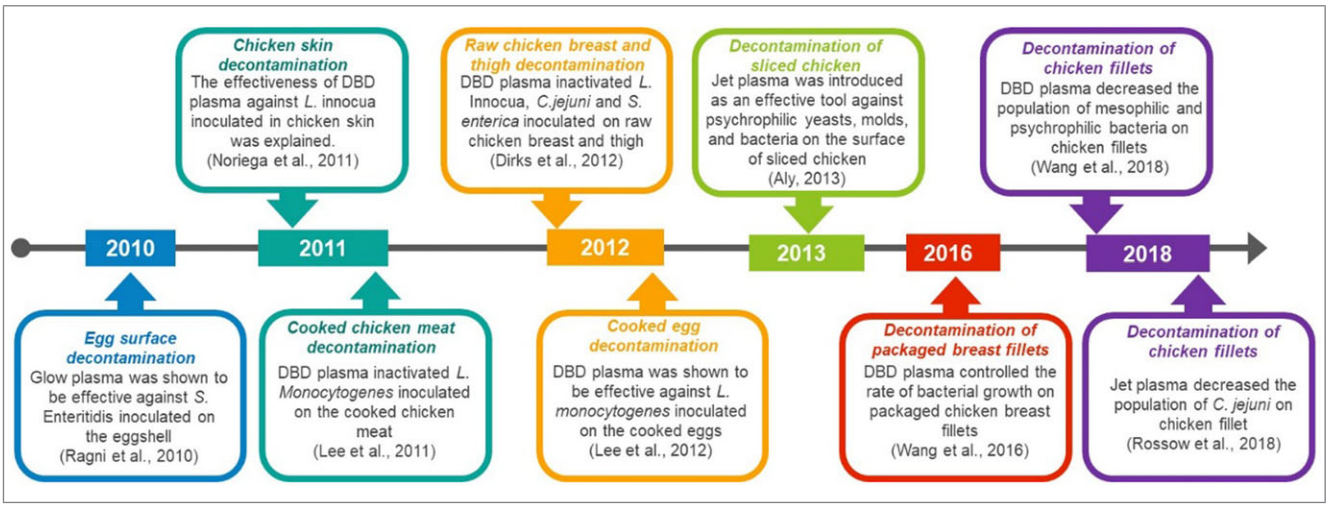

Figure 2–A historical overview of the recent development in the application of cold plasma for poultry product decontamination.

in a significant inactivation (60% inactivation) and completely inactivated of *C. jejuni*., respectively On the other hand, the same nonthermal process slightly inactivated *S.* Typhimurium and *P. fluorescens* (less than 20% inactivation). According to the authors, significant inactivation (60% inactivation) of these microorganisms required 3 min of plasma treatment. However, this study only evaluated the decontamination effects of cold plasma on pure liquid cultures. Therefore, the results of this study might be different from that of the industrial decontamination of poultry products wherein the microorganisms are mainly located on the chicken skin or eggshell with special topography and different chemical composition (for example, different protein, fat, and moisture levels). Therefore, food scientist assessed the decontamination effects of cold plasma on chicken meat (Dirks et al., 2012; Lee et al., 2011; Myers et al., 2016; Noriega, Shama, Laca, Díaz, & Kong, 2011; Rossow et al., 2018; Wang et al., 2016, 2018; Yong et al., 2014) and egg (Apostol et al., 2015; Georgescu et al., 2017; Lee et al., 2012; Ragni et al., 2010; Wan, Chen, Pankaj, & Keener, 2017; Figure 2).

Chicken meat and skin decontamination

Several studies have explored the feasibility of chicken meat and skin decontamination by nonthermal plasma (Table 1). Lee et al. (2011) assessed the effects of 2 min of jet plasma treatment on the cooked chicken breast that was contaminated by *Listeria monocytogenes* (Lee et al., 2011). They used He, N_2, He+O_2, and He+N_2 as carrier gases and observed that these plasma treatments decreased the bacteria population by 1.37 to 4.73 log units, depending on the types of carrier gas. According to the paper, the mixture of nitrogen and oxygen was the most effective carrier gas against the studied microorganism.

The atmospheric pressure jet treatments of chicken breast for 5 and 10 min reduced the *S.* Typhimurium from 5.66 to 5.14 and 4.41 log CFU/g, respectively (Kim et al., 2013). The authors also pointed out that the treatment distance, that is, the distance between the plasma generation point and chicken sample, can affect the effectiveness of the nonthermal decontamination. For example, 10 min plasma treatment of the chicken meat with the initial *S.* Typhimurium population of 8.25 resulted in a product with the *S.* Typhimurium concentration of 4.86, 4.48, and 5.87 log CFU/g when the treatment distance was 1, 2, and 3 cm, respectively. The authors concluded that the optimization of plasma treatment in terms of working distance and treatment time can enhance its decontamination effects on chicken breast.

Noriega et al. (2011) reported that greater values of the input voltage and frequency and higher concentrations of oxygen in the working gas enhanced the decontamination effects of the plasma treatment on chicken meat and chicken skin that were inoculated with *Listeria innocua* (Noriega et al., 2011). According to the paper, 8 min treatment proffered 1 log reduction of the *Listeria* in the chicken skin and a 4 min treatment resulted in about 3 log reductions in chicken meat. They used scanning electron microscopy (SEM) to investigate the surface topography of the chicken meat and skin and figured out that the effectiveness of nonthermal plasma can be influenced by the surface topography as some surface features, such as cracks or feather follicles, can protect microorganisms from the reactive species generated during nonthermal plasma treatment. It was also reported that some microorganisms can migrate from the surface of the chicken skin to the interior parts (up to 0.15 mm depths; Noriega et al., 2011). This fact along with the nonuniform topography of the chicken skin may increase the survival rate of the microorganism following the nonthermal plasma treatment. According to Noriega et al. (2011), the highly irregular topography of the skin enables microorganisms to be drawn through capillary action into surface irregularities, such as the feather follicles, which may increase their resistance against nonthermal plasma treatment. The red arrows show the bacteria cluster that remained on the skin surface. It seems that the rest of the inoculated bacteria penetrated into the cracks and other nonuniform structures of the skin.

Dirks et al. (2012) confirmed the decontamination effects of the atmospheric air DBD plasma on chicken breast and chicken thigh that were contaminated by antibiotic-resistant strains of the *C. jejuni* and *S. enterica* (Dirks et al., 2012). Nonthermal plasma treatment eliminated 10 CFU of *S. enterica* and *C. jejuni* on chicken breasts. A similar decontamination effect was observed on inoculated *C. jejuni* in the chicken thigh samples. However, 20 s of nonthermal plasma treatment did not inactivate the *S. enterica* on the chicken thigh. This research revealed that the type of treated sample can affect the decontamination level of plasma treatment. It seems that the inoculated bacteria on the chicken leg were more resistance than the ones on chicken breast. This could be related to the effect of surface texture and topography (Noriega et al., 2011) and the potential protective effect of lipid molecules (Gavahian,

Table 1–A summary of the conducted research on chicken meat and other related products decontamination by nonthermal plasma.

Product	Plasma source	PT*	PV	F	V	PD	CG	Microorganism	Initial load	MLR**	Salient results	Reference
Chicken Breast	Arc	10	1			500	N_2+O_2	*S.* Typhimurium	5.66	1.25	The decontamination efficacy depended on plasma process time, sample direction, and working distance. Process optimization can enhance the performance of the plasma process.	Kim et al., 2013
Cooked chicken breast	DBD	2	1	50	2	–	N_2+O_2	*L. monocyto-genes*	6.40	4.73	The composition of working gas affected the decontamination efficacy of the process.	Lee et al., 2011
Cooked chicken breast	DBD	2	1	50	2	–	He	*L. monocytogees*	6.40	1.90	The mixture of N2 and O2 was recognized as the working gas with the highest inactivation result.	
Cooked chicken breast	DBD	2	1	50	2	–	N_2	*L. monocytoge*	6.40	1.4	Cold plasma was introduced as an effective tool against Listeria monocytogenes on the surfaces of chicken meat.	
Cooked chicken breast	DBD	2	1	50	2	–	$He+O_2$	*L. monocytoge*	6.40	2.6	It was hypothesized that cold plasma can enhance the shelf-life of the chicken breast.	
Chicken skin	DBD	8	1	30	16	–	$He+O_2$	Generic	5.60	0.91	Plasma treatment successfully inactivated *L. innocua* on chicken meat and chicken skin samples.	Noriega et al., 2011
Chicken skin	DBD	8	1	30	16	–	$He+O_2$	*L.* innocua	7.70	0.94	The inactivation rate depended on the type of sample.	
Chicken muscle	DBD	8	1	30	16	–	$He+O_2$	*L.* innocua	7.70	3.30		
Skinless chicken breast	DBD	2.75	1	0.5	30		Air 0.15/cm^2	*L.* innocua	4.00	2.50	Cold plasma treatment successfully inactivated both *C. jejuni* and *S. enterica* on chicken breasts.	Dirks et al., 2012
Skinless chicken breast	DBD	3	1	0.5	30		Air 0.15/cm^2	*C.jejuni*	4.00	2.50	Cold plasma treatment successfully inactivated *C. jejuni* on chicken skin.	
Chicken thigh with skin	DBD	2.75	1	0.5	30		Air 0.15/cm^2	*C. jejuni*	4.00	3.10	Short duration, that is, 20 s, of plasma treatment was ineffective against *S. enterica* cells inoculated on the surface of chicken skin.	
Chicken thigh with skin	DBD	2	1	0.5	30		Air 0.15/cm^2	*S. enterica*	4.00	1.25	The initial concentrations of the inocula affected the decontamination efficacy of cold plasma.	
Skinless chicken breast	Jet	5	1	–	–	50	N_2	*E. coli*	6.00	0.96	Cold plasma was introduced as an effective tool for inactivation of *E. coli* on the surface of the chicken breast.	Yong et al., 2014
Skinless chicken breast	Jet	10	1	–	–	50	N_2	*E. coli*	6.00	1.28	Plasma treatment time, working distance, carrier gas composition, and initial concentration of inocula affected the decontamination efficacy of plasma treatment.	
Skinless chicken breast	Jet	5	1	–	–	50	N_2+O_2	*E. coli*	6.00	1.12		
Skinless chicken breast	Jet	10	1	–	–	50	N_2+O_2	*E. coli*	6.00	1.54		
Sliced chicken	Jet	0.5	1	0.025	15	–	He+Ar	Total bacteria count	3.75	2.4	Cold plasma was introduced as an effective tool for reducing the population of psychrophilic yeasts, molds, and bacteria on the surface of sliced chicken samples.	(Aly, 2013)
Sliced chicken	Jet	1	1	0.025	15	–	He+Ar	Total bacteria count	3.75	2.4	The chemical composition and quality attributes (for example, texture, appearance, and odor) of samples were not affected by cold plasma treatment.	
Sliced chicken	Jet	1.5	1	0.025	15	–	He+Ar	Total bacteria count	3.75	2.6		

(*Continued*)

Table 1–Continued.

Product	Plasma source	PT*	PV	F	V	PD	CG	Microorganism	Initial load	MLR**	Salient results	Reference
Chicken fillets	DBD	3	1	0.06	55	34	Air	Mesophile	2.72	0	Plasma treatments decreased the bacterial count of chicken fillets. and the color of chicken samples was altered after plasma treatment.	(Wang et al., 2018)
Chicken fillets	DBD	3	1	0.06	65	41	Air	Mesophile	2.72	0		
Chicken fillets	DBD	3	1	0.06	80	70	Air	Mesophile	2.72	0.11	In some cases, extending treatment times (for example, from 3 to 9 min) and elevating voltage (for example, from 55 to 80 kV) did not enhance the bactericidal effects of cold plasma. Prolonged PT (> 3 min) deteriorated the appearance of samples.	
Chicken fillets	DBD	3	1	0.06	80	70	Air	Mesophile	6.83	0.97		
Chicken fillets	DBD	6	1	0.06	80	70	Air	Mesophile	6.83	1.29		
Chicken fillets	DBD	9	1	0.06	80	70	Air	Mesophile	6.83	1.13		
Chicken fillets	DBD	3	1	0.06	80	70	Air	Psychrophile	7.86	1.14		
Chicken fillets	DBD	6	1	0.06	80	70	Air	Psychrophile	7.86	1.43		
Chicken fillets	DBD	9	1	0.06	80	70	Air	Psychrophile	7.86	1.64		
Chicken breast fillet	Jet	0.5	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	0.8	Cold plasma successfully decreased the population of *C. jejuni* on chicken breast fillet and chicken skin. Carrier gas composition and plasma treatment time affected the inactivation efficacy. Working distance affected the appearance of the plasma-treated samples.	(Rossow et al., 2018)
Chicken breast fillet	Jet	1	1	1,000	2 to 3	–	Air	*C. jejuni i*	6.0	0.7		
Chicken breast fillet	Jet	2	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	1.2		
Chicken breast fillet	Jet	3	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	1.4		
Chicken skin	Jet	0.5	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	1		
Chicken skin	Jet	1	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	1		
Chicken skin	Jet	2	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	0.7		
Chicken skin	Jet	3	1	1,000	2 to 3	–	Air	*C. jejuni*	6.0	1.1		
Chicken breast fillet	Jet	0.5	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	0.8		
Chicken breast fillet	Jet	1	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	1.3		
Chicken breast fillet	Jet	2	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	2		
Chicken breast fillet	Jet	3	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	2.1		
Chicken skin	Jet	0.5	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	0.7		
Chicken skin	Jet	1	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	1.1		
Chicken skin	Jet	2	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	2.2		
Chicken skin	Jet	3	1	1,000	2 to 3	–	Ar	*C. jejuni*	6.0	2.1		

(*Continued*)

Table 1–Continued.

Product	Plasma source	PT*	PV	F	V	PD	CG	Microorganism	Initial load	MLR**	Salient results	Reference
Chicken breast	DBD	1	1	15	–	2	Air	Total aerobic bacteria	3.3	0.3	Plasma treatment successfully reduced the number of viable aerobic bacteria, *S.* Typhimurium, *E. coli*, and *L. monocytogenes* on chicken breasts samples.	Lee et al., 2016
Chicken breast	DBD	3	1	15	–	2	Air	Total aerobic bacteria	3.3	0.4	Prolonged plasma treatments altered the cohesiveness, color values, and the flavor but did not affect general acceptability of the samples.	
Chicken breast	DBD	5	1	15	–	2	Air	Total aerobic bacteria	3.3	1.4	Salmonella mutagenicity assay showed no sign of genotoxicity in the samples.	
Chicken breast	DBD	10	1	15	–	2	Air	Total aerobic bacteria	3.3	3.3		
Chicken breast	DBD	2.5	1	15	–	2	Air	*Listeria monocytogenes*	5.88	0.54		
Chicken breast	DBD	5	1	15	–	2	Air	*L. monocytogenes*	5.88	1.07		
Chicken breast	DBD	7.5	1	15	–	2	Air	*L. monocytogenes*	5.88	1.51		
Chicken breast	DBD	10	1	15	–	2	Air	*L. monocytogenes*	5.88	2.14		
Chicken breast	DBD	2.5	1	15	–	2	Air	*E. coli*	5.84	1.16		
Chicken breast	DBD	5	1	15	–	2	Air	*E. coli*	5.84	1.82		
Chicken breast	DBD	7.5	1	15	–	2	Air	*E. coli*	5.84	2.30		
Chicken breast	DBD	10	1	15	–	2	Air	*E. coli*	5.84	2.73		
Chicken breast	DBD	2.5	1	15	–	2	Air	*S.* Typhimurium	5.48	1.31		
Chicken breast	DBD	5	1	15	–	2	Air	*S.* Typhimurium	5.48	1.9		
Chicken breast	DBD	7.5	1	15	–	2	Air	*S.* Typhimurium	5.48	2.25		
Chicken breast	DBD	10	1	15	–	2	Air	*S.* Typhimurium	5.48	2.71		
Packaged chicken breast fillets***	DBD	3	1	–	80	–	Air	Mesophilic	7.1	0	Plasma treatment controlled the rate of bacterial growth on chicken breast fillets.	Wang et al., 2016
Packaged chicken breast fillets***	DBD	3	1	–	80	–	Air	Psychrophilic	8.2	0.1	Plasma treatment did not affect the color values of the sample. The carrier gas was among the effective process parameters.	
Packaged chicken breast fillets***	DBD	3	1	–	80	–	Air	*Pseudomonas*	7.5	0	Cold plasma enhanced the shelf-life of fillets.	
MAP chicken breast fillets***	DBD	3	1	–	80	–	Air	Mesophilic	4.4	1.2		
MAP chicken breast fillets***	DBD	3	1	–	80	–	Air	Psychrophilic	4.6	0.7		
MAP chicken breast fillets***	DBD	3	1	–	80	–	Air	*Pseudomonas*	5.8	0.9		

* MLR, maximum log reduction; PV, pressure value (atm); F, frequency (kHz); V, voltage (KV); PD, power density (W); PT, process time (min); CG, carrier gas; DBD, dielectric barrier discharge; MAP, modified atmosphere packaged.
** Some of the values are approximated from the reported Figures.
*** The microbiological data are reported after 10 days of refrigeration in comparison to the non-plasma treated sample.

Chu, Mousavi Khaneghah, Barba, & Misra, 2018) in the chicken thigh due to the different chemical composition.

Likewise, Lee et al. (2016) reported that 10 min of DBD plasma treatment of chicken breast reduced the population of total aerobic bacteria, *E. coli*, *S.* Typhimurium, and *L. monocytogenes* by 3.36, 2.73, 2.71, and 2.14 Log CFU/g, respectively (Figure 3).

An investigation on the effects of atmospheric pressure jet plasma on the microbiological quality of the sliced chicken revealed that this nonthermal process improved the microbiological safety of the product (Aly, 2013). According to the paper, increasing the treatment time resulted in a further decrease in the total count of the product. Thirty and 90 s of nonthermal plasma process reduced the total count of the sliced chicken from 5.6×10^2 to 2.9×10^2 and 1.9×10^2 CFU/g, respectively. This study highlighted the importance of treatment time on the microbiological safety of the sliced chicken.

Wang, Zhuang, Lawrence, and Zhang (2018) studied the effects of plasma treatment time on the microbiological characteristics of the chicken fillets and reported that increasing the treatment time did not significantly affect the psychrophiles and mesophiles population on the chicken fillets and all the treatment times (70 W nonthermal plasma for 3, 6, and 9 min) resulted in about 1 to 1.5 log CFU/gram reduction in the population of these microorganisms (Wang et al., 2018). Ozone is one of the most important components in nonthermal plasma process that has antimicrobial activity and the higher concentration of this chemical can result in a better decontamination effect of plasma on the product (Gavahian, Chu, Mousavi Khaneghah et al., 2018). According to Wang et al. (2018), the concentration of ozone did not increase significantly after increasing the plasma treatment time from 3 min to 6 and 9 min and were 950, 950, and 1,000 ppm, respectively (Wang et al., 2018). Therefore, increasing the plasma exposure time did not increase the concentration of ozone. Consequently, these treatment times yielded chicken fillets with similar microbiological quality. Similar results were observed for increasing the input power. These findings showed that the excessive increase of the input power and treatment time could be ineffective in enhancing the microbiological safety of the chicken. Therefore, optimization of the plasma process in terms of process time and input power can result in faster and energy saving plasma treatment with similar decontamination effects to the longer or higher power ones.

The decontamination effects of the jet plasma on chicken breast fillet and chicken skin were evaluated by Rossow et al. (2018). They inoculated *C. jejuni* on the surface of these two poultry products and assessed the applicability of nonthermal plasma at atmospheric pressure using different working gases (air or argon), different treatment times (0.5, 1, 2, or 3 min), and different distances between samples and the plasma source (0.5, 0.8, or 1.2cm). The greatest decontamination effect was achieved when argon was the working gas and the treatment was continued for a long time (3 min). The authors suggested that adjusting process parameters can enhance the efficacy of the nonthermal plasma process (Rossow et al., 2018). However, all the studied plasma treatment conditions decreased the microbial load of the chicken skin and chicken fillet. According to the paper, the reduction in *Campylobacter* population following plasma treatment fluctuated between 0.65 and 1.42 or 0.78 and 2.55 log CFU/cm^2 when air or argon was used as the working gas, respectively. Therefore, the authors suggested the nonthermal plasma as an effective disinfection technique for chicken fillet and chicken skin due to its effectiveness against *C. jejuni* (Rossow et al., 2018), which can be transmitted to human mainly through poultry products and lead to food infections (Wieczorek et al., 2018).

Lee et al. (2016) reported that DBD plasma treatment successfully decreased the number of total aerobic bacteria and pathogens in the vacuum packaged chicken breasts (Lee et al., 2016). According to the authors, 10 min DBD plasma treatment of the samples reduced the number of total aerobic bacteria, *E. coli*, *S.* Typhimurium, and *L. monocytogenes* by 3.36, 2.73, 2.71, and 2.14 Log CFU/g, respectively. The authors did not observe any viable aerobic bacteria after 10 min of the nonthermal plasma process. Furthermore, increasing the treatment time enhanced the decontamination effects of plasma against all the studied microorganisms.

A recent study highlighted the effectiveness of DBD plasma against psychrophiles, *Campylobacter*, and *Salmonella* (Zhuang et al., 2019). Furthermore, jet plasma was proved to be an effective tool for inactivation of *Escherichia coli* inoculated on the surface of fresh chicken breasts (Yong et al., 2014). This research team investigated the optimum conditions for the arc plasma treatment of the studied samples to maximize the inactivation of *Escherichia coli* and concluded that several parameters, including the type of carrier gas, the distance between samples and the plasma source, treatment duration, and the initial concentration of the pathogen, affect the efficacy of the nonthermal process.

Wang et al. (2016) assessed the effect of 3 min of plasma treatment at the input voltage of 80 kV on the microbiological shelf-life of the fillets of chicken breast that were packaged under atmospheric or modified atmosphere (oxygen, carbon dioxide, nitrogen ratio of 65, 30, and 5, respectively) conditions (Wang et al., 2016). The authors did not observe any significant differences between the microbial count of control and plasma-treated samples packed under the atmospheric air condition. On the other hand, the microbial count of modified atmosphere packaged fillets was lower that of the control sample. The authors assumed that the decontamination effects of nonthermal plasma on packaged chicken fillets depend on the composition of the filled gas inside the packages. The results of this study showed that the combination of modified atmosphere packaging and nonthermal plasma treatment can extend the microbiological shelf-life of refrigerated chicken fillet from 1 to 2 weeks (Wang et al., 2016). In an interesting study, the effect of plasma process parameters on the inactivation rate of *Salmonella* inoculated on chicken breast model was investigated (Roh, Lee, Park, Lee, & Min, 2019). According to the authors, whey protein coating enhanced the *Salmonella* inactivation rate. In addition, the authors observed an increase in the D-value (from 0.2 to 1.3 min) by increasing the initial inoculum concentration (from 3.8 to 5.7 log CFU). These authors also reported that the composition of the chicken model system, that is, fat, water, and protein content, affected the efficacy of plasma treatment in *Salmonella* inactivation.

Egg decontamination

Raw and cooked egg decontamination by nonthermal plasma has recently attracted the attention of several researchers (Table 2). While a study conducted in the last decade showed that 5 min treatment of eggshell with plasma-generated gas (ionized air) was ineffective against *S.* Enteritidis (Davies & Breslin, 2003), recent investigations confirmed the decontaminations effects of nonthermal plasma on the egg surface (Apostol et al., 2015; Georgescu et al., 2017; Lee et al., 2012; Ragni et al., 2010; Wan et al., 2017).

The decontamination effects of 2 min of plasma jet treatment at the input voltage of 2 kV against *L. monocytogenes* inoculated

Table 2–A summary of the conducted research on chicken egg decontamination by nonthermal plasma.

Product	Plasma source	PT	PV	F	V	CG	Microorganism	Initial load	MLR	Salient results	Reference
Cooked egg white	Jet	2	1	–	2	He	*L. monocytogenes*	6.7	5	Cold plasma was introduced as an effective tool for the production of Listeria-free eggs.	Lee et al., 2012
Cooked egg white	Jet	2	1	–	2	$He+O_2$	*L. monocytogenes*	6.7	5	The carrier gas and the type of sample (egg white or yolk) affected the inactivation rate of the plasma process.	
Cooked egg white	Jet	2	1	–	2	N_2	*L. monocytogenes*	6.7	6.7	Cold plasma did not affect the sensory properties of egg whites but negatively affected the taste, flavor, and overall acceptability of yolk samples.	
Cooked egg white	Jet	2	1	–	2	N_2+O_2	*L. monocytogenes*	6.7	6.7	Genotoxic products were not detected in the plasma-treated samples.	
Cooked egg yolk	Jet	2	1	–	2	He	*L. monocytogenes*	7.1	7.1		
Cooked egg yolk	Jet	2	1	–	2	$He+O_2$	*L. monocytogenes*	7.1	7.1		
Cooked egg yolk	Jet	2	1	–	2	N_2	*L. monocytogenes*	7.1	7.1		
Cooked egg yolk	Jet	2	1	–	2	N_2+O_2	*L. monocytogenes*	7.1	7.1		
Egg	Jet	5	1	–	20	$He+O_2$	*S. enterica*	3.9	3.9	Cold plasma treatment inactivated Salmonella on the eggshell. Plasma treatment did not deteriorate the quality parameters of the eggs.	Apostol et al., 2015
Egg	Direct DBD	5	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	2.7	Cold plasma decreased the number of viable Salmonella on the egg surface. Carrier gas with an increased concentration of oxygen has the greatest decontamination effect. Plasma treatment did not alter the quality parameters of the sample.	Wan et al., 2017
Egg	Direct DBD	10	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	5.3	The composition of carrier gas affected the rate of Salmonella inactivation Plasma treatments did not deteriorate the quality attributes of eggs. An increase in the RH of the carrier gas improved the decontamination efficacy of cold plasma.	Georgescu et al., 2017
Egg	Direct DBD	15	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	6.4		
Egg	Direct DBD	5	1	–	85	Air	*S. enterica*	7.3	2		
Egg	Direct DBD	10	1	–	85	Air	*S. enterica*	7.3	3.6		
Egg	Direct DBD	15	1	–	85	Air	*S. enterica*	7.3	6.1		
Egg	Indirect DBD	5	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	2.3		
Egg	Indirect DBD	10	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	2.8		
Egg	Indirect DBD	15	1	–	85	$O_2+CO_{2+}N_2$	*S. enterica*	7.3	4.3		
Egg	Indirect DBD	5	1	–	85	Air	*S. enterica*	7.3	1.3		
Egg	Indirect DBD	10	1	–	85	Air	*S. enterica*	7.3	2.2		
Egg	Indirect DBD	15	1	–	85	Air	*S. enterica*	7.3	2.1		
Egg	Direct DBD	2	1	10	25	Dried He	*S. enterica*	8.01	0.10		
Egg	Direct DBD	4	1	10	25	Dried He	*S. enterica*	8.01	0.79		
Egg	Direct DBD	6	1	10	25	Dried He	*S. enterica*	8.01	1.06		
Egg	Direct DBD	8	1	10	25	Dried He	*S. enterica*	8.01	1.38		
Egg	Direct DBD	10	1	10	25	Dried He	*S. enterica*	8.01	1.51		

(*Continued*)

Table 2–Continued.

Product	Plasma source	PT	PV	F	V	CG	Microorganism	Initial load	MLR	Salient results	Reference
Egg	Direct DBD	2	1	10	25	Dried He+1% O_2	*S. enterica*	8.01	0.35		
Egg	Direct DBD	4	1	10	25	Dried He+1% O_2	*S. enterica*	8.01	0.89		
Egg	Direct DBD	6	1	10	25	Dried He+1% O_2	*S. enterica*	8.01	2.27		
Egg	Direct DBD	8	1	10	25	Dried He+1% O2	*S. enterica*	8.01	3.10		
Egg	Direct DBD	10	1	10	25	Dried He+1% O_2	*S. enterica*	8.01	3.90		
Egg	Direc DBD	2	1	10	25	Dried He+2% O_2	*S. enterica*	8.01	0.32		
Egg	Direct DBD	4	1	10	25	Dried He+2% O_2	*S. enterica*	8.01	0.99		
Egg	Direct DBD	6	1	10	25	Dried He+2% O_2	*S. enterica*	8.01	1.79		
Egg	Direct DBD	8	1	10	25	Dried He+2% O_2	*S. enterica*	8.01	2.66		
Egg	Direct DBD	10	1	10	25	Dried He+2% O_2	*S. enterica*	8.01	3.51		
Egg	Direct DBD	2	1	10	25	He+1% O_2 (RH = 40%)	*S. enterica*	7.97	0.81		
Egg	Direct DBD	4	1	10	25	He+1% O_2 (RH = 40%)	*S. enterica*	7.97	1.68		
Egg	Direct DBD	6	1	10	25	He+1% O_2 (RH = 40%)	*S. enterica*	7.97	2.82		
Egg	Direct DBD	8	1	10	25	He+1% O_2 (RH = 40%)	*S. enterica*	7.97	3.66		
Egg	Direct DBD	10	1	10	25	He+1% O_2 (RH = 40%)	*S. enterica*	7.97	4.84		
Egg	Direct DBD	2	1	10	25	He+1% O_2 (RH = 80%)	*S. enterica*	7.97	1.2		
Egg	Direct DBD	4	1	10	25	He+1% O_2 (RH = 80%)	*S. enterica*	7.97	2.71		
Egg	Direct DBD	6	1	10	25	He+1% O_2 (RH = 80%)	*S. enterica*	7.97	4.24		
Egg	Direct DBD	8	1	10	25	He+1% O_2 (RH = 80%)	*S. enterica*	7.97	5.54		
Egg	Direct DBD	10	1	10	25	He+1% O_2 (RH = 80%)	*S. enterica*	7.97	7.97		
Egg	Indirect DBD	5	1	10	25	Dry air	*S. enterica*	8.04	1.40		
Egg	Indirect DBD	10	1	10	25	Dry air	*S. enterica*	8.04	2.64		
Egg	Indirect DBD	15	1	10	25	Dry air	*S. enterica*	8.04	3.69		
Egg	Indirect DBD	20	1	10	25	Dry air	*S. enterica*	8.04	4.42		
Egg	Indirect DBD	25	1	10	25	Dry air	*S. enterica*	8.04	5.11		
Egg	Indirect DBD	30	1	10	25	Dry air	*S. enterica*	8.04	5.55		

(*Continued*)

Table 2–Continued.

Product	Plasma source	PT	PV	F	V	CG	Microorganism	Initial load	MLR	Salient results	Reference
Egg	Indirect DBD	5	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	0.76		
Egg	Indirect DBD	10	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	1.49		
Egg	Indirect DBD	15	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	2.11		
Egg	Indirect DBD	20	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	2.69		
Egg	Indirect DBD	25	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	3.56		
Egg	Indirect DBD	30	1	10	25	Air (RH = 40%)	*S. enterica*	8.04	3.93		
Egg	Indirect DBD	5	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	1.70		
Egg	Indirect DBD	10	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	2.98		
Egg	Indirect DBD	15	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	4.34		
Egg	Indirect DBD	20	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	5.40		
Egg	Indirect DBD	25	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	8.04		
Egg	Indirect DBD	30	1	10	25	Air (RH = 80%)	*S. enterica*	8.04	8.04		
Egg	Glow	10	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	1.03	Plasma treatment reduced the population of Salmonella on the egg surface. Treatment time and the carrier gas composition affected the inactivation rate. Plasma treatment did not deteriorate the quality parameters of the egg.	Ragni et al., 2010
Egg	Glow	20	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	1.61		
Egg	Glow	30	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	1.66		
Egg	Glow	45	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	1.42		
Egg	Glow	60	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	2.23		
Egg	Glow	90	1	12.7	15	Air (RH = 35%)	*S.* Enteritidis	6.76	2.49		
Egg	Glow	10	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	1.29		
Egg	Glow	20	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	1.61		
Egg	Glow	30	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	2.22		
Egg	Glow	45	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	2.41		
Egg	Glow	60	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	3.33		
Egg	Glow	90	1	12.7	15	Air (RH = 65%)	*S.* Enteritidis	6.26	4.55		
Egg	Glow	10	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	0.3		
Egg	Glow	20	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	0.5		
Egg	Glow	30	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	0.6		
Egg	Glow	45	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	1.4		
Egg	Glow	60	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	1.5		
Egg	Glow	90	1	12.7	15	Air (RH = 35%)	*S.* Typhimurium	5.6	2.4		
Egg	Glow	10	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	0.4		
Egg	Glow	20	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	0.7		
Egg	Glow	30	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	0.6		
Egg	Glow	45	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	1.8		
Egg	Glow	60	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	2.3		
Egg	Glow	90	1	12.7	15	Air (RH = 65%)	*S.* Typhimurium	5.8	3.4		

* MLR, maximum log reduction; PV, pressure value (atm); F, frequency (kHz); V, voltage (kV); PT, process time (min); CG, carrier gas; DBD, dielectric barrier discharge; PAW, plasma activated water; RH, relative humidity.
** Some of the values are approximated from the reported figures.

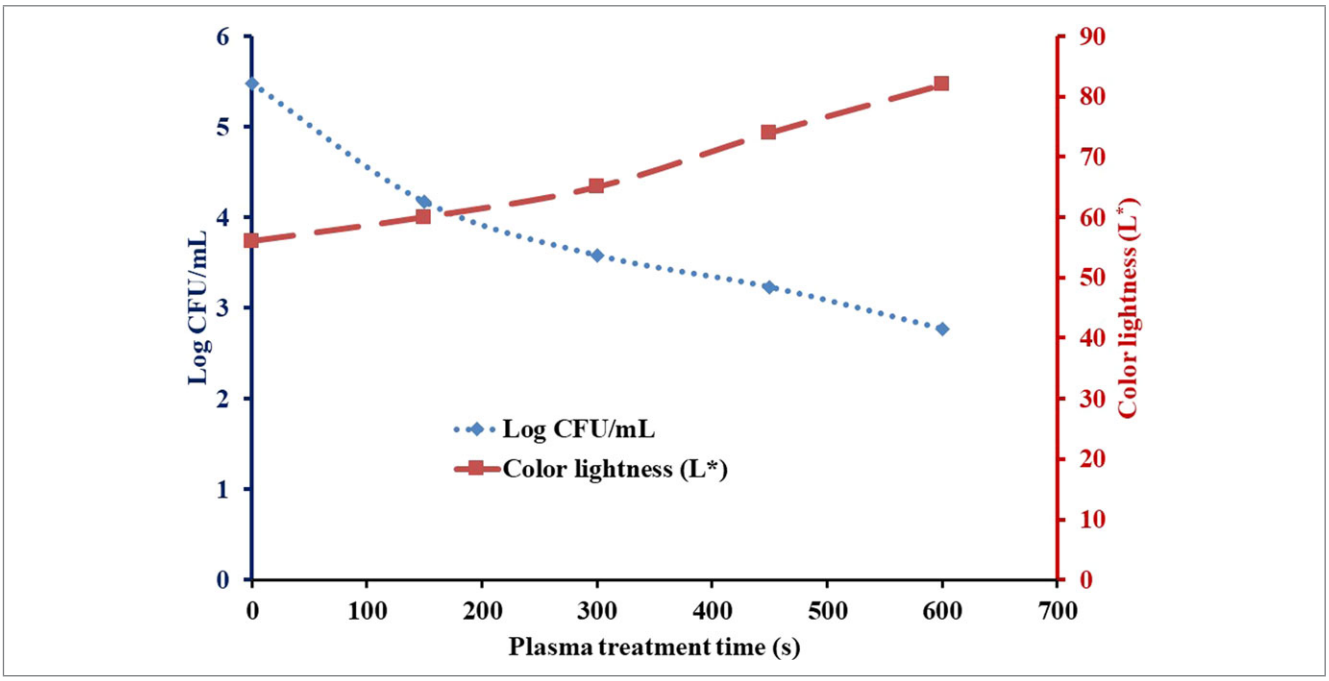

Figure 3–The effects of plasma treatment on the *Salmonella* count and the lightness of chicken breast samples according to the findings of Lee et al. (2016).

into the steam cooked egg yolk and egg white were confirmed by Lee et al. (2012). According to the authors, the optimization of the carrier gas composition can enhance the decontamination effects of the plasma jet. Using helium as the carrier gas decreased the population of the inoculated microorganism by 5 Log CFU in the cooked egg white, whereas replacing this gas with oxygen–nitrogen mixture boosted the decontamination efficacy of this process and reduced the *Listeria* counts by 6.7 Log CFU (Lee et al., 2012). In addition, this investigation showed that the rate of bacteria inactivation depends on the type of processed material as different results were reported for egg white and egg yolk under the same treatment conditions. This study highlighted the importance of process optimization, such as working gas composition, to enhance the decontamination effects of nonthermal plasma. The paper also highlighted the importance of selecting the appropriate food materials for plasma treatment as the results showed that both decontamination rate and quality attributes changes depend on the type of raw material (Lee et al., 2012). Similarly, Apostol et al. (2015) assessed the bactericide effects of jet plasma on the eggshells contaminated with *S. enterica*. According to the paper, 5 min of nonthermal plasma at the 20 kV amplitude inactivated all the available bacteria on the eggshell (Apostol et al., 2015).

Wan, Chen, Pankaj, and Keener (2017) explored the feasibility of *S.* Enteritidis deactivation by direct and indirect nonthermal plasma for eggshells. The study revealed that the decontamination efficiency depends on the carrier gas composition, treatment duration, and exposure mode, that is, direct or indirect plasma treatment. According to the results, the direct application of plasma was more effective than the indirect mode for *Salmonella* inactivation and 15 min of the direct and indirect plasma treatment under modified atmospheric conditions (65% oxygen, 30% carbon dioxide, and 5% nitrogen) reduced the *Salmonella* count by about 6.4 and 4.3 log cycles, respectively (Wan et al., 2017). It was previously proved that the UV radiation, charged particles, and short half-life species, such as O_2^-, N_2^+, OH^+, and N_2O^+, recombine before reaching the sample and only reactive species with longer half-lives, such as O_2, O_3, NO, NO_2, and CO, can interact with the sample in indirect plasma mode. On the other hand, all the above-mentioned components are in direct contact with the sample when plasma applied directly to the sample (Misra, Yadav, Roopesh, & Jo, 2019, Misra, Zuizina, Cullen, & Keener, 2013). A greater bactericidal effect can be expected in the extended plasma exposure times due to the increased concentrations of reactive species, such as ozone, and also because of subjecting microorganisms to reactive species for a longer period of time. Regarding the carrier gas composition, higher concentrations of oxygen resulted in a greater decontamination effect that was attributed to the generation of higher concentrations of reactive oxygen species. The results also demonstrated that increasing the carbon dioxide concentration in the gas mixture enhanced the decontamination effects of the plasma due to the generation of higher concentrations of carbon monoxide. Both carbon monoxide and carbon dioxide were reported to inhibit the growth of microorganisms and intensify the bactericidal effect of plasma (Chiper, Chen, Mejlholm, Dalgaard, & Stamate, 2011).

Georgescu (2015) proposed two DBD plasma-based systems for egg decontamination, namely direct and indirect nonthermal plasma. The egg was directly immersed into the helium–oxygen plasma in the proposed direct system. On the other hand, the produced plasma passed over the eggs that were placed outside the plasma volume in the indirect system. The author measured the ozone concentration, which is one of the major bactericidal agents of the nonthermal plasma, to explore the effectiveness of the proposed systems. According to the paper, the concentration of this bactericidal agent reached to about 2,500 and 500 ppm after 5 min of optimized direct and indirect plasma application, respectively. The author pointed out that the concentration of the generated ozone in the direct system depends on the oxygen concentration and applied voltage while the surface area of high-voltage electrode and chamber volume are also important parameters in the

indirect system. The author claimed that the concentration of the generated ozone in the direct system, that is, 2,500 ppm, provides the desired level of egg decontamination. However, microbiological studies are necessary to verify the effectiveness of the proposed system against egg contaminants (Georgescu, 2015). In a similar study, Georgescu, Apostol, and Gherendi (2017) assessed the inactivation of *S. enterica* on eggshell by direct (eggs were in direct contact with produced plasma gas) and indirect (eggs located outside the plasma generation area) DBD plasma treatments at the input voltage of 25 to 30 kV and frequency of 10 to 12 kHz. The carrier gases were air and a mixture of helium–oxygen in the indirect and direct systems, respectively. This study highlighted the importance of gas composition in the direct mode of plasma treatment. According to the authors, incorporating 1% oxygen into the pure helium (as the carrier gas), enhanced the decontamination effects of direct plasma treatment and deactivated 99% of *Salmonella* cells on the eggshell (Georgescu et al., 2017). On the other hand, 6 min of direct plasma treatment with pure helium gas did not affect the CFU values of the egg surface. The role of oxygen, as the carrier gas, in enhancing the decontamination effect of nonthermal plasma previously discussed in the literature (Misra et al., 2013). The conducted study by Georgescu et al. (2017) also highlighted the importance of the relative humidity (RH) of the carrier gas for the indirect plasma decontamination of hen eggs (Georgescu et al., 2017). According to the paper, subjecting the contaminated eggs (initial *Salmonella* concentration of 8.04 Log CFU/egg) to a 20 min indirect plasma treatment using stationary ambient air (with RH of 40%) and humid synthetic air (with RH of 80%) resulted in a product with the bacteria count of 5.35 and 2.64 Log CFU/egg, respectively. Other researchers previously explained the importance of the presence of appropriate concentrations of water molecules in the carrier gas (Dobrynin et al., 2011; Guo, Huang, & Wang, 2015).

The study conducted by Ragni et al. (2010) also highlighted the importance of selecting the appropriate treatment time and moisture content for nonthermal decontamination of hen eggs. The authors explored the applicability of glow atmospheric gas plasma at the input voltage of 15 kV against *S.* Enteritidis and *S.* Typhimurium inoculated on the eggshell and observed that extending the process time enhanced the decontamination effects of plasma (Ragni et al., 2010). Similarly, the results showed that operating the glow plasma at higher moisture content (RH of 65% instead of 35%) resulted in a greater decrease in *S.* Enteritidis population (reduction value of 4.5 log CFU/eggshell compared with 2.5 Log CFU/eggshell, respectively).

Davies and Breslin (2003) applied the plasma activated air to disinfect the surfaces of contaminated eggs with *S.* Enteritidis. According to the authors, subjecting the eggs to the plasma gas for 5 min did not enhance the microbiological safety of the eggs and 15 min of exposure to the same gas only decreased the number of contaminated eggs by 10% (from 38% contaminated control eggs to 28% contaminated 20-min plasma treated egg; Davies & Breslin, 2003). This finding disagrees with several reports that confirmed the effectiveness of plasma activated air (indirect plasma) against egg concerning flora (Apostol et al., 2015; Georgescu et al., 2017; Lee et al., 2012; Ragni et al., 2010; Wan et al., 2017). In the conducted study by Davies and Breslin (2003), the gas plasma was generated in an isolated tube and was pumped into a cabinet that held contaminated eggs. It seems that pumping the plasma-activated air for a long distance provided the required time for recombination and inactivation of several reactive species with a short half-life (Misra et al., 2013). Therefore, the eggs were probably in contact with limited reactive components as compared to the direct plasma treatment. Moreover, the concentration of reactive species in the generated plasma air depends on the volume of the cabinet that kept the egg for plasma treatment as the higher volume of the cabinet can be translated to the higher dilution of the plasma components. Furthermore, all the egg surface (the whole egg) were assessed for microbial decontamination by Davies and Breslin (2003) but in many studies, which confirmed the decontamination effects of plasma, only the part of the shell that was in direct contact with plasma investigated for microbiological tests (Georgescu et al., 2017). Finally, extending the plasma exposure time may result in a greater decontamination effect of plasma treatment (Wan et al., 2017) as longer process times enhanced the effectiveness of plasma gas application from 0% to 10% in their study. Therefore, a similar study with optimized conditions may result in a higher percentage of decontaminated eggs after indirect plasma treatment.

Effects on the Quality Parameters of Poultry Products

Most of the available processes in the poultry and food industries can affect product quality parameters such as its physical, nutritional, and sensory attributes. These changes are also inevitable in many emerging techniques including nonthermal plasma. Undesirable changes in the quality attributes of poultry products, such as their appearance and color, can affect the consumer acceptability (Samant et al., 2015). Research revealed that plasma treated products may experience color changes (Lee et al., 2016; Ragni et al., 2010), lipid oxidation (Gavahian, Chu, Mousavi Khaneghah, et al., 2018; Lee et al., 2012), and sensory quality deterioration (Aly, 2013; Lee et al., 2016).

Quality attributes of the plasma-treated eggs

External egg quality. Wan et al. (2017) reported that 15 min of glow plasma treatment of egg at the input voltage of 85 kV did not alter the external quality parameters of egg such as egg weight (Wan et al., 2017). A similar observation was made when chicken eggs were subjected to afterglow corona discharge air plasma for 12 hr (Puligundla, Choi, & Mok, 2016). On the other hand, Ragni et al. (2010) evaluated the effect of resistive barrier discharge plasma on the eggshell quality and reported that this decontamination process slightly altered the color of the eggshell and increased the greenness of the disinfected product (Ragni et al., 2010). According to the scanning electron microscope analysis, both cuticle and the inner surface of the internal shell membrane were not affected by this plasma treatment. This could be considered as a promising result as the cuticle is the first defensive structure of the egg against microorganisms and any damage to this layer can shorten the shelf-life of the egg (Messens, Grijspeerdt, & Herman, 2005). Similar results were reported by Georgescu et al. (2017) regarding the nonthermal processed eggs with good cuticle coverage. The results from the micrographs indicated that direct and indirect plasma processes did not destroy the cuticle structure as compared to the control sample.

Internal egg quality. The previously conducted studies showed that plasma treatment usually did not alter the pH of eggs (Lee et al., 2012; Puligundla et al., 2016; Ragni et al., 2010). Besides, it was reported that Haugh unit, vitelline membrane strength, and yolk color of untreated egg samples were similar to those of the eggs that were subjected to 85 kV glow plasma for 15 min (Wan et al., 2017). Likewise, Puligundla, Choi, and Mok (2016) studied the effects of a 20-kV afterglow corona discharge air plasma on some internal quality of chicken eggs and reported

that yolk index and Haugh units of the plasma-treated eggs were similar to those of untreated (control) samples (Puligundla et al., 2016). Similarly, Ragni et al. (2010) showed that resistive barrier discharge plasma treatment did not affect the yolk index. (Ragni et al., 2010). Lee et al. (2012) studied the effects of a plasma treatment (2 kV micro atmospheric pressure plasma jet for 2 min) on some quality parameters of cooked egg white and egg yolks. According to the authors, plasma treatment reduced the lightness (L* value) of both egg yolk and egg white but did not affect a* and b* values of the studied samples. These authors also showed that TBARS value of the plasma-treated samples were similar to those of the untreated samples. They also reported that the sensory quality of the plasma-treated egg white was similar to that of untreated samples (Lee et al., 2012). Likewise, Puligundla et al. (2016) reported that 12 hr of afterglow plasma treatment did not alter the sensory attributes (for example, appearance, texture, flavor, and aroma) of the chicken eggs (Puligundla et al., 2016). On the other hand, the plasma treatment changed the sensory attributes, such as taste, flavor, and overall acceptability, of the cooked egg yolk (Lee et al., 2012).

Quality attributes of the plasma-treated poultry meat products

Color and appearance. Wang, Zhuang, Hinton, and Zhang (2016) applied DBD plasma on the chicken fillet and observed no significant changes in the lightness of the treated sample for 3 min at the input voltage of 80 kV (Wang et al., 2016). Likewise, Wang et al. (2018) reported that the color values of the plasma-treated chicken fillets (9 min at the input voltage of 80 kV) were the same as the untreated sample (Wang et al., 2018). On the other hand, it was reported that DBD plasma treatment of chicken breast resulted in a meat product with a greener color (Lee et al. 2016). It is hypothesized that this type of discoloration can be induced by the conversion of myoglobin into other compounds including choleglobin, sulphmyoglobin, verdoheme, nitrimyoglobin, and nitrihemin (Yong et al., 2018). In a similar manner, Lee et al. (2016) reported that L* and b* values of chicken breast increased following 10 min of jet plasma treatment (Lee et al., 2016; Figure 3). On the other hand, this nonthermal process resulted in a product with a reduced a* value as compared to the control sample. Similar results, that is, no significant change in the a* and b* but an increase in the L* value, were reported when chicken breast samples were treated by DBD plasma (Zhuang et al., 2019).

It was reported that 3 min of jet plasma treatment did not affect the ΔL^* values of chicken breast and chicken skin samples using argon as the carrier gas when the working distance was 12 mm distance (Rossow et al., 2018). However, decreasing the working distance from 12 to 8 mm increased the ΔL^* value of the chicken breast by about 3 units. The authors mentioned that this change was visible as a slight centric brightening. According to the paper, dehydration and denaturation of meat proteins could be the possible reasons for this change in the product lightness as plasma treated samples experienced higher temperatures (about 45 °C) than the control samples (refrigerated samples). On the other hand, the same plasma treatment did not alter the chicken skin lightness as lower protein content and the lighter color of skin resulted in the reduced and concealed changes through the protein denaturation, respectively. The authors also showed that a* and b* values of the plasma-treated samples were similar to that of the control sample (Rossow et al., 2018). A research conducted by Lee et al. (2012) showed that 10 min of atmospheric pressure jet plasma decreased the lightness of both cooked egg yolk and egg white (Lee et al., 2012).

Sensory attributes. Aly (2013) showed that jet plasma treatment did not negatively affect the sensory properties of sliced chicken and the plasma-treated samples had the similar appearance, flavor, and texture to that of the control (no plasma treatment) sample (Aly, 2013). On the other hand, it was reported that nonthermal plasma treatment can induce unpleasant flavors in the chicken breast (Lee et al., 2016). According to the author, the plasma-treated chicken breast had a less intensity of pleasant chicken flavor and higher intensity of an unpleasant flavor. However, the sensory evaluation results implied that the sensory acceptability of this product was similar to that of the untreated (control) sample.

Lipid Oxidation. A limited number of reports have been published on the plasma-induced lipid oxidation in the poultry meat products. For example, Lee et al. (2016) reported that 10 min of nonthermal plasma treatment did not induce lipid oxidation in the chicken breast (Lee et al., 2016). However, it is necessary to monitor this deteriorative chemical reaction when high-fat content food materials, such as chicken skin, are treated by cold plasma (Gavahian, Chu, Mousavi Khaneghah, et al., 2018).

Considerations and Limitations

Despite numerous proposed applications of nonthermal plasma in the poultry industry, including chicken and egg decontamination, this technology is still in its infancy and its limitations should be considered and addressed prior to its commercialization. Safety validation of the product and process by regulatory bodies are a key consideration for many of its prospective applications in the poultry industry. Especially, the genotoxicity safety of the decontaminated egg and chicken meat should be confirmed by the legislative bodies. Fortunately, some research tried to address this concern such as Lee et al. (2012), and Lee et al. (2016). However, further comprehensive evaluations can facilitate the commercialization of this technique in the poultry industry.

Besides, the potential negative effects of plasma treatment on the quality attributes should be considered (Muhammad et al., 2018). While the unpleasant physical changes may only affect the consumer acceptability and result in the economic loss, the chemical changes, such as lipid oxidation, may lead to both economic loss and production of health-concerned products (Gavahian, Chu, Mousavi Khaneghah, et al., 2018). Fortunately, a number of previously conducted research showed these negative changes can be minimized by the optimization of process parameters, including the input power, carrier gas composition, and process time. In addition, selecting the appropriate raw materials and especially avoiding treatment of high-fat content products, such as egg yolk (Lee et al., 2012) and chicken skin (Rossow et al., 2018), should be taken into account to minimize unpleasant chemical reactions. These precautions could be combined with selecting appropriate carrier gas composition to limit the oxidation reactions (Gavahian, Chu, Mousavi Khaneghah, et al., 2018). Incorporation of antioxidant compounds (for example, essential oils) is also suggested as a technique to reduce the possibility of lipid oxidation during plasma treatment (Gavahian, Chu, & Sastry, 2018; Gavahian, Hashemi, Mousavi Khaneghah, & Mazaheri Tehrani, 2013; Lorenzo et al., 2018).

Regarding product decontamination by nonthermal plasma, it should be noted that the nonuniform surface of some poultry products, such as chicken skin or whole chicken, can enhance the survival rate of microorganisms and reduce the efficacy of the process. Besides, the uniformity and the penetration depth

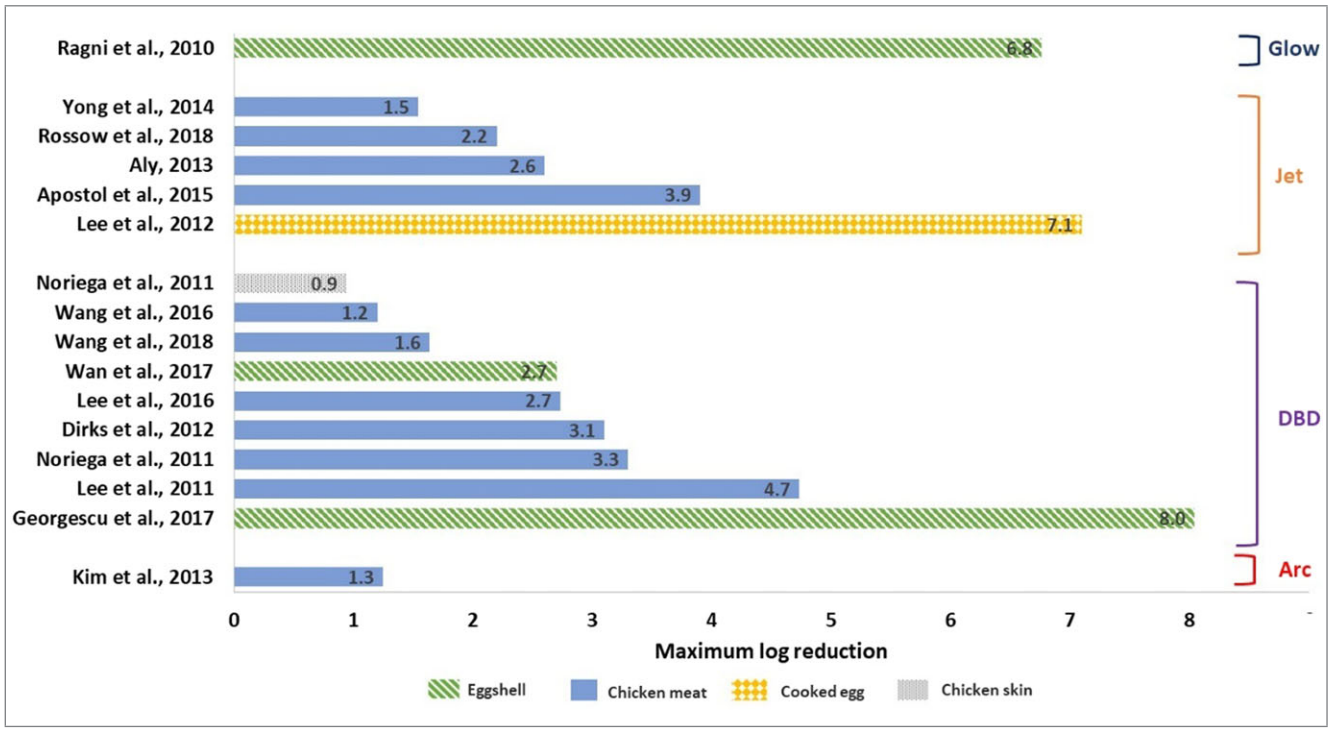

Figure 4–The highest decontamination efficacy (maximum log reduction) of various cold plasma technologies for eggshell, chicken meat, cooked egg, and chicken skin. The information provided regardless of process conditions and type of microorganism. Refer to Table 1 and 2 for detailed information of each study.

of the plasma are important considerations. Appropriate process design, process parameters optimization, and appropriate selection and preparation of the raw materials may address these concerns. Furthermore, the challenges involved in continuous process design may prevent several farmers and food processors from replacing the conventional methods with novel nonthermal plasma unless engineers and researchers can develop affordable continuous plasma equipment. Overall, there are some limitations for commercial application of cold plasma in the poultry industry at this moment that can be overcome after further research and technological development.

Future Trends and Research Needs

Further research may explore the optimizations of plasma conditions to maximize its beneficial effects (for example, the decontamination efficiency), and to minimize its potential deteriorative effects on the treated product including plasma-induced lipid oxidation (Gavahian, Chu, Mousavi Khaneghah, et al., 2018), unpleasant flavor (Lee et al., 2016), and color changes (Lee et al., 2016; Rossow et al., 2018). In addition, the previously conducted studies showed that employing various types of plasma technology (for example, DBD, glow, or arc) for various types of poultry products (for example, eggshell, chicken meat, or chicken skin) can result in different degrees of decontamination (Figure 4). Therefore, selecting the appropriate equipment for processing each product can be explored in future studies to improve the current understanding of the appropriateness of the available plasma technologies for poultry products processing.

In addition, further chemical and genotoxicity studies of the plasma-treated poultry products can be suggested. As one of the rare examples, Aly (2013) showed that jet plasma treatment did not introduce any undesirable change in the chemical composition of sliced chicken. Lee et al. (2012) reported that a plasma-treated chicken breast passed genotoxicological safety assessment using the Ames test. The genotoxicological safety of this nonthermal process was also confirmed for chicken breast in another study (Lee et al., 2016). Similar information and officially approved reports are prerequisites for the endorsement of regulatory bodies and industrial adoption of this emerging technology in the poultry industry. Furthermore, the safety of the operator of plasma equipment and the potential negative impacts of subjecting to free radicals and reactive species necessitate comprehensive physiological and oncological studies on this topic along with required safety precautions.

The future advancements and commercial applications of nonthermal plasma in the poultry industry are associated with the available process design knowledge, industrial equipment, their cost and effectiveness, and the importance of the drawbacks of the conventional technique that needed to be addressed by the new process. Upscaling studies are also necessary to comply with the high-capacity poultry production lines of many factories. Replacing the conventional production lines with plasma-based equipment might be disregarded unless the researchers can design effective and low-price plasma equipment, explore its benefits, and minimize associated challenges. A good effort regarding the continuous plasma treatment of fresh produce has been recently done (Ziuzina et al., 2016). However, more comprehensive efforts related to poultry products are also required. Furthermore, considerations in process design, such as hygienic design, should be taken into account in the future commercial design of nonthermal plasma.

Moreover, combining nonthermal plasma with other preservation technique can be considered in future studies. For example, decontamination of the poultry products along with appropriate

packaging techniques or in combination with suitable essential oil may enhance the product shelf-life and reduce the potential negative effects of plasma on product quality. It was previously reported that the antimicrobial and antioxidant effects of essential oils, as natural additives, may enhance the effectiveness of nonthermal processes, such as plasma, and reduce the required process intensity (Gavahian & Farahnaky, 2018; Gavahian, Chu, & Sastry, 2018; Lorenzo et al., 2018).

Finally, the potential applications of plasma-activated water in the poultry industry might also be an interesting topic for future research. It was reported that plasma-activated water can be effective against some of the major spoilage bacteria of the poultry products (Xiang, Kang, Niu, Zhao, & Li, 2004) but its effectiveness on poultry products and its effect on the product quality and safety should also be investigated.

Conclusions

Nonthermal plasma treatment has attracted the attention of food scientists because of its prospective benefits in enhancing the safety of poultry products. Academic research has so far revealed that this technique can be used for decontamination of chicken eggs and meat. Future research may reveal more potential applications of cold plasma for poultry products. Previously published reports introduced cold plasma as a promising tool for enhancing the microbiological safety of poultry products. In this regard, process optimization (for example, appropriate treatment time) is a crucial consideration. On the other hand, it should be noted that the uncontrolled plasma treatment may negatively affect the quality parameters of the product which should be considered in the commercial process design. Furthermore, the unavailability of high-capacity plasma equipment that can be applied to poultry products is among the obstacles for the successful commercial application of this emerging technique. Food and machinery engineers are also expected to develop appropriately upscaled and continuous plasma-based equipment with reasonable prices through prospective comprehensive studies in this area. From the current state of the research and published literature, we believe that future investigations may address these required steps for successful commercialization of nonthermal plasma in the poultry industry.

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Author Contributions

Mohsen Gavahian was responsible for designing the study, literature review, and drafting the manuscript. Yan-Hwa Chu supervised the work and collaborated in discussing challenges associated with industrial adaptation of this technique and future research needs. Cheorun Jo critically revised the manuscript and extended the discussions. All the authors reviewed the final manuscript before submission.

Nomenclature

CFU	colony-forming unit
CG	carrier gas
DBD	dielectric barrier discharge
F	frequency
MAP	modified atmosphere packaged
MLR	maximum log reduction
PAW	plasma activated water
PT	process time
PV	pressure value
RH	relative humidity
SEM	scanning electron microscopy
TBARS	2-thiobarbituric acid reactive substances
UV	ultraviolet
V	voltage

Conflict of Interest

The authors have declared no conflict of interest.

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