Food Science of Animal Products

Review Article

Salmonella inactivation on beef rump by plasma-activated water: a review

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Received: February 24, 2024; Revised: March 11, 2024; Accepted: April 7, 2024

Abstract: In recent years, advancements in the social economy and increases in societal productivity have intensified the focus on food quality, safety, and nutritional standards. A central challenge in advancing the food industry is improving food quality and safety at all stages of processing. Recent foodborne disease outbreaks have served as a critical alert, elevating food safety to a paramount concern globally. Pathogenic bacteria, particularly *Salmonella*, are primary contributors to foodborne illnesses, with *Salmonella* posing significant risks. It is a prevalent cause of food poisoning and a primary source of foodborne illness outbreaks. This review explores the dangers posed by foodborne illnesses specifically *Salmonella*, presenting an overview of the preparation of plasma-activated water. It elucidates the physical and chemical properties of plasma-activated water and reviews its mechanism for deactivating pathogens and its effectiveness against *Salmonella* in beef rump meat. The potential use of plasma-activated water in the food industry is also discussed.

Keywords: foodborne illness; *Salmonella*; plasma; plasma-activated water; physical-chemical properties; beef rump

Citation: X. Ouyang, L. N. Huang, H. T. Liu, et al., *Salmonella* inactivation on beef rump by plasma-activated water: a review, Food Sci. Anim. Prod. 2 (2024) 9240051. https://doi.org/10.26599/FSAP.2024.9240051.

1 Introduction

Analysis indicates that meat and its derivatives, rich in essential nutrients such as protein, fats, vitamins, and minerals, possess significant nutritional value[1]. Nevertheless, these nutrients also promote the growth of microorganisms, making meat and its products prone to contamination by pathogenic microorganisms and spoilage during production, processing, packaging, and transportation[2]. The proliferation of microorganisms in food products leads to oxidation and autolysis of key enzymes, causing spoilage that affects the quality of meat production and processing. Various bacteria, such as *Escherichia coli* and *Bacillus cereus*, can spoil meat, altering its nutritional value and flavor[3]. Moreover, during the meat handling stages, there is an increased risk of contamination by foodborne pathogens including *Salmonella*, *E. coli*, *Listeria*, and *Campylobacter*. These pathogens pose substantial health hazards, capable of triggering widespread foodborne illnesses and considerable economic losses[4].

Beef, known for its high nutritional value, is particularly susceptible to spoilage due to its rich protein content and microbial load. *Salmonella*, commonly found in beef, poses a significant risk of foodborne diseases[5]. The substantial economic impact on the meat industry highlights the importance of neutralizing *Salmonella* in beef[4]. Traditional sterilization techniques, such as ultra-high temperature processing, pasteurization, and ohmic heating, are effective in killing microorganisms and extending shelf life. However, these methods have limitations, including nutrient degradation and flavor alteration; furthermore, high temperatures can produce harmful substances, negatively impacting health[6–7]. As a result, innovative non-thermal processing technologies, including electrolyzed water, ultra-high pressure, pulsed electric fields, and plasma, are increasingly utilized for food sterilization. These approaches efficiently eliminate microorganisms while preserving nutritional and sensory properties[8].

Plasma-activated water (PAW) represents a cutting-edge approach to microbial sterilization. Effective techniques such as pulsed corona, plasma jet, dielectric barrier discharge, and microwave plasma have proven PAW's capability in inactivating microorganisms[9]. Unlike traditional high-temperature and other non-thermal sterilization methods, PAW offers greater efficiency, safety, ease of use, and reduced energy consumption[10]. Treatment with PAW produces peroxynitrite, which attacks cellular biomolecules, leading to their degradation. Commonly, substances like saline or hydrogen peroxide are added to enhance PAW's antimicrobial properties[11]. PAW has excellent sterilization performance and non-toxic nature, which make it suitable for eliminating microorganisms in food products. Hence, the use of PAW in treating *Salmonella* on beef rump meat warrants thorough exploration to assess its sterilization effectiveness. This review carefully examines the inactivation of *Salmonella* on beef rump meat via PAW, focusing on its efficiency and analyzing the physical and chemical properties of PAW.

1.1 Foodborne diseases

Foodborne illnesses, resulting from the consumption of contaminated food, have a significant impact on global human health and safety, causing widespread outbreaks[12]. The World Health Organization and other bodies report that foodborne illnesses account for a major portion of all disease categories, with an annual death toll surpassing 400 000. Notably, children under 5 years old represent about one-third of these deaths. By the 1980s, the incidence of foodborne illnesses in Asia and Latin America had escalated to hundreds of millions. The Centers for Disease Control and Prevention in the United States records up to 70 million cases

of foodborne illnesses annually, leading to over 300 000 hospitalizations and thousands of deaths[13]. Historically, substantial global outbreaks have occurred, such as the 2005 *Salmonella* outbreak in pre-cooked chicken in Spain, causing more than 2 000 deaths, and the 2011 outbreak of foodborne illness due to enterohemorrhagic *E. coli* in Germany, which spread to 16 countries, resulting in 3 941 illnesses and 52 deaths[14]. In recent years, foodborne disease outbreaks have been frequent in Chinese households, with 17 985 outbreaks reported in China between 2010 and 2020, leading to 73 252 illnesses, 38 829 hospitalizations, and 1 269 deaths[15].

Foodborne illnesses are caused by pathogenic agents, including toxic substances and biological pathogens, ingested through food. These illnesses may arise from various agents, such as viruses, bacteria, parasites, and chemicals, with pathogens playing a central role (Table 1)[16]. Notably, *Salmonella*, *Campylobacter*, and *E. coli* are among the most significant foodborne pathogens. Such illnesses are broadly categorized into 2 types: toxic and infectious. The majority of foodborne illnesses are transmitted through food, displaying outbreak patterns that affect a wide range of individuals, from a few to thousands, in a single event[13]. Outbreaks caused by microorganisms are notable for their extensive nature and can have an incubation period ranging from hours to days. In contrast, outbreaks stemming from non-microbial sources are characterized by their rapid onset, with incubation periods typically spanning minutes to hours[16]. In cases of food poisoning resulting from chemical or plant toxins, the spread of illness is more dispersed and does not show a clear link to the timing and location of infection onset. Additionally, the regional occurrence of foodborne illnesses is significant, often appearing more frequently in certain geographic areas and populations[17].

Table 1 Types of foodborne illnesses.

Categorization	Agents
Bacterial	*Salmonella*, *E. coli*, *Listeria monocytogenes*, *Orphanella parahaemolytica*, botox, and *Bacillus subtilis*
Viral	Norovirus, rotavirus, and hepatitis E virus
Parasite	*Chlorosis*, *Schistosomiasis*, *Trichinellosis*, and *Hepatic schistosomiasis*
Chemical contamination	Nitrite, methanol, organic phosphorus, and leptin

The concern over foodborne illness remains, with its prevention and control being crucial for human health and safety. The entire food distribution process, from acquiring raw materials to consumption, must rigorously comply with food safety regulations. Comprehensive and effective food safety education is essential for individuals involved in the food industry and for consumers. Enhancing food safety management across all stages of food production, including processing, sterilization, packaging, and transportation, is vital. The effective enforcement of these measures can significantly mitigate and prevent foodborne illnesses in humans[18].

1.2 *Salmonella*

Salmonella is a significant pathogen in the realm of foodborne illnesses. Various methods are utilized for its identification, with traditional techniques focusing on physical, physiological, and biochemical traits, as well as antigenic and phage characteristics[19]. Discovered during the 1885 cholera epidemic, the microorganism originally named *Salmonella cholerae* was later renamed simply *Salmonella*. This genus includes a wide array of strains, some pathogenic to humans, some to animals, and others to both. As a Gram-negative enterobacterium in the Enterobacteriaceae family, *Salmonella* comprises numerous strains. These are divided into groups A, B, C, D, and E based on their antigenic properties, with only *Salmonella paratyphi* A known to cause disease in humans. While many strains primarily affect livestock and poultry, the ingestion of food contaminated by feces from humans, animals, or carriers can lead to food poisoning and foodborne illnesses[20].

Salmonella demonstrates considerable viability, adapting to various environmental conditions. It can survive 1–2 months in feces, 3–4 months at refrigerated temperatures, and about 2 weeks to 1 month in water, where it does not naturally thrive. Studies showed that the optimal temperature for *Salmonella* to survive and multiplicate is around 20 °C. Therefore, while refrigeration at low temperatures cannot entirely prevent *Salmonella* growth, it significantly reduces its survival and proliferation[20].

The principal transmission pathway for *Salmonella*, as depicted in Figure 1, involves contaminated meat, eggs, and environmental sources. In the USA, up to 25% of meat products may be contaminated with *Salmonella*, compared to 10% in the UK and 10.3% in Japanese poultry. The global prevalence of typhoid fever in humans due to egg contamination with *Salmonella* is on the rise. Environmental contamination also serves as a critical transmission vector. Insufficient sterilization during processing, packaging, transportation, and distribution can lead to *Salmonella* presence in food products. The bacterium can persist in soil, water, feces, and food, occasionally for up to 2 years[21].

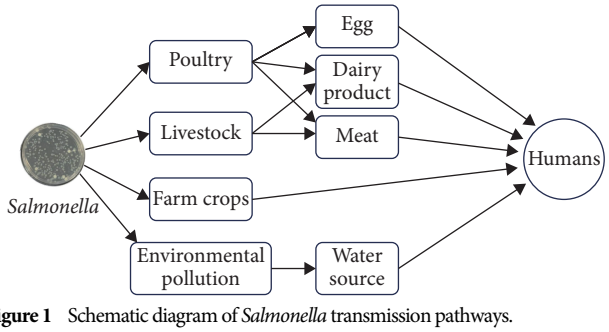

Figure 1 Schematic diagram of *Salmonella* transmission pathways.

1.3 Plasma

Plasma, an ionized gas, comprises positive and negative ions, created through the ionization of atoms and groups of atoms when they lose electrons[22]. This ionization occurs when atoms or molecules, with positively charged nuclei and negatively charged electrons, are stripped of their outer electrons by high temperatures or other factors, in a process known as "ionization". As plasma contains an equal number of positive and negative charges, it is essentially an electrically neutral entity[23].

As an ionized, electrically neutral gas, plasma predominantly interacts with electromagnetic forces, exhibiting collective behaviors. Distinct from the other 3 states of matter, plasma is recognized as the fourth state and is abundant in the universe. Its exceptional electrical conductivity allows plasma to be manipulated and contained through magnetic fields, enabling controlled movement and acceleration[24]. This unique characteristic makes plasma a crucial element in exploring new energy sources and materials, offering significant potential for breakthroughs in fields like physics and chemistry.

1.4 PAW

PAW is water that has undergone plasma treatment. This process involves plasma interacting with water to produce PAW, a solution rich in active substances, ions, and charged particles[25]. There are primarily 3 methods to prepare PAW: plasma discharge on the water surface, direct plasma discharge in water (or underwater discharges), and multiphase plasma discharge[26]. Figure 2 shows the process of plasma discharge used to generate PAW[27–28].

The production of PAW is notably effective in generating reactive oxygen species (ROS) and reactive nitrogen species (RNS), with outcomes dependent on the production environment, excitation voltage, and method of generation[24,29]. These reactive species typically form in liquid media and at the gas-liquid interface. PAW is generally acidic, establishing redox potentials where reactive oxides act as the primary active agents. Principal active components include nitrate (NO_3^-), nitrite (NO_2^-) ions, and hydrogen peroxide (H_2O_2). In PAW, peroxynitrite targets various biomolecules within cells, causing internal damage and leading to cell death, thus efficiently inactivating microorganisms while being environmentally benign. Compared to traditional heat treatment, studies indicate that PAW not only deactivates microorganisms in food but also maintains its nutritional and flavor qualities (Table 2). In the food industry, PAW can inactivate germs, thus the risk of foodborne diseases is significantly reduced[30]. Additionally, PAW is beneficial for preserving fresh fruits and aquatic products, as its high levels of NO_3^- and NO_2^- ions support the growth of plant seedlings. Seed soaking in PAW boosts their growth and enhances antibacterial properties. Consequently, PAW has extensive agricultural applications, offering the potential to increase crop yields and strengthen resilience against challenges such as floods, droughts, and pests[31].

1.5 Physical and chemical properties of PAW

1.5.1 pH value and oxidation reduction potential (ORP)

The pH value represents the hydrogen ion concentration in a solution. Acidification results from a chemical reaction between plasma and water, where the production of hydrogen peroxide, nitric acid, and peroxynitrite during the plasma reaction significantly lowers the pH over time. This reduction is linked to the antimicrobial properties of PAW[33]. In the initial phase of plasma treatment, Ma et al.[30] noted a rapid decline in pH, which then stabilized. Shainsky et al.[23] studied the pH of plasma generated using different gases (air, oxygen, argon) and found no significant pH change in PAW produced with argon, while air and oxygen resulted in pH values decreased to 2.07 and 2.01, respectively. Further, PAW from air plasma showed a minor decrease in pH over time[34], whereas the pH of oxygen-generated PAW increased linearly.

ORP indicates the ability of a substance to oxidize or reduce another substance, depending on the presence and strength of the oxidant. ORP is a quick and straightforward measure to assess PAW's disinfection potential[35]. It disrupts microorganisms' cell membranes and defense mechanisms, thereby deactivating them. Hydrogen peroxide is a key ROS in PAWs, playing an essential role

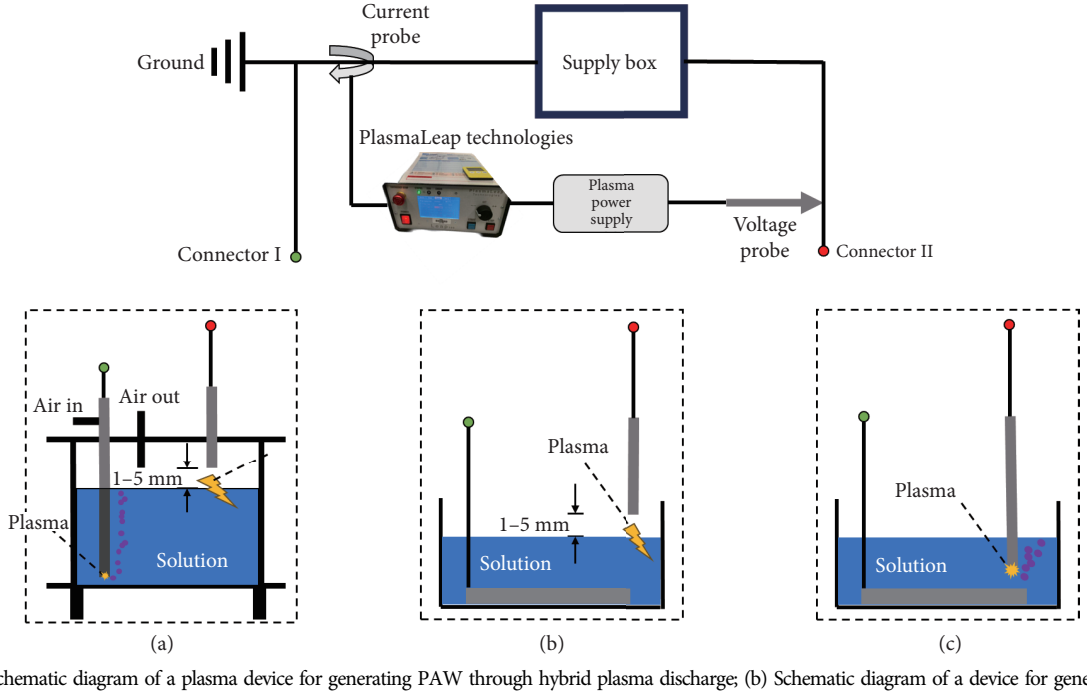

Figure 2 (a) Schematic diagram of a plasma device for generating PAW through hybrid plasma discharge; (b) Schematic diagram of a device for generating PAW by plasma discharge on the water surface; (c) Schematic diagram of a device for generating PAW through plasma discharge in water (or underwater discharges).

Table 2 Advantages and disadvantages of thermal and non-thermal processing.

Advantages and disadvantages	Thermal processing	Non-thermal processing
Advantages	Easy to apply in industrial or household processes; high inactivation efficiency due to fast heating; inactivation of enzymes	Preserves freshness; preserves nutritional value; no undesirable compounds formed[6]
Disadvantages	Loss of nutritional value of food; loss of original flavor, texture, and color; formation of toxic compounds[32]	No undesirable flavor compounds produced; does not lead to enzyme inactivation[7]; maintains spore integrity

in redox reactions as both an oxidant and reductant[36]. Locke et al.[37] observed that plasma generated on the surface of a liquid markedly differed from that generated within the liquid, due to differences in breakdown strength, density, and electrical conductivity of atmospheric gases. While storage temperatures slightly affect the pH of PAW, ORP values decrease over extended storage, suggesting temperature doesn't offset ORP loss. Studies showed a positive correlation between ORP values and antimicrobial activity.

1.5.2 Hydrogen peroxide production

PAW generates ROS, notably H_2O_2, which significantly contributes to its antimicrobial properties. The formation of H_2O_2 has been extensively studied, with researchers highlighting its role in PAW's antimicrobial efficacy. To quantify H_2O_2, various analytical techniques such as iodometric titration, potassium permanganate titration, titanium oxalate spectrophotometry, and peroxidase assay kits are utilized[30]. The interaction between H_2O_2 and the superoxide anion is vital in the acidic environment of PAW, influencing its oxidation properties. Lukes et al.[38] suggested that H_2O_2 formation is attributed to the reaction of OH radicals with water molecules, induced by electron dissociation. Stara et al.[39] examined factors affecting hydrogen peroxide production, finding that voltage and discharge time were directly proportional to its formation. They also noted that the interaction of nitrite with hydrogen peroxide during discharge might produce NO_3^-, which could account for the observed decrease in hydrogen peroxide concentration[40].

1.5.3 NO_3^- and NO_2^-

There has been increasing interest in the antibacterial properties of NO_3^- and NO_2^- ions in PAW, particularly due to their involvement in RNS production. PAW stores durable nitrate ions that form secondary products, extending its antibacterial efficacy[34]. Post-discharge, NO_2^- reacts with H_2O_2 to form peroxynitrite, which possesses potent antimicrobial effects[26]. Similar to ROS, the concentrations of NO_3^- and NO_2^- diminish over extended storage periods. In an experiment using a continuous gliding arc plasma reactor with variable flow rates, nitrogen oxides formed from nitrogen and oxygen dissociation in air plasma combined with water to produce NO_2^- ions. These ions subsequently reacted with H_2O_2 to yield NO_2^- ions[40]. Utilizing a gas plasma microspray pre-mixed with Ar/O_2 altered the concentrations of nitrite and nitrate in PAW, which varied depending on whether the discharge was directly in water or on the water surface. Direct water discharge resulted in slightly higher nitrate and NO_2^- concentrations compared to surface discharge[41].

1.5.4 Conductivity

According to the study of Thirumdas et al.[9], conductivity referred to water's ability to conduct electrical charges, significantly influenced by the presence of foreign ions. Plasma treatment introduces reactive species and ions into water, altering its conductivity[36]. During plasma activation, the generation of ROS and RNS increases PAW's conductivity. Conductivity is typically measured in microsiemens per centimeter (μS/cm), with distilled water's conductivity ranging from 0.5 to 3.0 μS/cm[30]. Moreover, the conductivity of PAW produced directly in water is higher than that of PAW generated at the water surface. Brisset et al.[42] noted an increase in conductivity using air plasma on the water surface, a change attributed to peroxynitrite's chemical actions. When nitrogen-free gases are used, the conductivity rise is due to H_3O^+ ion formation in the water. Lukes et al.[38] observed a correlation between water's electrical conductivity and voltage with the intensity of ultraviolet (UV) radiation from corona discharge, where an increase in conductivity boosts UV radiation intensity.

2 Inactivation mechanism of PAW

The inactivation mechanism of PAW involves various active substances, such as H_2O_2, NO_3^-, NO_2^-, ROS, and RNS (Figure 3). These agents penetrate the cell, causing oxidative damage to nucleic acids, proteins, and other cellular structures, which triggers a cellular oxidative stress response. This response disrupts normal cell functions, leading to bacterial inactivation[43]. Comparatively, PAW demonstrates superior efficiency and simplicity in sterilizing food during processing than conventional plasma. This efficacy is due to PAW's exceptional antioxidant and antimicrobial properties, which have been proven effective against a wide array of foodborne pathogens, spoilage organisms, and detrimental chemicals across various food products[44]. The generation mechanism of plasma focuses on different aspects related to biological and material mechanisms, whereas PAW's deactivation mechanism is attributed to the action of various nitrogenous compounds that break down the cellular components of harmful agents in food[33].

PAW is currently a subject of extensive research as a novel microbial decontamination technology[45]. It is effective in *in vitro* antimicrobial studies and shows potent bactericidal activity against plankton. Typically, biofilms are more resistant to PAW's decontamination effects than planktonic cells. Spore-forming microorganisms, which produce highly resilient spores, present additional challenges for PAW inactivation compared to regular cells[36]. Recently, PAW has been utilized to deactivate spores from *Bacillus*, *Aspergillus*, and various fungi, with the effectiveness of spore inactivation and viability reduction dependent on the

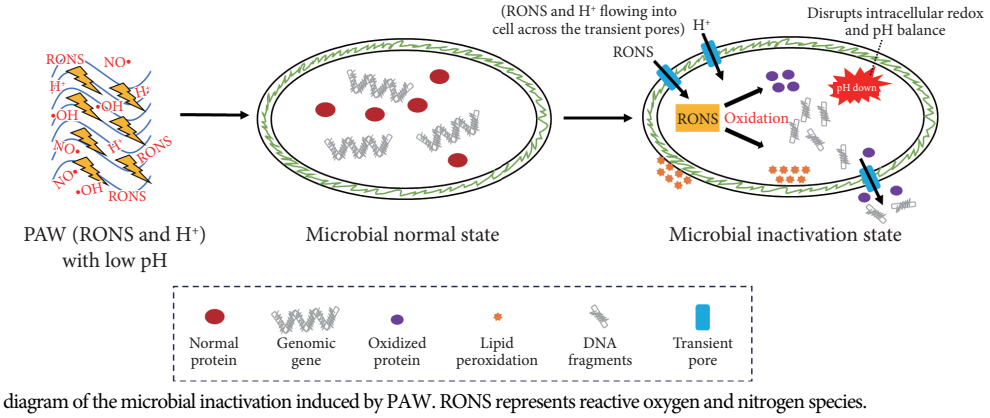

Figure 3 Schematic diagram of the microbial inactivation induced by PAW. RONS represents reactive oxygen and nitrogen species.

treatment environment and conditions. Beyond bacteria, biofilms, and spores, PAW has also been shown to efficiently deactivate certain viruses and phages[46].

The decontamination efficacy of PAW is influenced by several factors, primarily the composition and concentration of reactive oxygen and nitrogen species (RONS)[37]. Different plasma sources and plasma jets create distinct RONS in air plasma, and their transfer into the liquid affects PAW's deactivation efficacy[42]. An extended plasma activation duration enhances PAW's deactivation effect on food products, indicating that higher voltage in a plasma system increases PAW's sterilization impact. Yet, overly high voltage at the square wave point can reduce PAW's deactivation efficiency by producing a less uniform electric field and increasing the ambient temperature, which may shorten the active materials' lifespan in PAW[31]. While air is the most common and economical plasma gas, other gases like nitrogen, argon, and helium are also used. Recent findings suggest that helium with a trace of oxygen enhances deactivation efficiency. There is not a direct relationship between gas flow rate increase and PAW's deactivation effectiveness; too high gas flow rates might remove the active substances before they can effectively diffuse into the water.

Factors influencing the efficacy of PAW, beyond the plasma generation itself, include the methods used for its production, the temperature and volume of the surrounding environment, the water source, and critically, its storage duration. Submerged plasma generation, where plasma is directly discharged onto the water's surface, proves more effective, allowing immediate interaction with the water[36]. This efficiency is due to the reduced time needed for plasma discharge onto the surface, resulting in a smaller volume of water being treated and the heat within the PAW enhancing the deactivation synergistically. Moreover, improper storage can diminish PAW's deactivation efficiency.

The effectiveness of PAW varies across different microorganisms. Often, Gram-negative bacteria exhibit less resistance to PAW compared to Gram-positive bacteria, likely due to differences in their cell wall structures, with PAW showing greater efficacy against Gram-negative bacteria[29]. Additionally, variations in cell morphology influence PAW's inactivation effectiveness, as biofilms tend to be more resistant than planktonic cells. PAW's inactivation potency increases when microorganisms are initially at a lower temperature[36]. The condition of the food or its surface also affects PAW's efficiency, with the inactivation of microorganisms on rough food surfaces being less effective. This could be due to more favorable conditions for bacterial self-protection on rough surfaces, hindering the penetration of PAW's inactivating agents. Besides surface roughness, factors like surface hydrophobicity, pH, and the food's composition may affect bacterial adhesion, subsequently impacting PAW's sterilizing effectiveness.

Certain fresh produce items are particularly susceptible to microbial contamination and other hazardous agents, a concern that intensifies with their increasing consumer demand, thereby raising contamination risks. It is crucial to ensure the safety of these foods, especially since many are consumed raw[32]. Concerning meat, seafood, and poultry, the Consumer Protection Alliance directed its analysis towards poultry, beef, and fresh mackerel fillets. PAW demonstrates a significant inactivating effect on detrimental substances in processed foods like rice dumplings, rice cakes, and soy products, purifying the microbiota and thus prolonging their shelf life. Additionally, PAW is effective in inactivating pathogens in certain refrigerated products, contributing to the stability and safety of the production process.

While there is a broad agreement that the RONS produced in PAW are pivotal to its sterilizing capabilities and that PAW's acidic environment boosts this effect, the sole influence of low pH is relatively minor in bacterial inactivation[38]. Although the majority of PAW inactivation research occurs at the laboratory scale, there have been considerable advancements in applying PAW technology in production engineering within food processing facilities, enhancing energy efficiency, environmental sustainability, and cost-effectiveness[47].

3 Effect of PAW on *Salmonella* in beef rump

The plate count method is an established experimental technique for evaluating the effectiveness of PAW against *Salmonella* in beef rump. According to the study by Astorga et al.[48], PAW's sterilization efficacy on beef contaminated with *Salmonella* was examined. This assessment included 2 cleaning approaches: the spraying method and the immersion method. The specific procedures are detailed in Figure 4, where beef contaminated with *Salmonella* spp. was treated using both the spraying and immersion

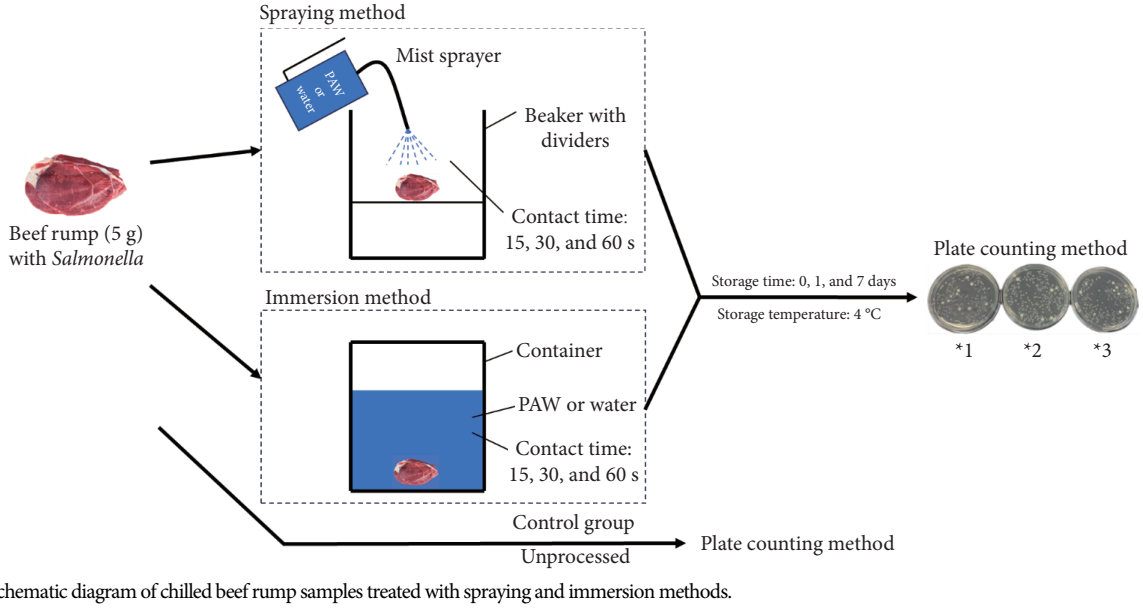

Figure 4 Schematic diagram of chilled beef rump samples treated with spraying and immersion methods.

methods. The experiments were conducted at a constant temperature of 4 °C, with the beef rump exposed to PAW (0, 1, and 7 days) and water for 15, 30, and 60 s, respectively. After these treatments, the plate count method was utilized to determine the sterilization effects.

The bacterial colonies were quantified using the plate count method, with the results expressed as logarithm reduction. The logarithm reduction was determined as $\lg(N_0/N)$[48], where N_0 represented the microbial cell counts for untreated samples (CFU/mL), N represented the microbial cell counts for samples treated with PAW or water (CFU/mL)[27].

According to the study of Hadinoto et al.[27], both the spraying and immersion methods significantly inactivated *Salmonella* in beef rump meat, with no notable difference in their effectiveness. However, the inactivation capability of PAW diminished over time.

4 Quality of beef enhanced by PAW

The presence of pathogenic microorganisms in improperly stored and transported fresh and frozen beef can result in spoilage through the proliferation of foodborne pathogens. PAW is endowed with outstanding oxidizing and antimicrobial properties, capable of effectively eradicating these microorganisms in beef[48]. The antimicrobial efficacy of PAW on beef is evaluated using several metrics, such as the counts of fungal and bacterial colonies, pH levels, H_2O_2 presence, and NO_2^- concentration. Additionally, a texture analyzer can assess the beef's texture, providing insights into its elasticity and firmness[28]. PAW contains various compounds, notably NO_2^- and H_2O_2, which are believed to play crucial roles in the deactivation of microorganisms in beef. A study by Astorga et al.[48] has demonstrated PAW's effectiveness in mitigating microbial contamination, thus enhancing the quality and safety of beef.

The pH is a key parameter for evaluating beef freshness. Studies have shown that the pH value of beef samples rises with increased storage time. However, for PAW-treated beef, this increase occurs more gradually compared to untreated samples[48], a result of PAW's sterilizing effect on beef, which effectively reduces microbial presence and creates an acidic environment, thus impacting oxygen levels. The total volatile basic nitrogen (TVB-N) content is essential for assessing beef degradation and bacterial spoilage, with PAW treatment leading to a reduction in TVB-N contents. Research has also revealed that plasma affects beef lipids during PAW treatment, causing a rise in thiobarbituric acid reactive substance (TBARS) values, which is linked to free radical generation during plasma treatment, promoting lipid peroxidation. Moreover, after atmospheric pressure plasma treatment, an increase in lipid oxidation in beef was observed. PAW releases substances into the air, including hydrogen peroxide, which breaks down into hydroxyl radicals, affecting beef's ionic composition. Recent studies show that PAW-treated beef has a minimal effect on lipid oxidation. PAW also alters beef's structure, with beef texture being vital for consumer acceptance. While beef elasticity typically diminishes over extended storage, PAW treatment slows this decline, as microbial protein degradation and PAW's oxidative properties affect beef's structural proteins, impacting elasticity. Hardness assessments reveal that PAW-treated beef tends to be less hard over time compared to untreated beef, with hardness linked to protein integrity, which PAW disrupts. Color is a crucial indicator of food quality and significantly influences consumer acceptance. Comparisons between PAW-treated and untreated beef reveal that PAW-treated beef exhibits a lighter color. This change is probably due to the oxidation of deoxygenated myoglobin, a decrease in pH on the surface of the PAW-treated beef, and the effect of acetic acid present in the beef on its color, resulting in a diminished red hue[27,48].

In summary, PAW treatment is an effective method for eliminating microbial contamination in beef, highlighting its potential as a valuable food safety intervention. However, the application of PAW must be carefully managed, as excessive treatment can adversely affect the beef's structural integrity and quality. Therefore, future research should focus on optimizing and refining PAW technology to maximize its benefits and applicability in the food industry, ensuring food safety without compromising quality.

5 Future trends and applications

PAW holds significant promise for food preservation due to its exceptional sterilization capabilities. Looking ahead, PAW could see broader applications in the preservation of various food types, including meat, eggs, fruits, and vegetables. Currently, one of the challenges is addressing the decline in PAW's sterilizing effect over time, particularly concerning the production and storage of PAW. In supermarkets, meat products are commonly stored at low temperatures to prolong shelf life, but this can affect their freshness, taste, and color. Furthermore, the need to defrost frozen meat products before cooking can be time-consuming. To address these issues, the PAW spraying system, which is intended to prolong the shelf life of meat products at moderately low temperatures while preserving their taste and nutritional quality, is applied. This system is depicted in Figure 5.

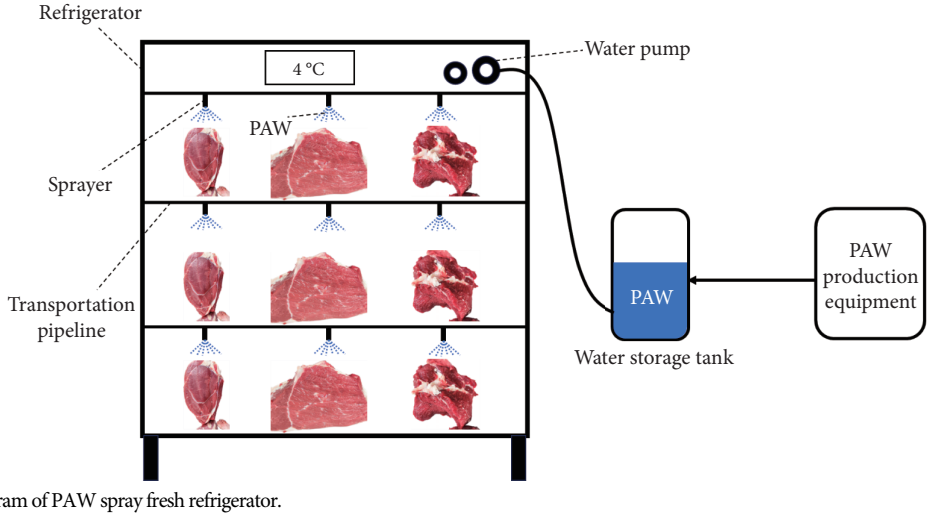

Figure 5 Schematic diagram of PAW spray fresh refrigerator.

The effectiveness of PAW in sterilization diminishes if it is not utilized promptly. To preserve its sterilizing properties, it's crucial to apply PAW to meat products promptly. Therefore, integrating a PAW production unit next to the refrigerator is suggested. This unit would generate PAW, which would then be stored in a water tank, circulated through pipes, and dispersed over the meat products via a sprayer to ensure their sterilization and freshness. While this concept is ideal and introduces a new strategy for meat preservation, its practical implementation may face challenges related to environmental factors and cost considerations.

6 Conclusion

This study offers a detailed examination of foodborne illnesses, with a particular emphasis on the risks posed by *Salmonella*. It introduces plasma and PAW as innovative non-thermal methods for food sterilization, reviewing their production processes, mechanisms of inactivation, and their physical and chemical characteristics. Additionally, the paper delves into PAW's effectiveness against *Salmonella* in the beef rump, outlining the experimental approaches used. A new application of PAW for meat products is presented. PAW's success in deactivating *Salmonella* in beef rump is attributed to its acidic environment, which establishes a redox potential and creates a solution abundant in ROS, RNS, and other components (H_2O_2, NO_3^-, NO_2^-, and $ONOO^-$), leading to the disintegration of *Salmonella* cells. As a cutting-edge, non-autoclave sterilization method, PAW is recognized for its high efficiency, operational simplicity, and eco-friendliness. Therefore, PAW demonstrates considerable promise for microbial sterilization across a range of food products. Future studies should aim to scale up PAW production, minimize costs, and investigate its combined use with other food processing technologies to broaden its applications in the treatment of fruits, vegetables, meats, and more within the food processing industry.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This study was support by the Start-Up Grant of Henan University of Technology (No. 2023BS006).

References

[1] J. N. Han, P. C. Dong, B. W. Holman, et al., Processing interventions for enhanced microbiological safety of beef carcasses and beef products: a review, Crit. Rev. Food Sci. Nutr. 64 (2022) 2105–2129. https://doi.org/10.1080/10408398.2022.2121258.

[2] A. C. Foddai, I. R. Grant, Methods for detection of viable foodborne pathogens: current state-of-art and future prospects, Appl. Microbiol. Biotechnol. 104 (2020) 4281–4288. https://doi.org/10.1007/s00253-020-10542-x.

[3] Y. Zhao, R. C. Chen, E. Tian, et al., Plasma-activated water treatment of fresh beef: bacterial inactivation and effects on quality attributes, IEEE Trans. Radiat. Plasma Med. Sci. 4 (2018) 113–120. https://doi.org/10.1109/TRPMS.2018.2883789.

[4] G. Vidyadharani, H. Vijaya Bhavadharani, P. Sathishnath, et al., Present and pioneer methods of early detection of food borne pathogens, J. Food Sci. Technol. 59 (2022) 2087–2107. https://doi.org/10.1007/s13197-021-05130-4.

[5] F. D. Gutema, G. Rasschaert, G. E. Agga, et al., Prevalence, antimicrobial resistance, and molecular characterization of *Salmonella* in cattle, beef, and diarrheic patients in Bishoftu, Ethiopia, Foodborne Pathog. Dis. 18 (2021) 283–289. https://doi.org/10.1089/fpd.2020.2869.

[6] P. Piyasena, E. Mohareb, R. Mckellar, Inactivation of microbes using ultrasound: a review, Int. J. Food Microbiol. 87 (2003) 207–216. https://doi.org/10.1016/S0168-1605(03)00075-8.

[7] C. Morris, A. L. Brody, L. Wicker, Non-thermal food processing/preservation technologies: a review with packaging implications, Packag. Technol. Sci. 20 (2007) 275–286. https://doi.org/10.1002/pts.789.

[8] E. Rifna, S. K. Singh, S. Chakraborty, et al., Effect of thermal and non-thermal techniques for microbial safety in food powder: recent advances, Food Res. Int. 126 (2019) 108654. https://doi.org/10.1016/j.foodres.2019.108654.

[9] R. Thirumdas, A. Kothakota, U. Annapure, et al., Plasma activated water (PAW): chemistry, physico-chemical properties, applications in food and agriculture, Trends Food Sci. Technol. 77 (2018) 21–31. https://doi.org/10.1016/j.tifs.2018.05.007.

[10] Q. Y. Wang, D. Salvi, Recent progress in the application of plasma-activated water (PAW) for food decontamination, Curr. Opin. Food Sci. 42 (2021) 51–60. https://doi.org/10.1016/j.cofs.2021.04.012.

[11] J. Qian, H. Zhuang, M. M. Nasiru, et al., Action of plasma-activated lactic acid on the inactivation of inoculated *Salmonella enteritidis* and quality of beef, Innov. Food Sci. Emerg. 57 (2019) 102196. https://doi.org/10.1016/j.ifset.2019.102196.

[12] J. Barrales Astorga, An investigation into the use of plasma activated water to improve the quality and safety of fresh meat, University of New South Wales, Sydney, 2022.

[13] D. G. Nyachuba, Foodborne illness: is it on the rise?, Nutr. Rev. 68 (2010) 257–269. https://doi.org/10.1111/j.1753-4887.2010.00286.x.

[14] Y. S. Yang, F. Meier, J. Ann Lo, et al., Overview of recent events in the microbiological safety of sprouts and new intervention technologies, Compr. Rev. Food Sci. Food Saf. 12 (2013) 265–280. https://doi.org/10.1111/1541-4337.12010.

[15] H. Cheng, J. Zhao, J. Zhang, et al., Attribution analysis of household foodborne disease outbreaks in China, 2010–2020, Foodborne Pathog. Dis. 20 (2023) 358–367. https://doi.org/10.1089/fpd.2022.0070.

[16] H. W. Cho, Enemy at the gate, Osong Public Health Res. Perspect. 10 (2019) 203. https://doi.org/10.24171/j.phrp.2019.10.4.01.

[17] D. Warmate, B. A. Onarinde, Food safety incidents in the red meat industry: a review of foodborne disease outbreaks linked to the consumption of red meat and its products, 1991 to 2021, Int. J. Food Microbiol. 398 (2023) 110240. https://doi.org/10.1016/j.ijfoodmicro.2023.110240.

[18] T. Zhang, C. L. Cao, H. T. Yu, et al., Design and implementation of dairy food tracking system based on RFID, in 2020 International Wireless Communications and Mobile Computing (IWCMC), Limassol, Cyprus, 2020, 2199–2203.

[19] A. Criscuolo, S. Issenhuth-Jeanjean, X. Didelot, et al., The speciation and hybridization history of the genus *Salmonella*, Microb. Genom. 5 (2019) e000284. https://doi.org/10.1099/mgen.0.000284.

[20] O. Ehuwa, A. K. Jaiswal, S. Jaiswal, Food safety and food handling practices, Foods 10 (2021) 907. https://doi.org/10.3390/foods10050907.

[21] G. L. Popa, M. I. Papa, *Salmonella* spp. infection-a continuous threat worldwide, Germs 11 (2021) 88–96. https://doi.org/10.18683/germs.2021.1244.

[22] H. Conrads, M. Schmidt, Plasma generation and plasma sources, Plasma Sources Sci. Technol. 9 (2000) 441. https://doi.org/10.1088/0963-0252/9/4/301.

[23] N. Shainsky, D. Dobrynin, U. Ercan, et al., Plasma acid: water treated by dielectric barrier discharge, Plasma Process. Polym. 9 (2012) e201100084. https://doi.org/10.1002/ppap.201100084.

[24] J. L. Brisset, B. Benstaali, D. Moussa, et al., Acidity control of plasma-chemical oxidation: applications to dye removal, urban waste abatement and microbial inactivation, Plasma Sources Sci.

Technol. 20 (2011) 034021. https://doi.org/10.1088/0963-0252/20/3/034021.
[25] M. J. Pavlovich, D. S. Clark, D. B. Graves, Quantification of air plasma chemistry for surface disinfection, Plasma Sources Sci. Technol. 23 (2014) 065036. https://doi.org/10.1088/0963-0252/23/6/065036.
[26] P. Lukes, E. Dolezalova, I. Sisrova, et al., Aqueous-phase chemistry and bactericidal effects from an air discharge plasma in contact with water: evidence for the formation of peroxynitrite through a pseudo-second-order post-discharge reaction of H_2O_2 and HNO_2, Plasma Sources Sci. Technol. 23 (2014) 015019. https://doi.org/10.1088/0963-0252/23/1/015019.
[27] K. Hadinoto, H. X. Yang, T. Q. Zhang, et al., The antimicrobial effects of mist spraying and immersion on beef samples with plasma-activated water, Meat Sci. 200 (2023) 109165. https://doi.org/10.1016/j.meatsci.2023.109165.
[28] K. Hadinoto, B. A. Niemira, F. J. Trujillo, A review on plasma-activated water and its application in the meat industry, Compr. Rev. Food Sci. Food Saf. 22 (2023) 4993–5019. https://doi.org/10.1111/1541-4337.13250.
[29] B. Benstaali, D. Moussa, A. Addou, et al., Plasma treatment of aqueous solutes: some chemical properties of a gliding arc in humid air, Eur. Phys. J. Appl. Phys. 4 (1998) 171–179. https://doi.org/10.1051/epjap:1998258.
[30] R. N. Ma, G. M. Wang, Y. Tian, et al., Non-thermal plasma-activated water inactivation of food-borne pathogen on fresh produce, J. Hazard. Mater. 300 (2015) 643–651. https://doi.org/10.1016/j.jhazmat.2015.07.061.
[31] Q. S. Xiang, L. M. Fan, Y. F. Li, et al., A review on recent advances in plasma-activated water for food safety: current applications and future trends, Crit. Rev. Food Sci. Nutr. 62 (2022) 2250–2268. https://doi.org/10.1080/10408398.2020.1852173.
[32] Y. C. Huang, D. Xiao, B. M. Burton-Freeman, et al., Chemical changes of bioactive phytochemicals during thermal processing, Reference Module in Food Science (2016) 1–9. https://doi.org/10.1016/B978-0-08-100596-5.03055-9.
[33] K. Oehmigen, M. Hähnel, R. Brandenburg, et al., The role of acidification for antimicrobial activity of atmospheric pressure plasma in liquids, Plasma Process. Polym. 7 (2010) 250–257. https://doi.org/10.1002/ppap.200900077.
[34] J. Shen, Y. Tian, Y. L. Li, et al., Bactericidal effects against *S. aureus* and physicochemical properties of plasma activated water stored at different temperatures, Sci. Rep. 6 (2016) 28505. https://doi.org/10.1038/srep28505.
[35] T. V. Suslow, Oxidation-reduction potential (ORP) for water disinfection monitoring, control, and documentation, Peer Reviewed Publications, New York, 2004.
[36] P. Lukes, B. R. Locke, J. L. Brisset, Aqueous-phase chemistry of electrical discharge plasma in water and in gas-liquid environments, Plasma Chem. Catal. Gases Liq. 1 (2012) 243–308. https://doi.org/10.1002/9783527649525.ch7.
[37] B. R. Locke, P. Lukes, J. L. Brisset, Elementary chemical and physical phenomena in electrical discharge plasma in gas-liquid environments and in liquids, in: V. I. Pârvulescu, M. Magureanu, P. Lukes (Eds.), Plasma chemistry and catalysis in gases and liquids, John Wiley & Sons, New York, 2012, pp. 185–241.
[38] P. Lukes, M. Clupek, V. Babicky, et al., Ultraviolet radiation from the pulsed corona discharge in water, Plasma Sources Sci. Technol. 17 (2008) 024012. https://doi.org/10.1088/0963-0252/17/2/024012.
[39] Z. Stara, F. Krčma, The study of H_2O_2 generation by DC diaphragm discharge in liquids, Czech. J. Phys. 54 (2004) C1050–C1055. https://doi.org/10.1007/BF03166529.
[40] R. Burlica, R. Grim, K. Y. Shih, et al., Bacteria inactivation using low power pulsed gliding arc discharges with water spray, Plasma Process. Polym. 7 (2010) 640–649. https://doi.org/10.1002/ppap.200900183.
[41] Y. Tian, R. N. Ma, Q. Zhang, et al., Assessment of the physicochemical properties and biological effects of water activated by non-thermal plasma above and beneath the water surface, Plasma Process. Polym. 12 (2015) 439–449. https://doi.org/10.1002/ppap.201400082.
[42] J. L. Brisset, J. Pawlat, Chemical effects of air plasma species on aqueous solutes in direct and delayed exposure modes: discharge, post-discharge and plasma activated water, Plasma Chem. Plasma Process. 36 (2016) 355–381. https://doi.org/10.1007/s11090-015-9653-6.
[43] P. Bruggeman, C. Leys, Non-thermal plasmas in and in contact with liquids, J. Phys. D. Appl. Phys. 42 (2009) 053001. https://doi.org/10.1088/0022-3727/42/5/053001.
[44] Z. Machala, B. Tarabova, K. Hensel, et al., Formation of ROS and RNS in water electro-sprayed through transient spark discharge in air and their bactericidal effects, Plasma Process. Polym. 10 (2013) 649–659. https://doi.org/10.1002/ppap.201200113.
[45] M. Chaijan, S. Chaijan, A. Panya, et al., Combined effects of prior plasma-activated water soaking and whey protein isolate-ginger extract coating on the cold storage stability of Asian sea bass (*Lates calcarifer*) steak, Food Control 135 (2022) 108787. https://doi.org/10.1016/j.foodcont.2021.108787.
[46] J. Małajowicz, K. Khachatryan, M. Kozłowska, Properties of water activated with low-temperature plasma in the context of microbial activity, Beverages 8 (2022) 63. https://doi.org/10.3390/beverages8040063.
[47] E. S. Wahyuningtyas, A. Iswara, Y. Sari, et al., Comperative study on manuka and indonesian honeys to support the application of plasma jet during proliferative phase, Clin. Plasma Med. 12 (2018) 1–9. https://doi.org/10.1016/j.cpme.2018.08.001.
[48] J. B. Astorga, K. Hadinoto, P. Cullen, et al., Effect of plasma activated water on the nutritional composition, storage quality and microbial safety of beef, LWT-Food Sci. Technol. 154 (2022) 112794. https://doi.org/10.1016/j.lwt.2021.112794.