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REVIEW ARTICLE

Cold Plasma Technology Impact on Microorganisms Inactivation in Foods: A Systematic Review

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KEYWORDS

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ABSTRACT: Cold plasma is a high-end technology that offers favorable opportunities for microorganism inactivation in contaminated food. This review aimed to evaluate the efficacy of cold plasma treatment to reduce different pathogen and spoilage microorganisms in various foods. In addition, the effect of influential factors related to plasma processing, including microorganism type, gas type, treatment time, and treatment voltage, on the reduction rate of microorganisms was assessed using principal component analysis and hierarchical cluster analysis. The extracted data showed that most researcher investigated plasma efficiency on the inactivation of *Escherichia coli* in different food samples. Also in most studies the plasma was generated using air as plasma gas. The microorganism inactivation rate obtained by cold plasma treatments was raging from -0.90 to 8.00 log CFU. The plasma voltage (0.7) and plasma gas (0.66) had a significant correlation with principal component 1 and had a negative correlation coefficient with treatment time (-0.76). The reduction rate (0.68) and microorganism (0.7) were positively correlated with principal components 2. The findings indicated that cold plasma has an excellent potential to decontaminate hazardous organisms in different food. Besides, plasma treatment conditions should be considered to optimize the effective inactivation rates. The reduction rate of microorganisms in different foods is strongly influenced by microbial factors and technical plasma performance factors. Regarding the crucial damage to microorganism cell components using plasma, this novel technology could efficiently apply for preservation and also promote the shelf life of food products.

INTRODUCTION

Plasma is one of the states of matter generated by gas ionization. Generated plasma contains various excited atomic, ions, radicals, and reactive species that have unique features. Based on thermodynamic, the plasma is classified into hot and cold. Cold plasma can produce by different gases, including oxygen, helium, argon, and air, via electrodes from the source power of dielectric barrier discharge or microwaves [1]. Plasma-generated reactive species have been demonstrated significant bactericidal effects and have a critical oxidative damage impact on the cell membrane, lipid, DNA and enzyme, and other intracellular components. Consequently, possible chain reactions might lead to the death of vulnerable microorganism cells [2, 3].

Food-borne diseases affect millions of people and cause hospitalization and death cases annually worldwide [4, 5]. The Rapid Alert System for Food and Feed (RASFF) has considered food contamination with pathogenic

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microorganisms as one of the top ten hazards in annual reports [4]. Generally, the raw and some low processed food product could contaminate from farm to fork chains and make it a carrier for pathogens [6-8]. The most countered outbreak pathogen reported from contaminated food were *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, *Campylobacter jejuni*, and *Staphylococcus aureus* [9]. On the other hand, several microorganisms cause food spoilage and result in vast amounts of food losses. Since both spoilage and pathogenic organisms in food products can provide an alarm on food safety, the inhibition/inactivation of harmful microorganisms in foods is a crucial need [10, 11]. Several chemical and physical-based methods have been used in the food industry to eliminate microbial contaminants [12-14]. Although some practices have successfully reduced food microorganisms, there are public concerns regarding the generation of a carcinogenic agent or their residues and the nutritional losses [3, 15-17]. Recently, cold plasma has been considered a non-thermal technology for disinfection and sterilization, especially for the inactivation of bacteria, yeasts, molds, and spores also inhibit biofilms formation. In comparing heat treatment and other food processing, this technique is simple, non-invasive, safe, available, and does not need complicated conditions. It has been appropriately applied for decontaminating food surfaces without any deterioration of overall quality [18-21].

Numerous studies have been carried out to investigate the impact of cold plasma on microorganisms. Moreover, cold plasma has been recommended as an effective alternative treatment for the inactivation of food microorganisms, including pathogens and spoilage ones. However, several factors related to the used experimental conditions may influence the technique's efficacy regarding microorganism inactivation rate [8, 22-26].

This systematic review aimed to evaluate the efficiency of cold plasma based on microorganism strain, food product, plasma type, plasma gas, plasma treatment condition, and the reduction rate. Besides, using multivariate statistical analysis to obtain information from the dataset regarding the operation conditions of plasma on microorganism inactivation efficiency in foods. These multivariate techniques were applied here to extract the information about the most relevant parameters.

MATERIALS AND METHODS

Search strategy

The significant studies were searched in references from Scopus, Google Scholar, Web of Science, and PubMed database since January 29th, 2021. The noticed keywords for the systematic search were including: ("cold plasma"; "cold plasma treatment" or "Atmospheric-Pressure cold plasma") and (“bacteria”; "food-borne pathogens"; "microorganism"; "bacterial endospores"; "yeast" or "fungi") and ("reduction"; "inactivation"; "shelf life"; "antimicrobial efficacy"; "antimicrobial"; "antibacterial"; "degradation”; “decontamination”; sterilization or “destruction”). The possible potential relevant publications were found by manual search and only the articles in English were considered. The doubled articles were eliminated, and two researchers have reviewed all reports based on the titles and the abstracts. Article screening was done according to determining criteria: (1) an experimental study, (2) use of the cold plasma technique for reducing microorganisms, (3) performed on food, (4) mention of the reduction/inactivation rate or content. Any article that didn't match the criteria was excluded and any conflicts were fixed by consensus. Data were extracted from relevant studies and recorded as follows: first author's name, publication year, microorganism strain, food product, plasma type, plasma gas, plasma condition, treatment condition, the mean content of microorganism before treatment, the mean range of microorganism after treatment, reduction rate, and reported effect size [27].

Statistical analysis

Multivariate statistical data was performed to describe the correlation among the treatment variables. The principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to explore and extract the contributing dimensions by SPSS software (Version 18.0; Illinois, USA).

RESULTS

Extracted data

The study's search process showed that in the initial systematic search, 1214 potentially relevant articles were found. From them, 91 publications were duplicates, and 1075 were not eligible based on performed screening. Finally, 48 publications were reviewed as included for the systematic review, and 29 were considered for the data extraction. The general characteristics of all included studies are classified in Table 1.

Table 1. The inactivation of microorganism using cold plasma in foods.

Microorganism	Food sample	Plasma gas	Treatment Time (min)	Reduction (log CFU)	Reference
Brochothrix thermosphacta ***Pseudomonas fragi*** ***Psychrobacter glacincola***	Fish balls	Air	5	3.32-6.87	[28]
Listeria innocua	Queso Fresco cheese cheese model	Air	5	0.80-5.00	[29]
total count ***Aspergillus flavus*** ***yeast–mold count***	Military rations snack	Air	6	2.98-4.64	[30]
Escherichia coli O157:H10 ***Escherichia coli O157:H11*** ***Listeria monocytogenes*** ***Salmonella Typhimurium***	Walnut, Black pepper, Apple, Red Pepper, Cabbage, Cherry tomato, Eggplant, Papaya	Air	20, 21, 22, 23, 24, 25, 26	1.00-5.16	[7]
Salmonella enterica serovar Heidelberg	Dry stainless steel, Chicken breast, *Romaine lettuce*, Wet stainless steel	Air	3- 10	2.50-6.50	[31]
Escherichia coli	Water	argon	15	7.00	[32]
Citrobacter freundii	Apple juice	Oxygen/Argon, Argon	8	0.00-4.40	[33]
Salmonella	Freeze-dried pet foods	Air	10	0.20-3.30	[34]
Methicillin-susceptible S. aureus ***Staphylococcus aureus***	Cooked chicken breast	Air	5,20	0.33-2.29	[35]
Listeria innocua	Chicken breast Rough chicken skin Smooth chicken skin Chicken meat	Helium Helium/Oxygen	0.5,1,2,4, 8, 20	0.06-3.30	[36]
Escherichia coli	Drinking water	Argon	1 - 8	0.20-8.00	[20]
Escherichia coli ***Saccharomyces cerevisiae***	Chokeberry juice	Air	4	2.27 – 1.23	[37]
Zygosaccharomyces rouxii	Water	Air	30	1.10 – 5.60	[38]
Escherichia coli	Lettuce	Argon	10	1.50 – 2.00	[39]
Escherichia coli	Sour cherry juice	Oxygen/Argon	9	6.00	[19]

Aspergillus flavus	Pistachio nut	Argon	2,6,10	-0.90 – 1.30	[40]
Salmonella Typhimurium	Lettuce, cabbage	Nitrogen/Oxygen	5,10	1.10 – 1.50	[41]
Staphylococcus aureus, Listeria innocua	Ready-to-eat fish product	Argon, Helium	4, 6, 10	0.19 – 2.18	[42]
Aspergillus parasiticus	Hazelnuts	Air, SF6	5, 15	1.00 – 5.00	[43]
Listeria monocytogenes, Staphylococcus aureus	Pastırma (a dry-cured beef product)	Oxygen	5	0.83 – 0.85	[44]
Aspergillus flavus	*Lentil beans*	Argon	5, 10, 15	3.20 – 7.20	[45]
Escherichia coli O157:H10, Escherichia coli O157:H7, Escherichia coli O157:H8, Escherichia coli O157:H9, Listeria innocua, Salmonella Typhimurium	Cantaloupe, Tomato-smooth surface, Tomato-stem scar, Spinach	H_2O_2	30	1.30-6.30	[46]
Escherichia coli, Salmonella Choleraesuis, Salmonella Typhimurium	Apple	Air	0.5, 4	0.60 – 5.50	[3]
Escherichia coli, Gluconobacter liquefaciens, Listeria monocytogenes, Pseudomonas agglomerans, Saccharomyces cerevisiae	Cantaloupe melon, Mango, Melon	Helium	0.1, 0.4, 0.5, 0.6, 0.8, 1.6	0.65 – 6.00	[47]
Escherichia coli, Listeria innocua,	Fresh-cut apple	Oxygen/argon, Argon, Nitrogen, Oxygen	3, 5, 10, 15, 20	0.10 - 1.68	[48]
Aspergillus spp.	Chickpea, Corn, Rye, Oats, Barley, Lentil, Wheat	SF6	240	0.47 – 2.60	[49]
Escherichia coli O157:H7	Baby kale (*Brassica oleracea*) leaves	Air	1-5	3.48 – 6.00	[50]
Aerobic Plate Count ***Enterobacteriaceae*** ***Escherichia coli*** ***Psychrotrophs*** ***Salmonella enterica*** ***Yeasts and Molds***	Wheat grains	Air	5,10, 15, 20	0.33-3.29	[51]
Escherichia coli, ***Listeria monocytogenes, Salmonella enterica***	Cherry tomatoes, Strawberries	Ozone	0.1, 0.75, 1, 2, 5	1.10 – 6.30	[52]

In total, most researches (14 studies) were investigated on inactivation of *Escherichia coli*. The rate of microorganism inactivation by cold plasma was raging from -0.90 to 8.00 log CFU. The highest reduction rate (8 log CFU) using cold atmospheric plasma was reported for the inactivation of *Escherichia coli* in drinking water [20]. The total mean inactivation rate from all reviewed studies was 2.71 log CFU. The reduction range related to each strain inactivated by cold plasma is given in Table 1.

The food samples used in cold plasma treatment were lettuce, cabbage, ready-to-eat fish product, pistachio nut, apple juice, chokeberry juice, drinking water, chicken breast, chicken skin freeze-dried pet foods, cabbage, black and red pepper, walnut, apple, papaya, eggplant, and cherry tomato.

Based on the used gas for the production of plasma, it was found that in most studies (13 studies); cold plasma was produced by air. The other gases were used for plasma generation for reducing food microorganisms were argon, helium, nitrogen, oxygen, ozone, SF_6, and H_2O_2. Also, in some studies, a mixture of gases (oxygen/argon, helium/oxygen, and nitrogen/oxygen) has been experimented. The sharing of studies regarding the used plasma gas is shown in Figure 1.

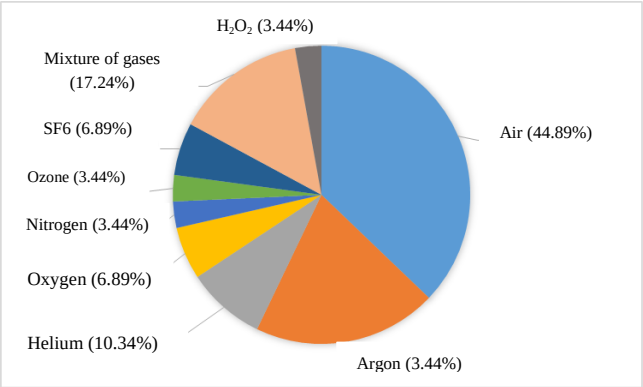

Figure 1. Sharing of studies regarding the used gas for plasma generation to inactivation of food microorganisms.

The principal component analysis

The multivariate statistical data analysis was used to investigate the variations of plasma-treated visually in food products. The reduction rate among the microbial groups was screened out at first, then, based on the plasma condition of this differential treatment, the PCA of microbial decontamination was performed to visualize the degree of reduction rate with cold plasma, which could clearly show the effect of plasma on food products. PCA was used to understand the relationships among the cold plasma processing conditions (time, voltage, and plasma gas) and microorganism type with inactivation rate. The cumulative contribution rate of principal components (PC) can be explained by 74% of the total variance. The plasma voltage (0.7) and plasma gas (0.66) had a very positive and significant correlation with PC1 (principal component group 1 as reduction rate) and had a negative correlation coefficient with treatment time (-0.76).

The results show that the reduction rate (0.68) and microorganism (0.7) were positively correlated with PC2 (principal components group 2 as cold plasma processing factors), and plasma gas had negative correlation coefficients. Hence, the plasma voltage showed the most similarity with the plasma gas. Discrepancies in the microbial decontamination found in the literature are depended on the operation conditions of plasma (voltage, time, and gas composition) [28, 29]. However, the data integrating microbial decontamination collected from the food products was misleading by neglecting experimental details of the operation and plasma flow. Thus, an interactive PCA with clustering analysis according to correlation information was created. Based on these observations, the inactivation efficiency of cold plasma processing was found to be mainly dependent on the treatment time and the type of microorganisms among all the samples (Figure 2).

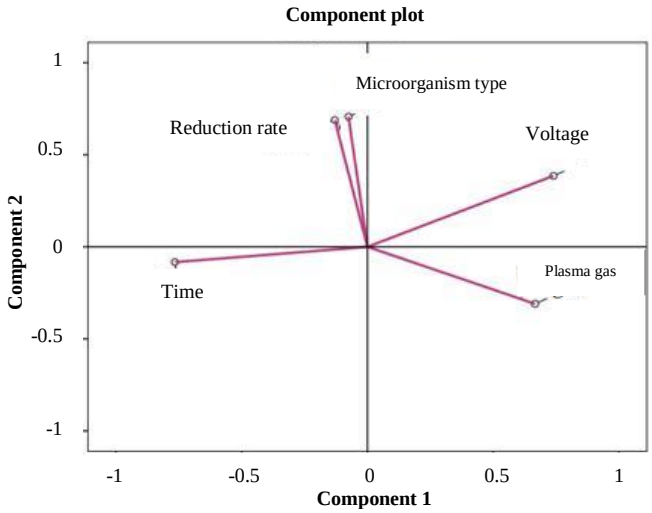

Figure 2. Principal component analysis (PCA) plot, performed on cold plasma processing for inactivation of microorganisms in foods.

Hierarchical cluster analysis

An overall cluster analysis based on cold plasma processing was conducted to investigate the general differences among microbial inactivation results. The similarities between the related factors were highlighted by a dendrogram produced by the HCA algorithm (Figure 3). There are two main clusters include; one set contains plasma voltage and gas composition, and the second one contains treatment time, reduction rate, and type of microorganism. Hence, reduction rate and type of microorganism had high similar effect trend in different samples. Also, the plasma voltage showed the most similarity with the plasma gas. The dendrogram can well reflect the impact of various conditions variables on cold plasma efficacy.

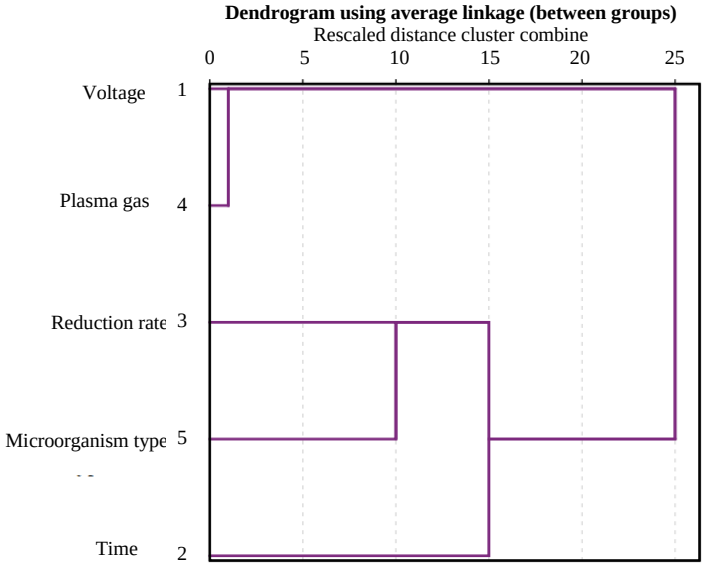

Figure 3. Hierarchical clustering dendrogram performed on cold plasma processing for inactivation of microorganisms in foods

DISCUSSION

The present study is a comprehensive review that systematically evaluated the cold plasma efficiency to inactivate food-borne and spoilage microorganisms. Based on the results, cold plasma had a significant capability to reduce microbial activities in different foods. In some cases, this technique can inactivate microorganism load in food samples thoroughly. The efficacy of plasma inactivation was strain-specific. Besides, the reduction rate depends on some treatment variables, including food type, plasma gas, voltage, and time.

The mechanism of microorganism inactivation using cold plasma

The focal point of the cold plasma technique is the cell membrane of microorganisms. The present electric force could cause severe damage to cell membranes. Besides, the generated reactive species in cold plasma provided oxidation conditions that stimulate damage or defects into the cell membrane and cellular constitutes [30, 31]. Consequently, all possible damages through cold plasma treatment seem to disrupt the cell and inactivate the microorganism. During the plasma process, the main component of microorganism cells such as DNA, proteins, enzymes, and lipid are changed significantly, resulting in loss of activity and cell death [30, 32, 33]. Taken together, some details associated with bacteria structure inactivation include denaturation of protein, peroxidation of lipid, deformation of cytoplasm, degradation of the cell wall, leakage of the cell, dissociation of the cell, degradation of DNA and RNA [34, 35].

Microbial factors affecting inactivation rate

Some microbiological aspects have a vital role in the inactivation process using cold plasma. The type and

strain of microorganisms directly impact the sensitivity to plasma treatment. In this regard, bacteria are more resistant than yeast and mold [36]. Although, viruses are more sensitive to plasma because of the lack of cell walls. Many different sensitivity outcomes have been reported among gram-positive and gram-negative bacteria. However, it was frequently estimated that the stable cell walls of gram-positive cells had more resistant to plasma-produced active species [37-39]. It was reported that the atmospheric cold plasma was more effective for the inactivation of *L. innouca* than *S. aureus* in ready-to-eat fish products [40]. Additionally, the growth mode of each pathogen is one of the main influencing factors. Based on the reviewed studies, microorganisms at the logarithmic phase were significantly sensitive to cold plasma, comparing stationary and death phases. It has been assumed that a more population of cells was affected by the electric field in the logarithmic phase and might be inactivated easily using cold plasma treatment [36].

The spore form of microorganism showed high resistance to any antimicrobial trial because of its structural properties. By applying cold plasma, the firm coat of the spore was damaged by reactive plasma species. Furthermore, it has been supposed that the germination process of spores is postponed through plasma treatment. Therefore, the inactivation of the spore could be well performed using the cold plasma technique [16].

The initial count of microorganisms could influence the effectiveness of cold plasma treatment. It was stated that the higher microbial concentration resulted in a lower inactivation rate. So the plasma is more efficient in the soft layer of cells. The survival model simulated in study by Wang revealed that increasing the initial content of *Zygosaccharomyces rouxii* in water samples had a significant negative correlation by yeast inactivation rate at plasma treatment. Whereas, the reactor dimensions variation had no notable effect [41]. The investigation of *Psychrobacter Giancola, Brochothrix thermosphacta*, and *Pseudomonas fragi* by cold plasma in fish ball samples resulted in a reduction trend depending on the used voltage, initial count, and contact time. The microstructure observation in plasma-treated cells indicated cell deformation, irregular wrinkling, surface pores, and irreversible damage in the cell wall and membrane [42].

Cold plasma efficacy against food-borne pathogens, including *Escherichia coli* O157: H7, *Salmonella Typhimurium*, and *Listeria monocytogenes* were studied in different foods. A negative correlation was observed between surface roughness and inactivation ratio. The cherry tomato had the more inactivation degree among other food samples. Also, a different reduction rate was obtained by increasing the time of treatment [7].

The main plasma technical factors affecting inactivation rate

Gas plasma

Different gas can be used to generate cold plasma, and microorganism inactivation grade will vary. The predominant gas that has been used in plasma investigation on an organism was the air. In various studies, the air-produced plasma has been experimented on different food products that illustrated significant microorganism inactivation results. It is found that the atmosphere cold plasma could successfully reduce *Psychrobacter glacincola, Brochothrix thermosphacta, and Pseudomonas fragi* in fish balls (6.8,4.8 and 3.3 log CFU) [42], *Listeria innocua* in cheese model (3.5 log CFU) [43], total count, yeast-mold count, and *Aspergillus flavus* in a snack (4.3, 4.6 and 2.9 log CFU) [44], *Escherichia coli* O157: H6 in cherry tomato, eggplant, papaya, apple, walnut, red pepper, and black pepper (4.1, 5.1, 4.7, 4, 1.5, 2.6, 2.6, 2.7 and, 1.3 log CFU, respectively) [7]. A survey showed argon plasma could significantly reduce the *S. aureus* survival (0.19-1.04 log CFU) compared to helium plasma (0.03 - 0.55 log CFU).

In an essay on optimum cold plasma conditions to reduce *Aspergillus flavus* in nuts samples, the reduction rate of 4 logs was obtained using argon [45]. Some researchers had followed the microorganism reduction by applying a mixture of more effective gases than pure gas in the plasma process. In a study reported, helium and oxygen mixture was used to reduce *Listeria innocua* in chicken samples. These authors reported that a notable reduction in D values was obtained by increasing the oxygen flow rate. Also, a significant log reduction resulted from

increased oxygen to helium at 10 s cold plasma treatment [46]. In a study reported that, by increasing the oxygen content in the combination of argon and oxygen as feeding gas, more *E. coli* were reduced in cherry juice samples. The combination of nitrogen and oxygen (4:1) in cold plasma treatment could reduce *Salmonella Typhimurium* population in cabbage (1.5 log) and lettuce (1.1 log) [47]. In the study of Jiang, the peroxide hydrogen gas was used in cold plasma method for inactivating *E. coli O157:H7*, *S. Typhimurium*, and, *L. innocua* on the plant food products, and the reduction rate was achieved to a remarkable level.

Different gas cold plasma models based on argon, nitrogen, oxygen, and argon-oxygen were investigated on apple samples against *Escherichia coli* and *Listeria innocua*. The results showed that argon, oxygen, and, mixture argon-oxygen as plasma-forming gas were more effective than nitrogen for inactivating *Escherichia coli* by 0.77, 0.61, and 0.65 log, respectively. Also, the most efficient treatment on *Listeria innocua* was gained via argon (0.64 log) and nitrogen (0.88) [48].

Plasma voltage

Effectiveness of cold plasma treatment to inactivate microorganisms can be influenced by plasma generation-related factors such as voltage and frequency. Although the used voltage depends on plasma equipment and other device parameters, the voltage should be selected carefully. Some studies indicated that the increase of voltage during cold plasma resulted in a higher microorganism inactivation rate. It has been reported that efficient reactive species are rising by increasing the voltage used in plasma treatment. The investigation of cold atmospheric plasma against pathogenic organisms (*E. coli*) and spoilage microorganisms (*Saccharomyces cerevisae, Pantoea agglomerans, and Gluconacetobacter liquefaciens*) in melon samples showed that voltage rising by 33% up to 16 kV resulted in more reduction rate [49]. High-level voltage may cause a notable decrease in sublethally injured cells and a significant rise in fatally damaged ones. Eventually, the trend of microbial damage tends to fatal way due to voltage increase. However, the effect of voltage regulation in plasma processing generally depends on the two leading treatment variables, including time and the type of gas. On the other hand, when plasma is used on food products, the applied voltage must fit food's Physico-chemical and rheological characterization. Based on the literature review, many different voltage ranges were applied for other gas in plasma treatment. In the case of plasma generation by air, the voltage of 220-226 kV was efficiently used for *Escherichia coli, Listeria monocytogenes, and Salmonella Typhimurium* inactivation in cherry tomato, eggplant, walnut, apple, cabbage, and red pepper [50], a voltage of 12.8 kV was significantly used for the reduction of *Psychrobacter glacincola, Brochothrix thermosphacta*, and *Pseudomonas fragi* in fish balls samples [42], also a voltage of 100 kV was applied for inactivation of *Listeria innocua* in cheese samples [51]. Furthermore, helium gas was significantly investigated at a voltage of 8 kV to reduce *Listeria innocua* in chicken samples [33]. A voltage of 12 kV could reduce *Listeria innocua* in ready-to-eat fish products [40]. Argon was efficiently applied at 20 kV to inactivate *Listeria innocua* and *Staphylococcus aureus* in ready-to-eat fish products [40]; however, plasma condition-related factors, including frequency, current, and electric field strength should be accounted for along with voltage.

Plasma time

In numerous studies, it was observed that the increase of plasma exposure time could enhance microorganism inactivation impact. The greater pathogen reduction rate occurs at a longer treatment time due to the production of more content of reactive plasma species. Besides, in increased treatment time, the plasma can inactivate such organisms is placed in the inner layer of food. However, some studies reported no significant change in microorganism reduction rate by increasing plasma processing time. A survey found that increasing the time of atmospheric cold plasma treatment from 5 to 20 min could increase the inactivation of *Staphylococcus aureus* from 0.44 to 2.09 log CFU in cooked chicken breast samples. An increasing trend was also observed in cold atmospheric gas plasma treatment for reduction of *Listeria innocua* in chicken breast in which expanded time (1,2,4, and 8 min) resulted in a higher inactivation rate (1.58, 1.61, 2.17, and 3.30 log CFU) [46]. Increasing the time from 2 to 5 min in cold plasma assessment on

strawberries samples showed a higher reduction of *Escherichia coli* (2.80 to 3.5 log CFU), *Salmonella enterica* (1.70 to 3.80 log CFU). However, no significant additional reduction (4.2 log CFU) was obtained for *Listeria monocytogenes* population at extended treatment time [52].

Other technical factors

The generation of reactive plasma species and their concentration also their activity may influence by some other technical factors. Regarding equipment parameters, the frequency and power are effective on cold plasma efficiency. Consequently, these factors should be noticed for better microbial disinfection. In aspect of process parameters, the electrode gap and relative humidity are also important factors that should optimize for an efficient cold plasma process. Based on equipment design some effective factors are including dielectric barrier material and its thickness, and electrodes materials, potency and its shape. All these operation condition influence the plasma properties. The control of influential factors is necessary before cold plasma treatment as pre-treatment stages.

Epilogue

This study systematically reviewed the literature on cold plasma treatment efficacy on pathogen and spoilage microorganisms inactivation in food. A multivariate statistical data analysis was used to evaluate the influence of the plasma processing conditions on organism reduction rate. According to extracted data, it was found that the cold plasma technique can significantly inactivate microorganisms in food. The most researchers were focused on the impact of cold plasma on *Escherichia coli.* Many different food samples from fruits, vegetables, meat, nuts, drinking water and juices were investigated in cold plasma experiments. Regarding the used gas for plasma generation in most studies it was produced by air. The microorganisms reduction achievement strongly depends on plasma operation performance. The principal component analysis confirmed that microbial decontamination rate was influenced by microorganism strain, gas type, treatment time, and voltage. Since hierarchical cluster analysis highlighted high similarity and correlation concerning the plasma variables, these factors need to be optimized for better efficiency. This novel nonthermal processing via energetic, reactive gases could apply for reducing microbial contamination in different food type. Also, for the subsequent process development and commercialization, the main technical factors must have been considered. Our findings provide insights into the effective inactivation of the harmful organisms in different food using cold plasma.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Competing interests

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

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