

Application of cold plasma technology in animal-derived foods: a review spanning 2019–2025

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Abstract: Animal-derived foods, including meat, aquatic products, dairy products, and eggs, constitute an important source of nutrition for humans. Traditional processing methods for animal-derived foods predominantly rely on thermal treatments; however, such approaches can lead to losses in nutritional components, texture, and flavour. Cold plasma technology, an emerging non-thermal processing technique, enables the treatment of animal-derived foods at low temperatures. This method effectively mitigates heat-sensitive losses of nutrients and textural properties while ensuring food safety. Consequently, it has garnered significant research interest in recent years regarding the processing and utilisation of animal-derived foods. This paper systematically reviews the research progress in applying cold plasma technology to animal-derived foods. The primary generation modes and operational mechanisms of cold plasma are initially reviewed. Subsequently, its characteristic effects within animal-derived food matrices—specifically microbial inactivation, textural modification, and alterations in nutritional components—are outlined. Finally, the limitations of current cold plasma technologies and potential future research directions are summarised. This review aims to provide a scientific reference for applying cold plasma technology to quality control and functional enhancement in the production and processing of animal-derived foods, whilst offering theoretical support for advancing its standardisation and industrial implementation.

Keywords: cold plasma; animal-derived food; nutritional components; food quality; food safety

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1 Introduction

Traditional animal-derived food processing techniques primarily rely on thermal processing methods such as high-temperature sterilisation, pasteurisation, drying, and evaporation. These thermal treatment technologies effectively deactivate microorganisms and extend the shelf life of food products^[1]. However, thermal processing techniques may adversely affect the nutritional content, flavour, and colour of food to some extent. For instance, excessive heating can lead to lipid oxidation and the denaturation of proteins and carbohydrates^[2]. Concurrently, excessive heat treatment can also alter the sensory, texture, and flavour properties of food, thereby compromising its overall quality^[1]. Therefore, finding a processing method that can effectively sterilise and preserve freshness while maximising the retention of food's original nutrients and flavour has become a significant challenge in the current food processing sector.

In physics, the four states of matter are solid, liquid, gas, and plasma. Among them, cold plasma refers to a non-equilibrium plasma in which the temperature of electrons is much higher than that of ions and neutral particles^[3]. Under atmospheric pressure and ambient temperature, cold plasma containing various active particles such as ions, free radicals, electrons, and photons can be generated through external electrical energy ionisation of gas. This technology, as an emerging non-thermal processing technique, has garnered significant attention in the food processing sector in

recent years^[4]. The high-energy electrons, ions, reactive free radicals, and other reactive species it generates can effectively inactivate microorganisms and decompose harmful substances without producing significant thermal effects on foodstuffs^[5], thereby avoiding the potential adverse impacts associated with conventional thermal processing. Research indicates that cold plasma not only effectively eliminates foodborne pathogens such as *Escherichia coli* and *Salmonella*, but also extends the shelf life of food products while reducing the use of chemical preservatives. Moreover, cold plasma has a relatively small impact on thermal-sensitive food constituents^[6], effectively reducing nutritional losses caused by thermal processing. Particularly for animal-derived foods, which are rich in heat-sensitive nutrients such as unsaturated fatty acids, vitamins, and proteins, these components are prone to degradation or loss during conventional thermal processing^[7]. Cold plasma technology, leveraging its non-thermal nature, effectively preserves the original texture, flavour, and key nutritional constituents while ensuring food safety^[8]. Moreover, the high perishability^[9] of animal-based products necessitates stringent microbial control, rendering cold plasma highly promising for non-thermal processing, storage, and preservation applications. Therefore, this review focuses on animal-derived foods to systematically review and explore the efficacy of cold plasma technology, providing a scientific basis for developing safe and quality-preserving processing strategies.

This review first systematically introduces the primary generation methods and operational mechanisms of cold plasma technology, encompassing the working principles of various techniques such as dielectric barrier discharge (DBD), plasma jet (PJ), and corona discharge (CD). Subsequently, it provides a detailed summary of research progress in applying cold plasma technology to meat, aquatic products, dairy, and eggs, outlining its advancements in enhancing food safety, extending shelf life, and modifying nutritional components. Furthermore, this review addresses the challenges and limitations encountered in applying cold plasma technology within the animal-derived food industry, whilst also outlining prospective avenues for its future development.

2 Primary generation methods and action mechanisms of cold plasma technology

The primary modes of cold plasma generation currently include DBD, PJ, CD, microwave discharge (MD), glow discharge (GD), gliding arc discharge (GAD), spark discharge (SD), and radio frequency discharge (RFD)^[9–10]. In Table 1 and Figure 1, we outline the process components of different cold plasma technologies alongside their application scenarios and respective advantages and disadvantages.

2.1 DBD

DBD is a widely adopted method for generating cold plasma. Its structure typically comprises two parallel electrodes and a layer of dielectric material^[26]. When an alternating voltage is applied between the electrodes, the intervening gas is ionised, thereby producing cold plasma. This technology operates under atmospheric conditions in an open environment, offering high compatibility with industrial equipment alongside advantages including low cost, operational safety, environmental sustainability, and user-friendliness^[27]. Consequently, DBD currently represents the most prevalent technique for cold plasma generation. The active

species generated by DBD primarily include reactive oxygen species (ROS), reactive nitrogen species (RNS), free radicals, and both positive and negative ions^[3]. These species effectively inactivate microorganisms on food surfaces through cellular structure disruption, thereby extending the shelf life of food products. Furthermore, they may induce modifications to food components such as proteins^[28] and lipids through oxidation. Such reactions can alter nutrient structures and reconfigure flavour compound profiles^[29–30], potentially affecting both nutritional value and sensory attributes. Therefore, precise control of process parameters such as treatment voltage, duration, and gas composition is essential in food processing to prevent excessive oxidation and unnecessary nutrient loss. DBD features simple operation^[31] and can easily produce uniform plasma under ambient conditions, making it highly suitable for surface sterilisation of bulk animal-derived foods such as meat. Nevertheless, owing to its limited penetration depth^[13] and requirement for a high electric field strength^[14], strict control over sample morphology and treatment distance is necessary when applied to aquatic products and liquid dairy matrices.

2.2 PJ

PJ, also known as atmospheric pressure plasma jet (APPJ)^[16], constitutes a technique whereby cold plasma is ejected through a nozzle onto food surfaces for treatment. The apparatus for generating such plasma typically comprises a power supply, gas source, discharge electrode, and nozzle components. The principle involves the ionisation of gas molecules under high pressure to form plasma. These active plasma particles are then delivered to the food surface via a nozzle in a spray form to achieve the desired effect. This technology offers considerable flexibility, being capable of generating uniform and stable discharges within localised areas^[15]. The resulting active particles effectively eliminate microorganisms on surfaces and within crevices, thereby delivering superior sterilisation efficacy and rendering it particularly well-suited for foodstuffs exhibiting complex surface shapes^[32]. This technology

Table 1 Advantages and disadvantages of cold plasma generation methods.

Cold plasma generation method	Advantages	Disadvantages	References
DBD	The electrode geometry can be flexibly modified to accommodate different configurations; readily available and cost-effective; operates at ambient temperatures, typically maintaining constant temperature during processing	Only capable of treating samples within a thickness range of several centimetres; the electric field strength of the supply gas must be sufficiently high	[11–14]
PJ	Generates uniform and stable discharges; enables precise localised treatment control; produces plasma discharges under low electric fields; compact size facilitates penetration into narrow crevices	Limited capability for large surface areas	[6,15–17]
CD	Simple apparatus, resulting in cost savings; operates at atmospheric pressure	Small and uneven treatment range; not suitable for processing thermally unstable foods	[13,16,18]
MD	Can substitute electrodes for plasma generation; capable of operating at both atmospheric and low pressure; suitable for continuous and scalable processes	Space constraints	[4,15–16,18]
GD	Operates at low pressure; operates at low temperatures	Requires a vacuum environment; cannot be directly applied to foods containing moisture or volatile components	[5,13,19]
Plasma-activated water (PAW)	Capable of disinfecting both regular and irregular surfaces; offers broad-spectrum germicidal efficacy, serving as an economical and environmentally friendly disinfectant; leaves no chemical residue	Difficult to achieve industrial standardisation; acidic properties may cause alterations in the physicochemical characteristics of food	[20–23]

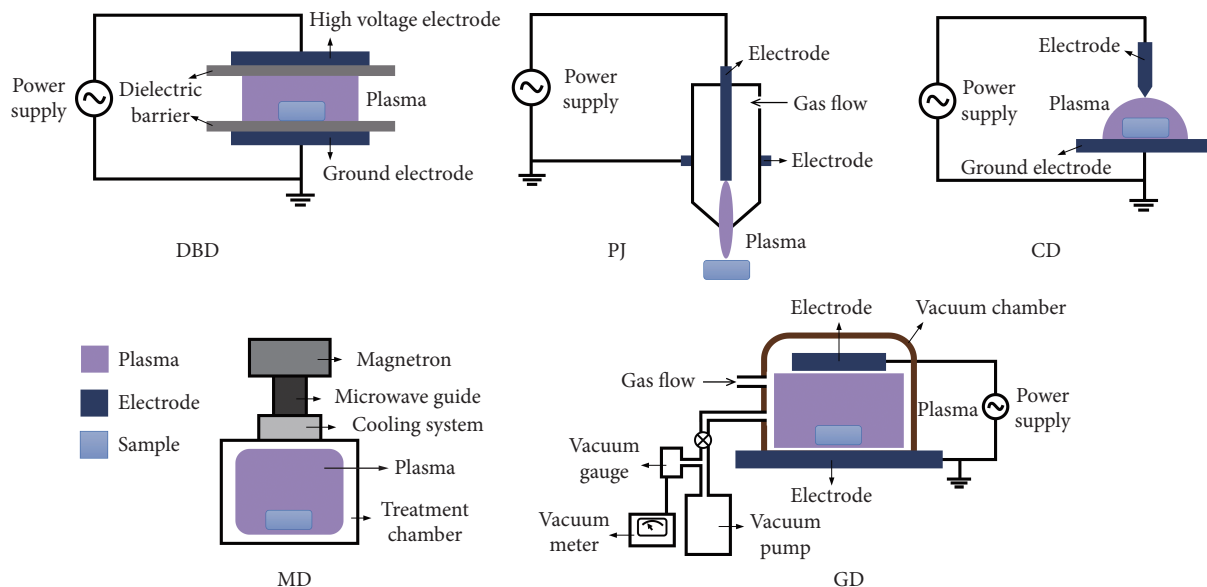


Figure 1 Schematic diagram of the main generation methods of cold plasma technology^[10,24–25].

enables spot sterilisation of foods with irregular surfaces, such as eggs and meat containing bones; however, its limited capacity for large-area treatment^[15] renders it unsuitable for processing bulky food items.

2.3 CD

CD is a gas discharge phenomenon that occurs within a non-uniform electric field, typically requiring high-voltage electric fields and pointed electrode structures for its formation. During CD, gas molecules undergo ionisation under the influence of a strong electric field, forming localised discharge zones. Simultaneously, a significant number of active particles are generated, thereby eliminating microorganisms from the food surface. Compared to DBD systems, it can generate plasma with higher energy and density^[20], and can be deployed on a large scale in multi-electrode configurations^[16]. The system operates in direct current or pulsed voltage current mode, offering straightforward operation that requires no complex equipment and reduces operational costs^[31]. However, owing to its characteristic of generating discharges near the tip electrode structure, it often affects only a small area and does so unevenly^[18]. CD is primarily employed for surface sterilisation, although research on its application in animal-derived foods remains limited.

2.4 MD

MD is a method of generating cold plasma by exciting gas ionisation through electromagnetic waves, characterised by its ability to produce high-density plasma at relatively low gas pressures. A MD generation apparatus typically comprises a microwave source, a cooling system, a processing chamber, a vacuum pump, and a parameter controller^[4]. Microwave energy excites gas molecules to undergo ionisation, generating a high-density, high-energy plasma^[16]. The abundant high-energy electrons and reactive species within this plasma can react with microorganisms and harmful substances in foodstuffs, thereby enhancing food quality and safety. MD offers high processing efficiency and is suitable for large-scale food processing. However, due to its relatively high cost and stringent operational

requirements, its current application scope remains limited^[25]. Research on its use in animal-derived foods is also limited.

2.5 GD

GD is a stable discharge phenomenon generated under low-pressure conditions. Its generation apparatus typically comprises a vacuum system, a low-voltage power supply, and a reaction chamber, wherein gas is ionised at low pressure to form a uniform plasma region. The active components generated through GD effectively eliminate microorganisms on food surfaces, reducing contamination by harmful bacteria^[5] and ensuring food safety. GD enables the stable generation of plasma with uniform distribution of active particles, delivering effective sterilisation while minimising impact on foodstuffs. However, its disadvantage lies in the requirement for a vacuum environment for application^[13]. GD generates stable plasma under low-pressure conditions^[3], making it suitable for laboratory-scale or small-scale food sterilisation research where precise control of treatment parameters is achievable. However, its application remains limited in large-scale industrial settings.

2.6 PAW

PAW is produced by treating water through cold plasma generation devices^[21]. It utilises high-energy electrons and reactive particles generated during the discharge process to react with water molecules, producing ROS, RNS, H₂O₂, O₃, and other substances. This process effectively removes microorganisms, pesticide residues, and other contaminants from food surfaces. PAW, as an economical and environmentally friendly disinfectant, is primarily used for sterilising and preserving foodstuffs^[20]. It can disinfect both regular and irregular surfaces, offering broad-spectrum sterilisation that is economical, environmentally friendly, and leaves no chemical residues^[23]. Suitable for surface sterilisation of aquatic products and eggs, it can also be applied to liquid foods or food items amenable to immersion. Although PAW can achieve highly effective cleaning and disinfection at ambient temperatures, its active substances are prone to decomposition, exhibit poor stability, and its treatment efficacy may be influenced by factors such as water quality and processing duration. Therefore, when employing

PAW for food processing, the operating parameters of the PAW generation apparatus should be adjusted, and the processing conditions optimised to minimise the loss of sensory characteristics and physicochemical properties in the food matrix^[22].

3 Effects of cold plasma technology on animal-derived food matrices

3.1 Meat products

3.1.1 Application in the sterilisation of meat products

Research indicates that cold plasma technology can effectively eliminate pathogenic and spoilage bacteria on the surfaces of meat products, including *E. coli*, *Salmonella*, and *Listeria*, thereby enhancing the safety of meat products. Zhao et al.^[33] treated chilled chicken breast meat with air and nitrogen cold plasma, observing reductions in the original microbial count of approximately 3.3 and 2.3 (lg (CFU/g)), respectively. This technology exhibited a relatively slow initial bactericidal effect; however, as the duration of cold plasma treatment increased, sterilisation efficacy gradually accelerated, ultimately achieving a significant reduction in bacterial counts. González-González et al.^[34] observed in their study of cold plasma treatment applied to ready-to-eat chicken breast that after 5 min of cold plasma exposure, *Salmonella* and *E. coli* O157:H7 counts decreased by 1.8 and 1.47 (lg (CFU/g)), respectively. This demonstrates the technology's capacity to substantially reduce common pathogenic bacteria on meat surfaces within a brief timeframe, thereby mitigating the risk of food contamination. Furthermore, Abdel-Naeem et al.^[35] found that cold plasma technology effectively reduced bacterial counts of psychrotrophs, *Staphylococcus aureus*, and Enterobacteriaceae in chicken meat. Zeraatpisheh et al.^[36] found that cold plasma treatment significantly reduced both yeast and mould counts in ready-to-eat chicken sausages. It is noteworthy that different cold plasma treatment methods and process parameters exert varying effects on sterilisation efficacy. For instance, as plasma treatment duration increases, the reduction in microbial counts within hamburger patties exhibits a more pronounced downward trend^[37]. The aforementioned research findings not only validate the high efficacy of cold plasma technology in sterilising meat products but also provide theoretical support for its application in practical production. The applicability of different cold plasma generation methods varies for different processing targets within meat products. DBD technology is suitable for surface sterilisation of whole cuts or sliced meat, and is currently the most commonly used cold plasma sterilisation technique in meat products due to its accessibility and relatively low cost^[31]. In contrast, PJ technology is better adapted to the decontamination of irregularly shaped surfaces, such as sausages^[36] or trimmed edges. Therefore, the selection of an appropriate technology should be guided by specific processing objectives. Table 2 summarises the sterilisation efficacy of different cold plasma treatment process parameters on meat products.

3.1.2 Effects on the sensory quality and nutritional composition of meat products

Cold plasma technology exerts a complex and multifaceted influence on the sensory qualities of meat products, primarily manifesting in aspects such as colour, texture, and flavour. In terms of colour, the redness value decreased significantly in ham samples

treated with DBD cold plasma, whilst the lightness and yellowness values showed little change^[38]. The redness value of the meat decreased, a trend also observed in the study by Zhao et al.^[33] on chilled chicken breast. This suggests that cold plasma treatment may induce changes in meat colour through oxidative accumulation of myoglobin^[45]. In terms of texture, cold plasma treatment markedly improved the tenderness of meat, particularly under 70 kV DBD cold plasma processing, where pork tenderloin exhibited significantly enhanced muscle tenderness^[46]. Furthermore, research indicates that cold plasma treatment can significantly reduce shear force values and pH levels in chicken samples^[35], resulting in meat that is more tender and possesses improved chewability. However, extended processing durations may adversely affect meat texture, leading to increased hardness. Oliinychenko et al.^[47] conducted texture profile analysis (TPA) on pork, revealing that a 6-min treatment had no significant impact on parameters such as hardness, elasticity, and chewiness. However, when treatment duration was extended to 9 min, hardness, elasticity, and chewiness increased significantly by 35%, 17%, and 42%, respectively. These findings indicate that processing time exerts a dual effect on meat quality, necessitating careful control of treatment duration in accordance with specific operational requirements. In terms of flavour, following 180 s of cold plasma treatment, the thiobarbituric acid reactive substances (TBARS) value of the ready-to-eat ham samples was significantly higher than that of the untreated group^[38]. This indicates that the oxidation reaction of fatty acids was accelerated, resulting in the production of greater quantities of volatile lipid oxidation products, thereby influencing the flavour profile of the meat product.

Cold plasma technology also exerts a certain influence on the nutritional constituents within meat products. Although cold plasma treatment is generally regarded as a mild processing method, prolonged exposure or high-voltage processing may induce alterations in certain nutritional components of meat, particularly concerning fatty acids, protein structure, and lipid oxidation. Qian et al.^[39] observed that TBARS values increased with storage duration following cold plasma treatment of chicken breast meat, with the DBD group exhibiting the highest TBARS values. Similar findings were reported by Ye et al.^[40] in their study of pork. This indicates that DBD treatment accelerates the lipid oxidation process in meat products, thereby affecting their nutritional value. Concurrently, cold plasma treatment significantly influenced the physiological properties of proteins within the meat. Research has revealed that DBD-treated dry-cured bacon exhibits significant alterations in free amino acid (FAA) concentration within myofibrillar proteins, alongside a reduction in α -helix content and increased β -sheet and random coil structure contents. This demonstrates that cold plasma treatment can modify the physicochemical structure of myofibrillar proteins^[30], potentially influencing meat texture and processing characteristics. Meanwhile, Luo et al.^[46] observed that during cold plasma treatment of pork tenderloin, the carbonylic content of myofibrillar proteins increased significantly while the total thiol content decreased markedly with rising treatment voltage. This phenomenon may arise from ROS generated during processing, causing protein oxidation, thereby affecting the physiological properties of the proteins. To mitigate excessive oxidation and nutrient loss induced by cold plasma treatment, practical applications must consider the specific characteristics of meat products and judiciously select key treatment parameters. For instance, lower voltages can be applied to reduce

Table 2 Application of cold plasma treatment in the disinfection of meat products.

Sample	Processing parameters	Disinfection efficacy	Reference
Ready-to-eat chicken breast	PDD; input voltage: 15 V; frequency: 50 kHz	After 5 min of treatment, <i>Salmonella</i> and <i>E. coli</i> O157:H7 decreased by 1.8 and 1.47 (lg (CFU/g)), respectively	[34]
Ready-to-eat ham	DBD; frequency: 3 500 Hz; gap: ~2 mm	Plasma treatment for 180 s produced a significant log reduction of 1.43 CFU/cm ² in <i>Listeria innocua</i>	[38]
Chilled chicken breast	CAPPJ; gas flow rate: 5 L/min; input power: 800 W; gas: air and nitrogen; time: 0–10 min	The final reduction of the original microflora on chicken breasts treated with air and nitrogen-CAP was approximately 3.3 and 2.3 (lg (CFU/g)), respectively. Sterilization rate was first slow and then fast	[33]
Chicken breast	DBD; discharge voltage: 20 kV; gas flow rate: 3 L/min; time: 3 and 5 min	The aerobic plate count, psychrotroph, <i>S. aureus</i> , and Enterobacteriaceae counts were all significantly reduced	[35]
Chicken breast	PALA (PJ; time: 0–180 s) + DBD; frequency: 50 Hz; voltage: 0–160 kV; time: 0–5 min	During 0–90 s, the total viable count (TVC) showed a significant downward trend with the extension of PALA preparation time. The sterilization effect varies with the DBD treatment time and voltage	[39]
Fresh pork	DBD; voltage: 140 kV; frequency: 50 Hz; time: 2 min	TVC and <i>Pseudomonas</i> content were lower than those of the control group	[40]
Meatball	DBD; voltage: 85 kV; time: 3, 6, 9 min; gas: argon	The TVC was significantly lower than that of the control group. The relative abundance of unclassified-f-Enterobacteriaceae and <i>Acinetobacter</i> was significantly reduced	[41]
Ready-to-eat cooked meat products	SBD; frequency: 9 kHz; time: 2 and 5 min/3 and 5 min	The number of <i>E. coli</i> decreased significantly, but the inhibitory effect on <i>Listeria</i> was relatively weak	[42]
Refrigerated hamburger	DBD/ACPJ; output voltage: 15 kV; frequency: 15 kHz; power: 100 W; time: 0, 30, 60, 90 s/0, 60, 180, 360 s	With the increase of processing time, the TVC, mould and yeast counts, as well as <i>E. coli</i> and <i>S. aureus</i> all decreased significantly	[37]
Ready-to-eat sliced chicken sausage	APPJ; power: 30 and 70 W; gas flow rate: 10 SLM; time: 200 and 400 s	The TVC, yeast and mould in the treatment group decreased significantly compared with that in the control group	[36]
Duck breasts	PAW (airflow: 28–32 L/min; power: 680–700 W; time: 0, 2, 4, 6 min)	As the duration of PAW application increased, the rate of growth in the TVC decreased	[43]
Pre-prepared tomato-stewed beef brisket	Voltage: 120, 140, 160 kV; time: 150, 300, 450 s	Sterilisation efficacy increased significantly with rising sterilisation voltage and duration	[44]

Note: PDD, piezoelectric direct discharge; CAPPJ, cold atmospheric pressure plasma jet; PALA, plasma-activated lactic acid solution; SBD, surface barrier discharge; ACPJ, atmospheric cold plasma jet; SLM, standard litre per minute.

the generation intensity of ROS and thereby suppress accelerated oxidation reactions; treatment duration should be minimised to prevent prolonged nutrient degradation; and inert gases (such as argon or nitrogen) should replace air as the working gas to eliminate oxygen exposure^[11,48–49]. These strategies collectively enhance the retention of nutritional components in meat products while mitigating the adverse effects of oxidative processes.

Overall, the application of cold plasma technology in meat products exerts complex effects on sensory quality and nutritional composition. Although it can effectively improve the tenderness of meat and certain sensory characteristics, it also accelerates lipid oxidation and alterations in protein structure, thereby affecting the nutritional value of the meat. Therefore, in practical applications, it is necessary to select appropriate cold plasma treatment conditions based on different processing objectives to achieve optimal results. For different cold plasma generation methods, PJ and DBD techniques generate uniform discharge zones, offering relatively controllable effects on meat surface colouration. However, prolonged treatment may induce protein and lipid oxidation^[38], leading to adverse quality outcomes. PAW exerts a milder influence on meat texture and flavour, although its acidic nature may reduce pH^[22], potentially compromising product quality. In contrast,

research on the application of CD, MD, and GD in meat processing remains limited, with their precise impacts on meat quality not yet fully elucidated. Table 3 summarises the effects of cold plasma on the sensory quality and nutritional composition of meat products.

3.2 Aquatic products

3.2.1 Application in the sterilisation of aquatic products

Aquatic products represent a nutrient-rich category of food products. During capture, transportation, and processing, these products are highly susceptible to microbial contamination. Such microorganisms not only jeopardise the safety of aquatic products but also reduce their shelf life, accelerating quality deterioration^[54]. Current research has demonstrated that cold plasma technology effectively suppresses common bacteria in aquatic products, including mesophilic aerobic bacteria^[55] and psychrophilic bacteria^[56]. Tappi et al.^[57] applied surface DBD cold plasma to fresh sea bream fillets inoculated with pathogenic bacteria, demonstrating significant suppression of total aerobic mesophilic bacteria, *E. coli*, and *L. innocua*. Zhu et al.^[58] treated Atlantic salmon fillets with PAW, observing a lower TVC in treated samples versus controls. This intervention reduced *Shewanella putrefaciens* counts from 7.16

Table 3 Effect of cold plasma treatment on the sensory quality and nutritional composition of meat products.

Sample	Processing parameters	Experimental results	Reference
Pork loin chops	APPJ; voltage: 30 kV; frequency: 20 kHz; flow rate: 11 L/min	The samples treated with cold plasma showed significant differences in fatty acid content	[50]
Pork loin	DBD; voltage: 50, 60, 70 kV; time: 5 min	The 60 and 70 kV treatment significantly enhanced the emulsifying properties of myofibrillar protein and increased the hydrophobicity of the myofibrillar protein surface. The 70 kV treatment significantly improved the tenderness of muscle. The redness value and pH value decreased significantly	[46]
Ready-to-eat chicken breast	PDD; input voltage: 15 V; frequency: 50 kHz	The malondialdehyde content showed no significant difference from that of the control group	[34]
Ready-to-eat ham	DBD; frequency: 3 500 Hz; gap: ~2 mm	The TBARS values were significantly higher than those of the untreated group samples. There was no significant change in lightness and yellowness values, while the value of redness was significantly lower than those of the untreated samples	[38]
Chilled chicken breast	CAPPJ; gas flow rate: 5 L/min; input power: 800 W; gas: air and nitrogen; time: 0–10 min	The total volatile basic nitrogen (TVB-N) content decreases with the extension of processing time. There was no significant difference in the yellowness value, the lightness value decreased first and then increased, and the redness value continued to decline	[33]
Charcoal-grilled beef steak	DBD (ICP); voltage: 85 kV; time: 180 s	After ICP treatment, the contents of the eight PAHs in most treatment groups decreased	[51]
Chicken breast	DBD; discharge voltage: 20 kV; gas flow rate: 3 L/min; time: 3 and 5 min	The pH value and shear force value decreased significantly. There were no significant changes in the TBARS value, TVB-N content and cooking loss	[35]
Dry-cured bacon	DBD; voltage: 50, 60, 70 kV; time: 150 s	DBD-cold plasma treatment significantly affected the concentration of FAAs and changed the structure of myofibrillar proteins	[30]
Beef patties	DBD; time: 120 s; voltages: 50, 60, 70 kV with a fixed frequency of 50 Hz/frequencies: 50, 70, 90, 110 Hz with a fixed voltage of 60 kV	Redness value decreases and MMb accumulates. During storage, MRA decreases and lipid oxidation increases. The higher the processing voltage, the more significant the changes in MRA and TBARS value. The influence of processing voltage is greater than that of frequency	[45]
Chicken breast	PALA (PJ; time: 0–180 s) + DBD; frequency: 50 Hz; voltage: 0–160 kV; time: 0–5 min	During the storage process, the TVB-N content and the TBARS value gradually increased. Centrifugal loss and shear force decreased	[39]
Fresh pork	DBD; voltage: 140 kV; frequency: 50 Hz; time: 2 min	The TVB-N content was lower than that of the control group and increased with the increase of storage time. The TBARS value and peroxide value (PV) were slightly higher than those of the control group	[40]
Beef tallow	APCP; voltage: 2.0 kV; frequency: 10 kHz; time: 0, 5, 10, 20, 30, 60 min	The degree of oxidation increases with the extension of treatment time. Plasma-treated beef tallow increased the volatiles derived from lipid oxidation in Maillard reaction products	[52]
Ready-to-eat cooked meat products	SBD; frequency: 9 kHz; time: 2 and 5 min/3 and 5 min	The redness value of the sausage sample decreased significantly, and the yellowness value increased slightly after 5 min of treatment	[42]
Roasted lamb	DBD; power: 40 W; frequency: 10 kHz; gas flow rate: 20 L/min	Plasma treatment had no significant effect on the tenderness of roasted lamb. The redness value increases with the extension of processing time	[53]
Refrigerated hamburger	DBD/ACPJ; output voltage: 15 kV; frequency: 15 kHz; power: 100 W; time: 0, 30, 60, 90 s/0, 60, 180, 360 s	No significant effect on colour parameters, hardness, and TBARS value	[37]
Ready-to-eat sliced chicken sausage	APPJ; power: 30 and 70 W; gas flow rate: 10 SLM; time: 200 and 400 s	No significant changes in pH and texture parameters. PV increased slowly during storage. As the processing time extends, the lightness value decreases and the redness value increases	[36]
Duck breasts	PAW (airflow: 28–32 L/min; power: 680–700 W; time: 0, 2, 4, 6 min)	PAW effectively inhibited the formation of TVB-N content. The pH value of duck breast meat treated with PAW was significantly lower than that of the control group	[43]
Pre-prepared tomato-stewed beef brisket	Voltage: 120, 140, 160 kV; time: 150, 300, 450 s	Low-temperature plasma treatment effectively preserved aldehydes and ketones associated with meat flavour	[44]

Note: ICP, in-package cold plasma; PAH, polycyclic aromatic hydrocarbon; MMb, metmyoglobin; MRA, metmyoglobin reducing activity.

to 2.04 (lg (CFU/mL)), confirming PAW's potent bactericidal efficacy. Mechanistically, ROS and RNS generated during cold plasma treatment disrupt microbial metabolic and genetic processes via cell wall destruction or direct biomolecular interactions, thereby inhibiting growth^[59]. Consequently, cold plasma treatment effectively reduces microbial load, delays spoilage, and extends shelf life in aquatic products. DBD technology is well-suited for the surface decontamination of large-area aquatic products, such as fish chunks^[59] and whole prawns^[60]. In contrast, PAW can penetrate fish muscle tissue via immersion, rendering it particularly suitable for processing filleted seafood^[58]. In practical applications, the appropriate technology should be selected based on the type of aquatic product and processing requirements. The sterilisation efficacy of cold plasma technology applied to aquatic products is shown in Table 4.

3.2.2 Effects on the sensory quality and nutritional composition of aquatic products

Cold plasma treatment exerts a certain influence on the sensory quality of aquatic products. Regarding colour appearance, studies have revealed that when the treatment voltage exceeds 20 kV, the lightness and yellowness values of golden pompano increase significantly, whilst the redness value decreases sharply with increasing voltage. This is hypothesised to result from the oxidation of pigments, lipids, and proteins caused by reactive species generated by the cold plasma^[61]. In terms of texture, cold plasma technology can enhance the elasticity and firmness of aquatic products. Chen et al.^[64] observed that treating snakehead surimi with ACP for 90 s improved the gel properties of the surimi. This process activated relevant protein components, inducing structural protein rearrangement. By altering the spatial configuration of proteins, it increased the surimi's water-holding capacity (WHC), gel strength, and viscoelasticity, thereby effectively enhancing the texture of the aquatic product. Moreover, cold plasma treatment can promote the formation of characteristic volatile flavour compounds in aquatic products, thereby further enhancing their sensory quality. For instance, Ke et al.^[65] observed that exposure to cold plasma-treated air (CPTA) during the processing of dry-cured

black carp facilitated the generation of certain characteristic volatile flavour compounds. This process exerts a positive influence on flavour development in aquatic products and enhances consumers' sensory experience.

Appropriate cold plasma treatment can preserve the sensory qualities of aquatic products without significantly compromising their nutritional value. For instance, in their study investigating the effects of plasma treatment on the quality of sea bass, Mol et al.^[55] found that cold plasma treatment did not result in a significant increase in TBARS values, indicating that no rancidity occurred. Furthermore, Pérez-Andrés et al.^[66] found that cold atmospheric plasma treatment of mackerel fillets had no significant effect on lipid oxidation, fatty acid composition, or nutritional quality indicators. In studies employing DBD for tuna processing, the TVB-N contents and histamine levels in the treated group were significantly lower than those in the control group^[59]. This indicates that cold plasma treatment slows the rate of protein degradation, thereby reducing amino acid losses caused by protein breakdown and better preserving the nutritional quality of aquatic products. However, prolonged cold plasma treatment may induce certain adverse reactions in aquatic products, thereby compromising their quality. For instance, 30 min of PAW processing results in the loss of polyunsaturated fatty acids (PUFAs) in sardine fillets and promotes the formation of volatile oxidation products generated by the hydroperoxide cleavage of PUFAs^[61], causing damage to certain sensitive nutrients in aquatic products. Moreover, both the PV and TBARS values of DBD-treated tilapia fillets exhibit an upward trend as processing voltage and duration increase^[48], indicative of enhanced lipid oxidation. Consequently, precise control of parameters such as processing time and power is essential to achieve optimal treatment outcomes. Furthermore, the applicability and potential impacts of different cold plasma generation technologies vary in aquatic product processing. DBD treatment effectively suppresses microbial populations while preserving the colour and flavour of fish muscle; however, excessively high voltages may induce minor denaturation of lipids and proteins^[59]. PAW treatment, by contrast, is comparatively mild and better preserves the sensory qualities of aquatic products, though its acidic

Table 4 Application of cold plasma treatment in the disinfection of aquatic products.

Sample	Processing parameters	Disinfection efficacy	Reference
Fresh sea bass	Frequency: 20 kHz; voltage: 30 kV; gas: helium or air; time: 0.5, 1, 3, 5, 7, 10 min	Cold plasma treatment effectively reduced bacterial load. Air-plasma (7 and 10 min) showed a higher reduction in mesophilic bacteria, while He-plasma was more effective in suppressing psychrophilic bacteria growth during storage	[55]
Blue swimming crab	DBD; HVCP; time: 0, 5, 10, 15 min	Effectively reduce the contents of TVC and psychrophilic bacteria count	[56]
Tuna	DBD; inter-electrode separation distance: 40 mm; time: 3 min; voltage: 0, 30, 40, 50, 60, 70 kV	The bactericidal effect of DBD treatment significantly increases with higher treatment voltages	[59]
Fresh sea bream fillets	SDBD; gas: air (80% N ₂ , 20% O ₂), argon (80% argon, 20% O ₂); time: 10, 20 min	The number of total aerobic mesophilic bacteria, <i>E. coli</i> and <i>L. innocua</i> decreased	[57]
Atlantic salmon fillets	PAW (APPJ; power: 320 W; time: 5 min); time: 20 min	Effectively reduce TVC and inactivate <i>S. putrefaciens</i>	[58]
Sardine fillets	PAW (PCD; voltage: 18 kV; frequency: 5 kHz; time: 1 min); time: 10, 20, 30 min	PAW reduced <i>Pseudomonas</i> spp. and TVCs by 0.20 and 0.22 log units	[61]
Ready-to-eat drunken shrimp	DBD; voltage: 40 kV; time: 100 s	The TVC in the cold plasma treatment group was significantly lower than that in the control group	[60]
Red shrimp	DBD; voltage: 35 kV; one-time treatment/cyclical treatment	The cyclical ACP treatment mode more effectively suppressed microbial growth and delayed the proliferation of spoilage bacteria	[62]

Note: HVCP, high voltage cold plasma; SDBD, surface dielectric barrier discharge; ACP, atmospheric cold plasma.

nature may promote lipid oxidation^[61]. Consequently, in practical applications, a balanced approach must be adopted between microbial inactivation and quality retention, with the selection of appropriate technology and optimisation of operational parameters tailored to the specific species of aquatic product and the intended processing objective. In Table 5, we summarise the effects of cold plasma on the sensory quality and nutritional composition of aquatic products.

3.3 Dairy products

3.3.1 Application in the sterilisation of dairy products

Conventional dairy sterilisation techniques typically involve heat treatment, such as pasteurisation or ultra-high temperature sterilisation. High temperatures may adversely affect dairy product quality, leading to non-enzymatic browning, loss of heat-sensitive nutrients, and diminished flavour characteristics^[69]. Research has demonstrated that cold plasma technology can effectively suppress common microorganisms in dairy products, such as bacteria, moulds^[70], and yeasts^[71], achieving sterilisation without significant

heating and thereby extending the shelf life of dairy products. For instance, TVC in whole milk and skim milk were effectively controlled following 10 min of cold plasma treatment, extending shelf life to 15 days^[72]. It is noteworthy that cold plasma treatment effectively reduces the total bacterial count in milk, with the inactivation rate gradually increasing as the treatment duration extends^[73]. Ribeiro et al.^[74] employed cold plasma technology to treat whey dairy beverage, observing a reduction in aerobic mesophilic bacteria counts and no detection of *Salmonella*. Consequently, the products met hygiene standards and were deemed safe for consumer consumption. Heo et al.^[75] developed an inkjet-printed flexible dielectric barrier discharge (FXDBD) device to suppress pathogenic bacteria in sliced cheese. They found that O₃ and NO_x generated by the FXDBD plasma played a primary role in inactivating microorganisms, providing a theoretical foundation for investigating the mechanism of sterilisation. Overall, cold plasma technology has demonstrated distinct advantages in the sterilisation of dairy products, playing a significant role in extending shelf life. DBD is the most widely adopted technique, suitable for both in-package and surface sterilisation of solid dairy products such as

Table 5 Effect of cold plasma treatment on the sensory quality and nutritional composition of aquatic products.

Sample	Processing parameters	Experimental results	Reference
Fresh sea bass	Frequency: 20 kHz; voltage: 30 kV; gas: helium or air; time: 0.5, 1, 3, 5, 7, 10 min	TBARS value did not increase significantly; 7 min air plasma treatment is the best	[55]
Tilapia fillets	DBD; voltage: 40, 50, 60, 70, 80 kV (3 min); time: 0, 60, 120, 180, 240, 300 s (70 kV); storage temperature: 4, 15, 25, 35, 45 °C	The processing voltage and time have a significant impact on the PV and TBARS value	[48]
Blue swimming crab	DBD; HVCP; time: 0, 5, 10, 15 min	Both PV and TBARS value increased significantly with the extension of high-voltage treatment time	[56]
Dry-cured black carp	DBD; CPTA; output voltage: 20 kV; frequency: 10 kHz; time: 3, 6, 9, 12 min	CPTA exposure promote the production of characteristic volatile flavour compounds. The levels of several lipid oxidation indexes, including PV, TBARS value, and HNE, were elevated	[65]
Tuna	DBD; inter-electrode separation distance: 40 mm; time: 3 min; voltage: 0, 30, 40, 50, 60, 70 kV	With the increase of voltage intensity, the TBARS value rises significantly. The TVB-N content and histamine levels in the treatment group were lower than those in the control group	[59]
Mackerel	DBD; voltage: 80 kV; frequency: 50 Hz; time: 5 min	No significant effect on the lipid oxidation and nutritional indices; the formation of carbonyl groups is accelerated	[66]
Fresh sea bream fillets	SDBD; gas: air (80% N ₂ , 20% O ₂), argon (80% argon, 20% O ₂); time: 10, 20 min	No significant difference in protein content, the concentration of TBARS value increased significantly	[57]
Atlantic salmon fillets	PAW (APPJ; power: 320 W; time: 5 min); time: 20 min	The TVB-N content and TBARS value decreased significantly. The hardness and springiness of the salmon fillets treated with PAW were both higher than those of the control	[58]
Sardine fillets	PAW (PCD; voltage: 18 kV; frequency: 5 kHz; time: 1 min); time: 10, 20, 30 min	Longer treatment durations resulted in a loss of PUFAs and an increase in volatile oxidation products from PUFA hydroperoxide cleavage	[61]
Ready-to-eat drunken shrimp	DBD; voltage: 40 kV; time: 100 s	Cold plasma pretreatment maintained MP content while inhibiting muscle protein oxidation and degradation	[60]
Tilapia	DBD; voltage: 70 kV; time: 3 min; electrode-to-sample distance: 3.0 cm	The TVB-N value in the treated group was significantly lower than that in the control group	[67]
Semi-dried golden pomfret	PAW (PJ; power: 650 W; time: 90 s; air flow rate: 0.9 L/min)	Cold plasma effectively inhibited LOX activity through multifaceted structural alterations	[68]
		Samples cured using the PAW method exhibited higher lightness and yellowness values, reduced hardness, lower salinity, and superior sensory quality	

Note: HNE, 4-hydroxy-2-nonenal; LOX, lipoxygenase.

cheese. In contrast, CD is less commonly employed and is generally confined to the treatment of liquid dairy products^[72]. The sterilisation efficacy of cold plasma treatment on dairy products is shown in Table 6.

3.3.2 Effects on the sensory quality and nutritional composition of dairy products

Beyond its application in the sterilisation of dairy products, the impact of cold plasma technology on dairy product quality has also attracted widespread attention. In terms of colour, the lightness and redness values of Kashar cheese treated with cold plasma exhibited a decreasing trend, while the yellowness value increased^[70]. As processing time increases, the lightness value of sliced cheese decreases, while the yellowness value and total colour difference increase^[75], indicating that cold plasma treatment imparts a more yellow hue to the dairy product. In terms of texture, research indicates that during the treatment of skim milk with cold plasma, viscosity exhibits a gradual increase with extended processing time. This may be attributed to alterations in the particle size and volume fraction of dispersed particles within the milk—such as casein micelles—during processing, leading to the formation of insoluble aggregates that enhance the milk's viscosity^[79]. Moreover, the cohesiveness and chewiness of mozzarella cheese were significantly enhanced following cold plasma treatment^[76]. For certain dairy products such as yoghurt and cheese, this contributes to improved palatability and texture, thereby enriching the consumer's sensory experience. Moreover, cold plasma treatment has demonstrated positive effects on the technological processing characteristics of dairy products. For instance, after 2–3 min of cold plasma treatment, sheep's milk casein exhibited significant improvements in WHC, solubility, foaming capacity, and stability^[80]. This demonstrates that cold plasma effectively enhances technical processing characteristics such as foaming and water retention in dairy products, providing empirical support for its application in dairy processing.

Cold plasma technology also exerts a significant influence on the nutritional components of dairy products, particularly in terms of protein structure, antigenicity, and amino acid composition. Research indicates that the degree of protein phosphorylation in sheep's milk casein progressively increases following cold plasma treatment^[80], demonstrating that cold plasma can induce structural modifications in dairy proteins, thereby enhancing their functional properties. However, as the duration of cold plasma treatment increases, the content of free sulfhydryl groups in milk gradually decreases. This may be attributed, on the one hand, to oxidative reactions mediated by ROS/RNS generated during cold plasma treatment, and on the other hand, to the oxidation of sulfhydryl groups by reactive species such as hydroxyl radicals or O₃^[79]. This indicates an increased degree of protein oxidation and a consequent alteration in their physiological conformation. It is noteworthy that cold plasma treatment also influences the antigenicity of different proteins in dairy products. Sharma et al.^[81] employed ACP to treat skim milk, observing a reduction in casein antigenicity with increasing treatment duration. Furthermore, depending on the composition of the treatment gas, both α -lactalbumin and β -lactoglobulin exhibited varying degrees of antigenicity alteration. This demonstrates that cold plasma can modify the antigenic properties of milk proteins, potentially contributing to a reduction in the risk of allergic reactions. Moreover, as processing time increased, the secondary structure of milk proteins underwent alterations. Both SD and GD treatments resulted in reduced β -sheet content within milk casein, accompanied by a slight increase in α -helix content, whilst the proportion of random coils remained largely unaffected^[10]. These secondary structural changes may influence the antibody-binding capacity of milk proteins, thereby offering an alternative approach to reducing milk-derived allergens during dairy processing. Table 7 summarises the effects of different cold plasma treatment modalities on the sensory quality and nutritional composition of dairy products.

Table 6 Application of cold plasma treatment in the disinfection of dairy products.

Sample	Processing parameters	Disinfection efficacy	Reference
Kashar cheese	Frequency: 42 kHz; voltage: 25 kV; gas: argon and O ₂ ; time: 100, 200, 400 s	The quantities of both <i>Aspergillus flavus</i> and <i>Penicillium crysogenum</i> have decreased by 3–4 logs	[70]
Whey dairy beverage	CD; supply voltage: 15 kV; time: 5, 10, 15 min; temperature: ~ 17 °C	The number of total and thermotolerant coliforms < 3 MPN/mL, the number of mesophilic bacteria is 2–2.5 (lg (CFU/mL)), and there is no <i>Salmonella</i> in 25 mL of the product	[74]
Sheep milk	DBD; input power: (40 ± 0.25) W; pretreatment time: 3 s; time: 30, 180, 300 s	Cold plasma treatment for 300 s resulted in a maximum reduction of 94.2% in total microorganisms in raw sheep milk	[73]
Sliced cheese	FXDBD; voltage: 2.170 kV; frequency: 3 kHz; time: 0, 5, 10, 15, 20 min	After 20 min, the survival levels of <i>E. coli</i> O157:H7, <i>Salmonella</i> Typhimurium and <i>Listeria monocytogenes</i> were significantly reduced by 2.65, 2.80, and 2.03 (lg (CFU/g)) respectively	[75]
Mozzarella cheese	DBD; voltage: 75 kV; gas: 10:90 oxygen-to-nitrogen; time: 2, 3, 5 min	The content of <i>E. coli</i> (EHEC) decreased; the microbial count was significantly reduced by more than 2 logs after treatment	[76]
Sliced Iranian white cheese	GAD; voltage: 26 kV; power: 300 W; frequency: 50 Hz; time: 0, 2, 5 min	Cold plasma treatment exerted a significant inhibitory effect on the growth of <i>A. flavus</i> . Its inhibitory effect on <i>E. coli</i> and <i>L. monocytogenes</i> was time-dependent	[77]
Bovine colostrum	Direct static DBD/direct continuous DBD/indirect static DBD/static CD/static GAD; frequency: 18 kHz; voltage: 6–18 kV; time: 1–21 min	The effectiveness in reducing natural microflora followed the order: continuous DBD > direct static DBD > static CD > static GAD	[78]

Note: MPN, most probable number; EHEC, enterohemorrhagic *E. coli*.

Table 7 Effect of cold plasma treatment on the sensory quality and nutritional composition of dairy products.

Sample	Processing parameters	Experimental results	Reference
Sheep's milk casein	DBD; frequency: 10 kHz; voltage: 20 kV; time: 0, 2, 3, 4, 5 min	The phosphorylation degree of casein gradually increased from 0 to 4 min. The WHC, solubility, foaming capacity, and foaming stability all showed a significant increase after 2 to 3 min of treatment. The optimal processing duration is 3 min	[80]
Kashar cheese	Frequency: 42 kHz; voltage: 25 kV; gas: argon and O ₂ ; time: 100, 200, 400 s	The pH and water activity values declined, while the lightness and redness values decreased and the yellowness value increased	[70]
Whey dairy beverage	CD; supply voltage: 15 kV; time: 5, 10, 15 min; temperature: ~17 °C	The beverages treated with plasma showed reduced heat load indicators and an increased concentration of bioactive compounds. The optimal processing time is 15 min	[74]
Bovine milk	SD/GD; distance: 2.5 mm/5 mm; voltage: 8 kV/5 kV; frequency: 25 kHz; time: 0, 10, 20, 30 min	It effectively reduced the antigenicity of casein and α -lactalbumin, increased the antigenicity of β -lactoglobulin, and induced changes in the secondary structure content and amino acid composition of milk proteins	[10]
Sheep milk	DBD; input power: (40 $\pm$ 0.25) W; pretreatment time: 3 s; time: 30, 180, 300 s	Longer processing time reduced the moisture content, pH, and redness value, while increasing casein micelle size and yellowness value in cold plasma-treated sheep milk	[73]
Skim milk	DBD-based jet; voltage: 20 kV; flow velocity: 5 L/min; gas: N ₂ /0.9 mol N ₂ & 0.1 mol O ₂	The content of free sulfhydryl decreased with the extension of treatment time. Viscosity increases with the extension of processing time	[79]
Sliced cheese	FXDBD; voltage: 2.170 kV; frequency: 3 kHz; time: 0, 5, 10, 15, 20 min	The pH value lower than the control group. With the extension of processing time, the lightness value decreased, while the yellowness value, total colour difference and TBARS value increased, while the redness value remained unchanged	[75]
Mozzarella cheese	DBD; voltage: 75 kV; gas: 10:90 oxygen-to-nitrogen; time: 2, 3, 5 min	There were no significant changes in moisture, protein and pH value. The cohesiveness and chewiness were significantly enhanced	[76]
Raw sheep milk	Power: 400 W; gas flow rate: 20 mL/min; voltage: 0.5, 0.7, 0.9 kV; time: 3, 5, 7 min	CP treatment resulted in an increase of the pH value from 6.72 to 6.82. The protein and fat contents have both increased slightly. The values of lightness, redness, and yellowness have increased	[82]

3.4 Egg products

3.4.1 Application in the sterilisation of egg products

In the application of cold plasma technology in egg products, it can effectively eliminate bacteria on the surface of eggshells, especially showing a strong inhibitory effect on *E. coli* and *Salmonella*. This reduces microbial contamination within the eggs, thereby enhancing egg safety. Research has found that at 300 W power, cold plasma treatment can reduce the concentration of *E. coli* on eggshell surfaces by 1.14 log, while at 400 W, the reduction reaches 1.52 log^[83]. In the study by Gavahian et al.^[84], treatment of duck eggs using arc atmospheric pressure plasma effectively eliminated *Salmonella* on the eggshell surface, with the sterilisation efficacy increasing with longer treatment duration. At higher power levels and longer exposure times during cold plasma treatment, the efficacy of *Salmonella* inactivation becomes markedly more pronounced. For instance, at 800 W power, following 120 s of cold plasma treatment, *Salmonella* on egg surfaces was almost entirely inactivated, with no viable cells detected^[85]. The above research findings indicate that the power and treatment duration of cold plasma directly influence its bactericidal efficacy. By adjusting these parameters, cold plasma can effectively reduce the levels of *E. coli* and *Salmonella* on egg surfaces, thereby enhancing the microbiological safety of eggs. In egg processing, PJ and PAW are

the two predominant technologies. PAW facilitates uniform disinfection through immersion in a treated solution, enhancing shelf life without compromising egg integrity. PJ sterilises the eggshell surface, rapidly reducing surface microorganisms while avoiding water usage. The sterilisation efficacy of cold plasma treatment on egg products is shown in Table 8.

3.4.2 Effects on the sensory quality and nutritional composition of egg products

Sensory quality is one of the key criteria by which consumers assess the acceptability of food products. Current research indicates that cold plasma treatment does not exert significant adverse effects on the sensory quality of eggs. For instance, following cold plasma treatment, the strength of eggshells exhibited no significant alteration, indicating minimal detrimental effects on the physical properties of the shell. Concurrently, the pH levels of albumen and yolk remained largely unchanged post-treatment^[85,87], demonstrating that cold plasma processing exerts no significant influence on the acidity or alkalinity of the egg. Moreover, following cold plasma treatment of eggs, neither the yolk colour nor the yolk height exhibited significant alteration^[84], indicating that this technology effectively preserves the internal quality of eggs. Concurrently, research indicates that employing cold PAW as a disinfectant for egg washing not only achieves effective sterilisation but also does

Table 8 Application of cold plasma treatment in the disinfection of egg products.

Sample	Processing parameters	Disinfection efficacy	Reference
Eggshell surface	PJ; power: 300 to 400 W; airflow rate: 35 L/min; distance: 1 cm	The <i>E. coli</i> concentration on eggshells decreased by 1.14 log at 300 W and by 1.52 log at 400 W	[83]
Table eggs	ACPJ; power: 600, 700, 800 W; time: 0, 60, 90, 120 s	After treatment, the population of SE could be significantly reduced ($P < 0.01$), and the reduction was proportional to the increase in time and power. No viable cells were detected after the plasma process at 800 W in 120 s	[85]
Duck eggs	APPL; relative humidity: 65%; working distance: 65 mm; pressure: 101 kPa; treatment time: 0, 10, 20, 30, 40 s; temperature: 20–49 °C; plasma voltage: 12 000 V; current: 1.9–2 A	After treatment for 10, 20, 30 and 40 s, the number of <i>Salmonella</i> decreased by 2.29, 2.6, 3.62 and 4.09 log cycles respectively	[84]
Egg	PAW (temperature: ~50 °C; pH: 2.95 ± 0.02; ORP: 575.8 mV)	PAW resulted in more than 5 log reduction in <i>Klebsiella michiganensis</i> population	[86]

Note: SE, *Salmonella enterica* serotype Enteritidis; APPL, arc atmospheric pressure plasma; ORP, oxidation-reduction potential.

not compromise shell strength or cuticle coverage^[86], suggesting this technology holds promising application prospects.

Cold plasma technology also exerts a relatively positive influence on the nutritional composition of egg products. Moderate processing does not significantly affect the nutritional content within eggs and holds potential for enhancing certain functional components. Zhang et al.^[85] found that DBD cold plasma significantly enhanced the digestibility of egg white protein (EWP), while also increasing its foaming and emulsifying capabilities. This demonstrates that cold plasma technology can improve the processing characteristics of proteins in food manufacturing, exhibiting considerable potential for application in the preparation of foamed and emulsified food products. Nasiru et al.^[89] observed that with increasing cold plasma treatment time, the solubility of EWP improved, its particle size decreased, and the secondary structural units— α -helix, β -sheet, and β -turn—increased, while

random coils decreased. These alterations provide a foundation for enhancing the protein's bioavailability and functional properties, opening possibilities for its broader application in food processing. Concurrently, research indicates that cold plasma treatment exerts no significant effect on physicochemical properties such as fatty acid profile, acid value, and TBARS value in duck egg yolks^[84]. This demonstrates its capacity to maintain yolk fat quality effectively while achieving sterilisation, without inducing excessive fat oxidation or deterioration. Consequently, it holds considerable promise for preserving the quality of yolk fat. Table 9 lists the effects of cold plasma on the sensory quality and nutritional composition of egg products. Research on cold plasma applications in eggs remains limited, and the impact of different plasma technologies on egg quality attributes and storage stability requires systematic evaluation.

Table 9 Effect of cold plasma treatment on the sensory quality and nutritional composition of egg products.

Sample	Processing parameters	Experimental results	Reference
Table eggs	ACPJ; power: 600, 700, 800 W; time: 0, 60, 90, 120 s	After treatment, no significant effects were found on eggshell strength or the pH of albumen and yolk	[85]
Duck eggs	APPL; relative humidity: 65%; working distance: 65 mm; pressure: 101 kPa; treatment time: 0, 10, 20, 30, 40 s; temperature: 20–49 °C; plasma voltage: 12 000 V; current: 1.9–2 A	The internal quality of the samples (Haft units, yolk color, yolk height and pH) and the physicochemical properties of yolk (such as fatty acid composition, acid value and TBARS value) were not affected by plasma treatment	[84]
Chicken eggs	DBD; voltage: 100 kV; relative humidity: 60%; T1: 0.5 min treatment + 24 h post treatment; T2: 8.5 min treatment + no post treatment	After T1 and T2 treatments, there were no significant effects on the pH of egg whites and yolks, Haft units, yolk colour, yolk membrane strength and eggshell strength	[87]
Egg	PAW (temperature: ~50 °C; pH: 2.95 ± 0.02; ORP: 575.8 RmV)	PAW caused minimal damage to the cuticle layer as opposed to quaternary ammonia	[86]
EWP	DBD; voltage: 110 kV; frequency: 50 Hz; input current: 200 mA; time: 10, 20, 30, 40, 50, 60 min; electrode plate distance: 26 mm	CP treatments reduced the immunoreactivity and enhanced the functional properties of EWP, especially in 30 min. CP treatment can significantly improve the digestibility of EWP. The foaming capacity and emulsifying capacity of EWP were increased by 140% and 8.03%, respectively	[88]
EWP	DBD; voltage: 40 kV; discharge gaps: 50 and 10 mm; time: 0, 60, 120, 180, 240, 300 s	The solubility of EWP has improved and the particle size has decreased	[89]
gd-SDEW	DBD; input voltage: 25, 35, 45 V; time: 1, 2, 3, 4 min	LTP treatments decreased the luminosity of gd-SDEW. The oil holding capacities values gradually increased with the duration of LTP treatment. The secondary structure has changed, with an increase in β -sheet structure	[90]

Note: gd-SDEW, gelatinized desalted salted duck egg white; LTP, low-temperature plasma.

4 Limitations and future development directions of cold plasma technology

4.1 Limitations of cold plasma technology

Although cold plasma technology demonstrates significant application potential in the food industry, the issue of equipment costs^[84] remains one of the important factors limiting its widespread promotion. On the one hand, the manufacture of cold plasma treatment equipment involves the selection of high-precision control parameters and complex process design^[91]. On the other hand, equipment installation and personnel training also require substantial capital investment, thereby increasing the economic burden on food processing enterprises^[31]. Moreover, as cold plasma technology is still in the development stage and has not yet achieved large-scale industrial production^[92], this further exacerbates the high cost of the equipment. Furthermore, certain critical components of the discharge structure, such as electrodes and insulation layers, require periodic replacement, thereby increasing operational costs. Therefore, the high cost characteristic of cold plasma limits its widespread adoption within the food industry.

Beyond equipment costs, the processing efficiency of cold plasma technology in practical applications also warrants attention. At present, cold plasma technology faces the dual challenges of slow processing speeds and insufficient uniformity when treating animal-derived foods. Firstly, the mechanism of action of cold plasma relies on the generation of reactive species and their interaction with food components. This process typically requires a certain amount of time to achieve the desired effect, which directly impacts food production efficiency. Secondly, the issue of treatment uniformity in cold plasma processing is also particularly pronounced^[9], especially when treating irregularly shaped or thicker food items; the distribution of active particles cannot be guaranteed to be entirely uniform, resulting in suboptimal treatment outcomes in certain areas. Moreover, different discharge methods exhibit certain variations in their antibacterial performance^[93], necessitating the selection of an appropriate discharge method based on the type and characteristics of the food being processed to enhance treatment efficiency. Therefore, how to enhance the processing speed and uniformity of cold plasma technology remains a key issue that requires resolution.

Currently, while cold plasma is recognised to achieve sterilisation and preservation through synergistic effects of reactive species, electric fields, and ultraviolet radiation, its specific action pathways and molecular mechanisms within animal-derived food matrices remain incompletely elucidated^[8]. Moreover, experimental data are lacking regarding its efficacy against diverse microorganisms and specific impacts on nutrient components such as lipids and proteins. Furthermore, as optimal processing parameters for cold plasma technology vary according to food type, precise optimisation of treatment variables (e.g., duration, power, gas composition, and flow rate) proves challenging in practical applications^[94]. Consequently, these limitations substantially constrain the technology's efficient implementation and broader adoption.

4.2 Future development directions

In the future, cold plasma technology could enhance its penetration capability, treatment depth, and treatment consistency by

optimising the generation process and control parameters (e.g., treatment duration, gas flow rate, voltage, and frequency)^[14]. This optimisation would maximise the retention of food nutritional value and sensory qualities. Furthermore, developing more efficient cold plasma generators and processing equipment is expected to enhance their operational feasibility and cost-effectiveness for the food industry. Additionally, technologies such as digital twins and artificial intelligence^[95] could be employed to establish precise simulation models of cold plasma processing, facilitating intelligent regulation of process parameters.

Furthermore, cold plasma technology can be integrated with other preservation and processing techniques (e.g., microwave^[96], ultraviolet^[97], ultrasonic^[98], and pulsed electric field^[99]) to leverage synergistic effects from their distinct action mechanisms. Such integration amplifies combined efficacy in sterilisation, preservation, and quality enhancement while mitigating cold plasma's adverse impacts on food quality^[49], thereby maximising technological benefits^[100]. Concurrently, it can be combined with bio-based materials^[101] to develop novel packaging with antimicrobial and preservation properties, which further extends the shelf life of animal-derived foods.

Future research into the interaction mechanisms between cold plasma active particles and nutritional components in food matrices will require advanced analytical techniques, including proteomics, metabolomics, molecular dynamics simulations^[102], and molecular biology technologies. These will enable the molecular-level elucidation of cold plasma's action pathways and regulatory mechanisms on microorganisms and food constituents. Based on in-depth studies of these mechanisms, the optimal operating parameters for cold plasma treatment across various animal-derived foods should be established. This will provide robust theoretical support for developing standardised operational procedures and quality control systems for the advanced processing of animal-derived foods.

5 Conclusion

Cold plasma technology, as an emerging non-thermal processing technique, has become a research focus in the field of animal-derived food processing due to its significant advantages in food safety, preservation, and quality enhancement. This paper outlines the research progress of cold plasma technology in various animal-derived foods, including meat, aquatic, egg, and dairy products, describing its effects on microbial inactivation and shelf-life extension. It reviews the potential effects of cold plasma technology on modifying the sensory qualities and nutritional composition of animal-derived food matrices. Different cold plasma generation technologies exhibit distinct efficacies in animal-derived foods. DBD offers large treatment areas and uniform plasma distribution, making it suitable for most animal-derived products. PJ enables precise spatial control, ideal for surface decontamination of eggs and localized treatment of irregularly shaped meat products. PAW, as a novel disinfectant, can be employed for immersion sterilisation of aquatic products and eggs. Research into the application of technologies such as CD, MD, and GD in animal-derived food processing remains relatively limited, and their impact on product quality requires further investigation. Although cold plasma technology has demonstrated broad application prospects, its practical applications still face challenges such as controllability of treatment efficacy, equipment energy efficiency issues, and potential impacts on food components. These

necessitate further technological innovation and mechanism research. In the future, as cold plasma equipment advances technologically and research deepens, its application within the food industry is poised for broader adoption. It is anticipated that this technology will integrate with other advanced techniques to form multifunctional synergies, thereby further enhancing its comprehensive benefits in food processing.

Declaration of competing interest

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

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Author contributions

Ruijie Hou: conceptualization, investigation, writing-original draft, visualization. Baodong Zheng: conceptualization, investigation. Hongliang Zeng: conceptualization, investigation. Yi Zhang: conceptualization, writing-review & editing, funding acquisition. Boyuan Guan: conceptualization, methodology, writing-review & editing, supervision, funding acquisition.

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