AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 11 (November, 2026)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Plasma-Activated Water: An Emerging Non-Thermal Technology for Sustainable Poultry Production and Processing

*A. Aruljothi[1], M. Suryaselvi[1] and Er. S. Barath Karthick[2]
[1]UG Scholar, Final Year, B.Tech – Poultry Technology (2023-2024 Batch), College of Poultry Production and Management, Hosur, Tamil Nadu, India
[2]Assistant Professor, Dept. of Food Business Management, College of Poultry Production and Management, Hosur, Tamil Nadu, India
*Corresponding Author's email: aruljothi123778@gmail.com

The poultry industry plays a significant role in global food security by providing affordable animal protein through meat and egg production (Zhang *et al*., 2024). With increasing demand for safe, nutritious and high-quality poultry products, the industry faces several challenges, including microbial contamination, food spoilage, antimicrobial resistance, poor water quality and biofilm formation in processing equipment (Chowdhury *et al*., 2023; Prasad *et al*., 2024). Conventional sanitation practices mainly rely on chemical disinfectants, chlorination and thermal treatments (Ezzatpanah *et al*., 2022; Kim *et al*., 2017). Although these methods are widely used, concerns regarding chemical residues, environmental effects, processing efficiency and possible changes in product quality have encouraged researchers to explore alternative technologies (Roobab *et al*., 2022). Among the emerging innovations, **Plasma-Activated Water (PAW)** has gained considerable attention as a promising non-thermal technology for microbial control and food preservation (Perinban *et al*., 2019). It combines the antimicrobial properties of cold atmospheric plasma with the practical advantages of water-based sanitation (Vaka *et al*., 2019). Recent studies have demonstrated its potential applications in poultry meat preservation (Große-Peclum *et al*., 2023; Ju *et al*., 2025), microbial inactivation, drinking-water treatment and biofilm management (Vyas, 2025). This technology may provide new opportunities to improve poultry production, processing hygiene and food safety.

Understanding Plasma-Activated Water Technology

Plasma is commonly known as the fourth state of matter, consisting of positively and negatively charged particles, free electrons, ions, excited molecules and reactive species (Oruncak *et al*., 2024). Depending on its temperature and operating conditions, plasma can be classified into thermal and non-thermal forms (Misra *et al*., 2011). Cold atmospheric plasma (CAP) is particularly important in biological and food-processing applications because it produces reactive species without requiring conventional high-temperature treatment (Chiappim *et al*., 2024).

Plasma-Activated Water is generated when water interacts with cold atmospheric plasma (Hadinoto *et al*., 2021). During this interaction, energy from the plasma discharge activates water molecules and surrounding atmospheric gases, resulting in the formation of various reactive oxygen and nitrogen species (RONS) (Hadinoto *et al*., 2021).

The important reactive species associated with PAW include hydrogen peroxide (H_2O_2), ozone (O_3), nitrite (NO_2^-), nitrate (NO_3^-), hydroxyl radicals (•OH), superoxide radicals ($O_2^{\bullet-}$) and nitric oxide (NO) (Montalbetti *et al*., 2024). These compounds modify the physicochemical properties of water, including pH, electrical conductivity and oxidation-reduction potential (ORP), contributing to its antimicrobial activity (Cingesar *et al*., 2025).

The composition and effectiveness of PAW depend on several factors, including plasma reactor design, electrode arrangement, discharge voltage, treatment duration, input gas and water characteristics (Hadinoto *et al*., 2021). Oxygen-rich systems generally favour the production of reactive oxygen species, whereas nitrogen-rich conditions promote reactive nitrogen species (Mai-Prochnow *et al*., 2021). Therefore, PAW can be tailored according to the intended application.

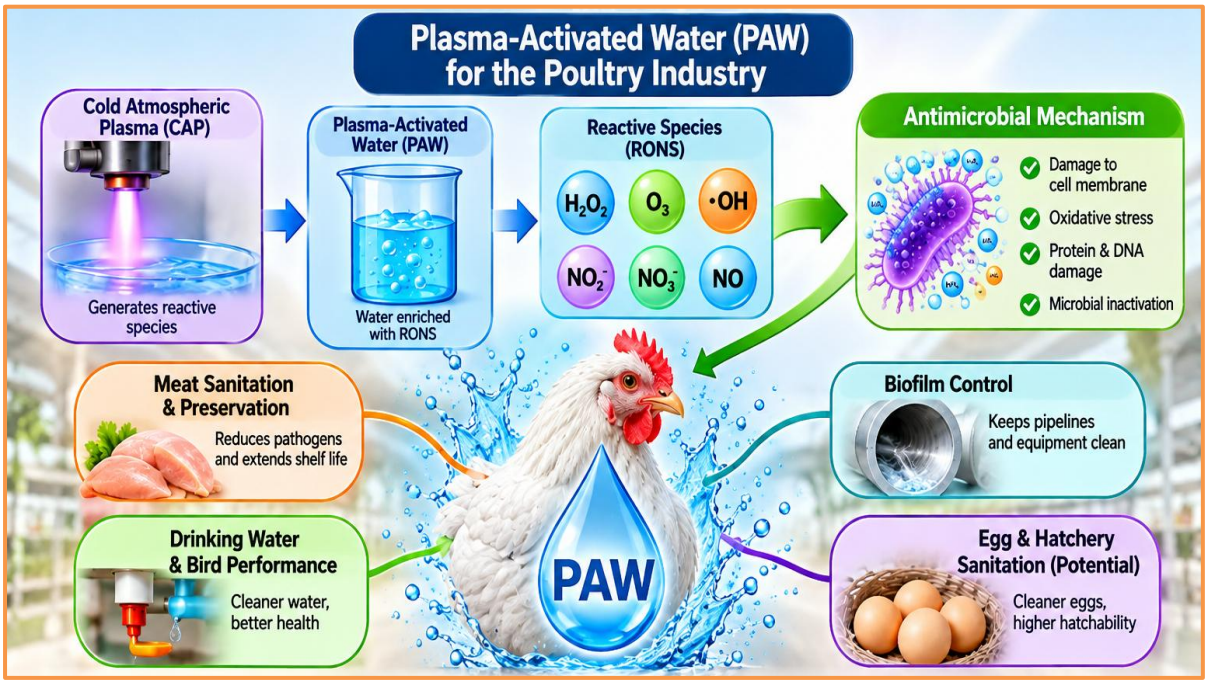
Scientific Mechanism: How Does PAW Inactivate Microorganisms?

The antimicrobial potential of PAW is mainly associated with the combined action of reactive oxygen and nitrogen species (Wei *et al*., 2026). These reactive compounds attack several essential cellular structures of microorganisms, making it difficult for microbial cells to maintain their normal functions.

Initially, reactive species interact with the microbial cell membrane and oxidize membrane lipids. This increases membrane permeability and disturbs the normal movement of substances across the membrane (Arango *et al*., 2018). Subsequently, reactive compounds affect cellular proteins and enzymes, interfering with important metabolic activities (López *et al*., 2019). They can also damage nucleic acids and disturb microbial replication (Kashef & Hamblin, 2017).

Furthermore, reactive species entering microbial cells produce intracellular oxidative stress. The accumulation of excessive reactive compounds disrupts cellular balance, damages essential biomolecules and eventually results in microbial inactivation (Mahmoud *et al*., 2025).

An important characteristic of PAW is its ability to attack multiple cellular targets simultaneously (Boonmee *et al*., 2026). This mechanism makes it an attractive alternative for controlling different groups of microorganisms, including Gram-positive bacteria, Gram-negative bacteria and certain fungi.



Applications of Plasma-Activated Water in the Poultry Industry

1. Poultry Meat Sanitation and Microbial Inactivation

Microbial contamination is one of the major concerns in poultry meat processing (Bolder, 2007). During slaughtering, defeathering, evisceration, washing, handling and storage, poultry meat may become contaminated with foodborne microorganisms such as *Escherichia coli*, *Salmonella* and other pathogenic or spoilage bacteria (Ellerbroek, 2004). These microorganisms can compromise food safety and reduce the storage quality of poultry products.

PAW offers a potential non-thermal approach for reducing microbial contamination through washing, immersion and other controlled treatment methods (Hadinoto *et al*., 2023). Its reactive compounds can interact with microorganisms present on meat surfaces and damage their cellular structures (Rahman *et al*., 2022).

A significant investigation by (Moonsub *et al*., 2024), published in *Processes*, evaluated the combined effects of PAW, micro/nanobubbles (MNB), ultraviolet (UV) treatment and ultrasonication (US) on *E. coli* inactivation in chicken meat. The researchers investigated whether combining these technologies could improve the antimicrobial effectiveness of PAW.

The results demonstrated that the integration of PAW with micro/nanobubbles and UV treatment achieved approximately a 6-$\log_{10}$ reduction in *E. coli* under optimized experimental conditions. The optimized treatment involved 10 minutes of micro/nanobubble treatment followed by 20 minutes of UV treatment. Although ultrasonication was investigated as an additional treatment, it was not essential to the optimized combination identified by the response-surface analysis.

This research demonstrates the potential of combining plasma technology with other physical treatment methods to improve microbial inactivation in poultry meat. Such systems could be further developed for advanced poultry-processing sanitation.

2. Improving Poultry Meat Preservation and Shelf Life

Maintaining the freshness and quality of poultry meat during storage is another important challenge. Poultry meat contains high moisture and nutrients that support microbial growth and biochemical deterioration (Sánchez *et al*., 2026). During refrigerated storage, microbial multiplication, lipid oxidation and protein degradation contribute to undesirable odours (Hassan *et al*., 2026), changes in texture and reduced consumer acceptability (Augustyńska-Prejsnar *et al*., 2024).

A study by Ju *et al*. (2025), published in *Food Chemistry: X*, investigated the influence of PAW treatment on the cold-storage stability and flavour profile of duck fillets. The experiment evaluated different plasma treatment durations and examined changes in microbial populations, moisture retention, lipid oxidation, protein degradation and volatile flavour compounds during refrigerated storage at 4°C.

The researchers reported that PAW significantly suppressed the total viable microbial count, maintaining the microbial population below the spoilage threshold for nine days under the experimental conditions (Ju *et al*., 2025). PAW treatment also improved water retention, reducing moisture loss to 2.17% compared with 6.3% in the control over nine days (Ju *et al*., 2025). Furthermore, it reduced the formation of the undesirable flavour compound 1-nonanol (Ju *et al*., 2025).

These findings demonstrate that PAW may contribute to both microbial control and the maintenance of meat quality during refrigerated storage. Its combined antimicrobial and antioxidant effects make it a promising preservation approach for poultry products. However, further studies are required to establish its effectiveness in different poultry meat varieties and commercial storage conditions.

3. PAW Application in Poultry Drinking Water and Bird Performance

Water is an essential nutrient in poultry production and plays a major role in digestion, metabolism, nutrient transportation and temperature regulation (Kalita *et al*., 2020). However, microbial contamination in drinking-water systems can create health risks and reduce water quality (Mustedanagic *et al*., 2023). Biofilm formation inside pipelines, storage tanks and drinkers further complicates water sanitation (Ban-Cucerzan *et al*., 2026).

PAW has also been investigated as a potential water-treatment approach in live poultry production (Mahmoud *et al*., 2024). Mahmoud *et al*. (2024), in a study published in *BMC Veterinary Research*, evaluated the effects of PAW-supplemented drinking water on behaviour, performance, carcass characteristics, biochemical parameters and histopathological changes in Japanese quail.

The experiment investigated different PAW supplementation levels and assessed their influence on growth performance, blood biochemical characteristics, intestinal microbial populations and internal organs.

The study reported no significant differences in body weight, feed consumption or feed conversion ratio among the experimental groups (Mahmoud *et al*., 2024). However, certain biochemical parameters, including total protein and globulin, showed changes in the PAW-treated groups (Mahmoud *et al*., 2024). The researchers also reported an increase in Lactobacilli populations in the higher PAW supplementation group (Mahmoud *et al*., 2024), along with changes in some blood biochemical measurements (Mahmoud *et al*., 2024).

These findings suggest that PAW may influence selected physiological and microbial characteristics in Japanese quail. Nevertheless, the reported results do not establish PAW as a growth promoter or a universally safe drinking-water additive. More detailed investigations are necessary to determine suitable treatment concentrations, long-term safety and species-specific responses before practical application in commercial poultry farms.

4. Biofilm Control in Poultry Equipment and Water Pipelines

Biofilms represent another major challenge in poultry production and processing (Jordá *et al*., 2023). They are structured communities of microorganisms attached to surfaces and surrounded by a protective extracellular polymeric substance (EPS) matrix (Joseph & Kurian, 2026). This matrix protects microorganisms against environmental stress (Liu *et al*., 2019) and reduces their susceptibility to conventional disinfectants (Simões *et al*., 2010).

In poultry farms, biofilms may develop inside drinking-water pipelines, nipple drinkers, storage tanks, water distribution systems and processing equipment (Ban-Cucerzan *et al*., 2026). In hatcheries and poultry-processing plants, contaminated surfaces and equipment can also act as potential sources of microbial transmission (Hudson & Mead, 1989; Rothrock *et al*., 2024).

Vyas (2025), in the article *Plasma-Activated Water: A Powerful Tool Against Pesky Biofilms*, published in *Microbiology Australia*, highlighted the emerging role of PAW in biofilm management. The article explained how reactive oxygen and nitrogen species can damage microbial membranes, proteins and other cellular components. It also discussed research demonstrating the potential of PAW in surface decontamination, food safety and water treatment.

For poultry production, these findings provide a scientific basis for investigating PAW-based cleaning systems for water pipelines, drinkers and processing equipment. In particular, controlled PAW flushing could be explored for reducing microbial contamination in pipeline bends, joints and difficult-to-clean sections.

However, the effectiveness of PAW against mature biofilms under actual poultry-farm conditions requires further experimental validation. Its ability to remove the protective biofilm matrix must also be distinguished from its ability to kill microorganisms within the biofilm.

Potential Applications in Egg and Hatchery Sanitation

Eggshell contamination is an important concern in commercial hatcheries because microorganisms present on the eggshell surface may enter the incubation environment and create risks for embryonic development and chick quality (Clímaco *et al*., 2018).

Conventional egg sanitation methods use different chemical disinfectants and washing procedures (Rivera-García *et al*., 2019). However, there is increasing interest in exploring alternative technologies that can reduce microbial contamination while preserving the natural protective properties of the eggshell (Meireles *et al*., 2026).

PAW offers a potential water-based sanitation approach that could be investigated for eggshell surface treatment, hatchery tray sanitation, egg-handling equipment and incubation-room surfaces.

One promising concept is a two-stage PAW egg-washing system. The first stage could involve preliminary removal of loose dirt and organic material, followed by a controlled PAW treatment to reduce surface microbial contamination. Such a system would

require optimization of treatment duration, PAW chemistry, temperature and contact conditions.

Nevertheless, the four studies discussed in this article do not directly demonstrate PAW-based hatching-egg sanitation. Future experiments must evaluate eggshell cuticle integrity, microbial reduction, hatchability, embryonic mortality, chick quality and potential effects on shell properties before recommending commercial use.

Integration of PAW with Emerging Technologies

Although PAW has demonstrated antimicrobial potential (Traylor *et al*., 2011), its effectiveness can be improved through integration with complementary technologies. Recent research has particularly focused on micro/nanobubbles, ultraviolet radiation and ultrasonication (Esua *et al*., 2021).

***Micro/Nanobubble Technology*:** Micro/nanobubbles are extremely small gas bubbles that provide a large gas-liquid interfacial area (Σερίδου & Kalogerakis, 2021). Their integration with PAW may improve the interaction between reactive compounds and microorganisms and enhance treatment efficiency.

***Ultraviolet Technology*:** UV radiation provides an additional antimicrobial mechanism by damaging microbial genetic material (Adeniyi & Jimoh, 2024). When combined with PAW, it may improve microbial inactivation through complementary oxidative and photochemical effects.

***Ultrasonication*:** Ultrasonic waves generate acoustic cavitation, which produces mechanical forces and localized energy effects (Cravotto *et al*., 2013). These effects may improve contact between PAW and microorganisms and assist the treatment process.

The integration of these technologies offers opportunities for developing advanced poultry meat washing systems and water sanitation equipment. The findings of Moonsub *et al*. (2024) provide experimental evidence for the effectiveness of combining PAW with micro/nanobubbles and UV treatment against *E. coli* in chicken meat (Moonsub *et al*., 2024).

Advantages and Challenges of PAW Technology

PAW offers several potential advantages for the poultry industry. It is a non-thermal treatment approach that can be generated using water and electrical energy (Soni *et al*., 2021). Its antimicrobial activity is associated with multiple reactive compounds (Machala *et al*., 2018), and its properties can be adjusted through changes in plasma-generation conditions (Cai *et al*., 2023). It also offers opportunities for meat preservation, water sanitation, equipment cleaning and biofilm management (Vyas, 2025; Zhou *et al*., 2020).

Despite these advantages, certain challenges must be addressed before commercial implementation. The composition and antimicrobial effectiveness of PAW can vary according to plasma power, treatment duration, electrode configuration, gas composition and water quality (Zhao *et al*., 2020; Zhou *et al*., 2020). Some reactive species have very short lifetimes (Zhou *et al*., 2020), making preparation and application time important factors. Excessive oxidative activity may also influence meat colour, flavour, protein quality and other product characteristics (Dias *et al*., 2026).

In addition, the safety of PAW for live poultry, its effects on long-term physiological performance, equipment durability, electricity consumption and overall economic feasibility require systematic evaluation. Standardized production methods and application-specific quality-control parameters are essential for developing reliable commercial systems.

Future Prospects and Research Opportunities

The development of PAW technology provides several opportunities for future research in poultry science and engineering. The integration of plasma generation systems with automated washing equipment, sensors and controlled treatment units could improve sanitation efficiency and process monitoring.

Promising research directions include the development of PAW-based egg sanitation machines, automated drinking-water pipeline flushing systems, PAW-assisted hatchery tray

cleaning and advanced poultry meat washing equipment. Sensor-based monitoring of pH, oxidation-reduction potential, electrical conductivity and hydrogen peroxide concentration could help maintain consistent PAW quality during operation.

Further investigations should also focus on optimizing treatment conditions for different poultry products, evaluating microbial reduction under commercial conditions, studying the effects on product quality and establishing the long-term safety of PAW applications in live birds.

Combining plasma engineering, microbiology, food science and poultry production management may support the development of cost-effective and sustainable sanitation technologies for both small-scale farms and large commercial processing facilities.

Conclusion

Plasma-Activated Water represents an emerging non-thermal technology with considerable potential to improve microbial control, food preservation and sanitation practices in the poultry industry. Research on chicken meat, duck fillets and Japanese quail has demonstrated promising results in microbial inactivation, refrigerated storage quality and selected physiological and microbial characteristics (Große-Peclum *et al*., 2023; Royintarat *et al*., 2020). In addition, emerging research on biofilm control highlights its potential for improving hygiene in water systems and processing equipment (Vyas, 2025).

Although several applications have shown encouraging results under experimental conditions (Zhao *et al*., 2020), further investigations are required to establish standardized production methods, optimum treatment conditions, product quality, animal safety and economic feasibility. The integration of PAW with micro/nanobubble technology, UV radiation and automated engineering systems may further expand its applications.

With continued research and technological development, Plasma-Activated Water could become an important component of next-generation poultry sanitation, preservation and food safety management.

References

1. Adeniyi, A. O., & Jimoh, M. O. (2024). Decontamination Potential of Ultraviolet Type C Radiation in Water Treatment Systems: Targeting Microbial Inactivation. *Water*, *16*(19), 2725. https://doi.org/10.3390/w16192725
2. Arango, J. S., Brelles-Mariño, G., Rodero, A., & García, M. C. (2018). Characterization of an Air-Based Coaxial Dielectric Barrier Discharge Plasma Source for Biofilm Eradication. *Plasma Chemistry and Plasma Processing*, *38*(3), 535–556. https://doi.org/10.1007/s11090-018-9877-3
3. Augustyńska-Prejsnar, A., Kačániová, M., Hanus, P., Sokołowicz, Z., & Słowiński, M. (2024). Microbial and Sensory Quality Changes in Broiler Chicken Breast Meat During Refrigerated Storage. *Foods*, *13*(24), 4063. https://doi.org/10.3390/foods13244063
4. Ban-Cucerzan, A., Morar, A., & Imre, K. (2026). Environmental Biofilms in Livestock Production Systems: Reservoirs of Pathogens and Antimicrobial Resistance. *Life*, *16*(6), 888. https://doi.org/10.3390/life16060888
5. Bolder, N. M. (2007). Microbial challenges of poultry meat production. *World s Poultry Science Journal*, *63*(3), 401–411. https://doi.org/10.1017/s0043933907001535
6. Boonmee, T., Sinpoo, C., Nakpla, S., Disayathanoowat, T., & Chaimanee, V. (2026). Antimicrobial activity of plasma-activated water against Paenibacillus larvae, the causative agent of American foulbrood. *Scientific Reports*, *16*(1). https://doi.org/10.1038/s41598-026-58906-z
7. Cai, Z., Wang, J., WANG, Y., Sang, X., Zeng, L., Deng, W., & Zhang, J. (2023). Effect of different process conditions on the physicochemical and antimicrobial properties of plasma-activated water. *Plasma Science and Technology*, *25*(12), 125501. https://doi.org/10.1088/2058-6272/acde34
8. Chiappim, W., Kodaira, F. V. de P., Castro, G. de F. S. de, Silva, D. M. da, Tavares, T. F., Almeida, A. C. de P. L., Leal, B. H. da S., Quade, A., Koga-Ito, C. Y., & Kostov, K.

G. (2024). Proposing an Affordable Plasma Device for Polymer Surface Modification and Microbial Inactivation. *Molecules*, *29*(17), 4270. https://doi.org/10.3390/molecules29174270

9. Chowdhury, M. A. H., Ashrafudoulla, Md., Mevo, S. I. U., Mizan, Md. F. R., Park, S. H., & Ha, S. (2023). Current and future interventions for improving poultry health and poultry food safety and security: A comprehensive review. *Comprehensive Reviews in Food Science and Food Safety*, *22*(3), 1555–1596. https://doi.org/10.1111/1541-4337.13121
10. Cingesar, I. K., Stulić, V., Markić, F., Muratović, S., Kurek, M., Herceg, Z., Maltar-Strmečki, N., & Pavičić, T. V. (2025). Aging Stability and Radical Activity of Plasma-Activated Water Treated in Liquid- and Gas-Phase Reactors. *Molecules*, *30*(23), 4585. https://doi.org/10.3390/molecules30234585
11. Clímaco, W. L. dos S., Melo, É. de F., Vaz, D. P., Saldanha, M. M., Pinto, M. F. V. da S., Fernandes, L. C. C., Baião, N. C., Oliveira, L. G. de, Sant'Anna, F. M. de, Souza, M. R. de, & Lara, L. J. C. (2018). Eggshell microbiology and quality of hatching eggs subjected to different sanitizing procedures. *Pesquisa Agropecuária Brasileira*, *53*(10), 1177–1183. https://doi.org/10.1590/s0100-204x2018001000011
12. Cravotto, G., Gaudino, E. C., & Cintas, P. (2013). On the mechanochemical activation by ultrasound. *Chemical Society Reviews*, *42*(18), 7521. https://doi.org/10.1039/c2cs35456j
13. Dias, M. M. dos S., Nalon, G. A., Pereira, V. L., Souza, D. A. de, Cunha, J. S., Medeiros, H. S. de, & Júnior, B. R. de C. L. (2026). Non-Conventional Processing Technologies in Meat and Meat Products: Toward Clean-Label, Quality, and Sustainable Innovation. *Foods*, *15*(16), 2874. https://doi.org/10.3390/foods15162874
14. Ellerbroek, L. (2004). *Research update on major pathogens associated with the processing of poultry and poultry products* (pp. 81–98). https://doi.org/10.3920/9789086865222_006
15. Esua, O. J., Cheng, J., & Sun, D. (2021). Novel technique for treating grass carp (Ctenopharyngodon idella) by combining plasma functionalized liquids and Ultrasound: Effects on bacterial inactivation and quality attributes. *Ultrasonics Sonochemistry*, *76*, 105660. https://doi.org/10.1016/j.ultsonch.2021.105660
16. Ezzatpanah, H., Gómez-López, V. M., Koutchma, T., Lavafpour, F., Moerman, F. T., Mohammadi, M., & Raheem, D. (2022). New food safety challenges of viral contamination from a global perspective: Conventional, emerging, and novel methods of viral control. *Comprehensive Reviews in Food Science and Food Safety*, *21*(2), 904–941. https://doi.org/10.1111/1541-4337.12909
17. Große-Peclum, V., Siekmann, L., Krischek, C., Avramidis, G., Ochs, C., Viöl, W., & Plötz, M. (2023). Using TRIS-Buffered Plasma-Activated Water to Reduce Pathogenic Microorganisms on Poultry Carcasses with Evaluation of Physicochemical and Sensory Parameters. *Foods*, *12*(5), 1113. https://doi.org/10.3390/foods12051113
18. Hadinoto, K., Astorga, J. B., Masood, H., Zhou, R., Alam, D., Cullen, P. J., Prescott, S. W., & Trujillo, F. J. (2021). Efficacy optimization of plasma-activated water for food sanitization through two reactor design configurations. *UNSWorks (University of New South Wales, Sydney, Australia)*, *74*, 102867. https://doi.org/10.1016/j.ifset.2021.102867
19. Hadinoto, K., Niemira, B. A., & Trujillo, F. J. (2023). A review on plasma-activated water and its application in the meat industry. *Comprehensive Reviews in Food Science and Food Safety*, *22*(6), 4993–5019. https://doi.org/10.1111/1541-4337.13250
20. Hassan, M., Hossen, K., Rahman, M., Hashem, M., & Rahman, Md. M. (2026). Effect of yoghurt, lemon juice and garlic-ginger paste marination on the quality of chicken meat during refrigerated storage. *Meat Research | ISSN (Online Version) 2790-1971*, *6*(1). https://doi.org/10.55002/mr.6.1.137
21. Hudson, W. R., & Mead, G. C. (1989). Listeria contamination at a poultry processing plant. *Letters in Applied Microbiology*, *9*(6), 211–214. https://doi.org/10.1111/j.1472-765x.1989.tb00328.x

22. Jordá, J., Lorenzo-Rebenaque, L., Montoro-Dasi, L., Marco-Fuertes, A., Vega, S., & Marín, C. (2023). Phage-Based Biosanitation Strategies for Minimizing Persistent Salmonella and Campylobacter Bacteria in Poultry. *Animals*, *13*(24), 3826. https://doi.org/10.3390/ani13243826
23. Joseph, M. G., & Kurian, N. K. (2026). The Biofilm World: Structure, Formation, and Impact. *Exon.*, *3*(1), 52–69. https://doi.org/10.69936/en05y0026
24. Ju, S., Li, J., Chen, B., Niu, L., Pan, D., Yu, Q., & Du, L. (2025). Influence of plasma-activated water treatment on the cold storage stability and flavor profile of duck fillets. *Food Chemistry X*, *32*, 103321. https://doi.org/10.1016/j.fochx.2025.103321
25. Kalita, S., Mahanta, J., Sapcota, D., Kalita, N., & Saikia, R. (2020). Effect of different sources of drinking water on the haematological and biochemical parameters of commercial broiler chicken. *International Journal of Chemical Studies*, *8*(1), 2943–2945. https://doi.org/10.22271/chemi.2020.v8.i1as.8715
26. Kashef, N., & Hamblin, M. R. (2017). Can microbial cells develop resistance to oxidative stress in antimicrobial photodynamic inactivation? *Drug Resistance Updates*, *31*, 31–42. https://doi.org/10.1016/j.drup.2017.07.003
27. Kim, S. A., Park, S. H., Lee, S. I., Owens, C. M., & Ricke, S. C. (2017). Assessment of Chicken Carcass Microbiome Responses During Processing in the Presence of Commercial Antimicrobials Using a Next Generation Sequencing Approach. *Scientific Reports*, *7*(1), 43354. https://doi.org/10.1038/srep43354
28. Liu, Y., Shi, L., Su, L., Mei, H. C. van der, Jutte, P. C., Ren, Y., & Busscher, H. J. (2019). Nanotechnology-based antimicrobials and delivery systems for biofilm-infection control. *Chemical Society Reviews*, *48*(2), 428–446. https://doi.org/10.1039/c7cs00807d
29. López, M., Calvo, T. R., Maradona, M. P., Múgica-Vidal, R., Muro-Fraguas, I., Alba-Elías, F., & Álvarez-Ordóñez, A. (2019). A Review on Non-thermal Atmospheric Plasma for Food Preservation: Mode of Action, Determinants of Effectiveness, and Applications. *Frontiers in Microbiology*, *10*, 622. https://doi.org/10.3389/fmicb.2019.00622
30. Machala, Z., Tarabová, B., Sersenová, D., Janda, M., & Hensel, K. (2018). Chemical and antibacterial effects of plasma activated water: correlation with gaseous and aqueous reactive oxygen and nitrogen species, plasma sources and air flow conditions. *Journal of Physics D Applied Physics*, *52*(3), 34002. https://doi.org/10.1088/1361-6463/aae807
31. Mahmoud, U. T., El-Reda, G. A., Ali, F. A. Z., Mahmoud, M. A. M., ABD-ALLAH, S. M. S., El-Hossary, F. M., & Khalil, N. S. A. (2024). Plasma activated water effects on behavior, performance, carcass quality, biochemical changes, and histopathological alterations in quail. *BMC Veterinary Research*, *20*(1), 391. https://doi.org/10.1186/s12917-024-04231-4
32. Mahmoud, Y. A. -G., Elkaliny, N. E., Elshikh, F. M., Ashraf, Y., Metwally, K. A., Yahya, G., & Sherif, S. (2025). Cold Plasma as a Revolutionary Antimicrobial Modality: A Multifaceted Weapon Against Antibiotic Resistance. *Antibiotics*, *14*(9), 930. https://doi.org/10.3390/antibiotics14090930
33. Mai-Prochnow, A., Zhou, R., Zhang, T., Ostrikov, K., Mugunthan, S., Rice, S. A., & Cullen, P. J. (2021). Interactions of plasma-activated water with biofilms: inactivation, dispersal effects and mechanisms of action. *Npj Biofilms and Microbiomes*, *7*(1), 11. https://doi.org/10.1038/s41522-020-00180-6
34. Meireles, I. M. de F., Lemos, W. J. F., Martins, A. M. D., Silva, M. A. P. da, Cipolat-Gotet, C., & Cappato, L. P. (2026). Non-Thermal and Mild Thermal Technologies for Table Egg Shell Surface Decontamination: Microbial Efficacy, Egg Quality, and Industrial Considerations. *Microorganisms*, *14*(2), 442. https://doi.org/10.3390/microorganisms14020442
35. Misra, N. N., Tiwari, B. K., Raghavarao, K. S. M. S., & Cullen, P. J. (2011). Nonthermal Plasma Inactivation of Food-Borne Pathogens. *Arrow - TU Dublin (Technological University Dublin)*, *3*, 159–170. https://doi.org/10.1007/s12393-011-9041-9

36. Montalbetti, R., Machala, Z., Gherardi, M., & Laurita, R. (2024). "Production and Chemical Composition of Plasma Activated Water: A Systematic Review and Meta-Analysis." *Plasma Processes and Polymers*, *22*(1). https://doi.org/10.1002/ppap.202400249
37. Moonsub, K., Seesuriyachan, P., Boonyawan, D., & Wattanutchariya, W. (2024). Synergistic Effect of Plasma-Activated Water with Micro/Nanobubbles, Ultraviolet Photolysis, and Ultrasonication on Enhanced Escherichia coli Inactivation in Chicken Meat. *Processes*, *12*(3), 567. https://doi.org/10.3390/pr12030567
38. Mustedanagic, A., Matt, M., Weyermair, K., Schrattenecker, A., Kubitza, I., Firth, C. L., Loncaric, I., Wagner, M., & Stessl, B. (2023). Assessment of microbial quality in poultry drinking water on farms in Austria. *Frontiers in Veterinary Science*, *10*, 1254442. https://doi.org/10.3389/fvets.2023.1254442
39. Oruncak, B., Özkan, M., & Özer, Z. N. (2024). Solution Plasma Process (SPP) for Nanoparticle Production: Its Role, Opportunities, and Limitations. *International Journal of Computational and Experimental Science and Engineering*, *10*(3). https://doi.org/10.22399/ijcesen.5485
40. Perinban, S., Orsat, V., & Raghavan, V. (2019). Nonthermal Plasma–Liquid Interactions in Food Processing: A Review. *Comprehensive Reviews in Food Science and Food Safety*, *18*(6), 1985–2008. https://doi.org/10.1111/1541-4337.12503
41. Prasad, A., Wynands, E., Roche, S. M., Romo-Bernal, C., Allan, N. D., Olson, M. S., Levengood, S., Andersen, R. C., Loebel, N. G., Sabino, C. P., & Ross, J. A. (2024). Photodynamic Inactivation of Foodborne Bacteria: Screening of 32 Potential Photosensitizers. *Foods*, *13*(3), 453. https://doi.org/10.3390/foods13030453
42. Rahman, M., Hasan, Md. S., Islam, R., Rana, M. R., Sayem, A. S. M., Sad, Md. A. A., Matin, A., Raposo, A., Zandonadi, R. P., Han, H., Ariza-Montes, A., Vega-Muñoz, A., & Sunny, A. R. (2022). Plasma-Activated Water for Food Safety and Quality: A Review of Recent Developments. *International Journal of Environmental Research and Public Health*, *19*(11), 6630. https://doi.org/10.3390/ijerph19116630
43. Rivera-García, A., Santos-Ferro, L., Ramírez-Orejel, J. C., Agredano-Moreno, L. T., Jiménez-García, L. F., Paez-Esquiliano, D., Andrade-Esquivel, E., & Cano, J. A. (2019). The effect of neutral electrolyzed water as a disinfectant of eggshells artificially contaminated with Listeria monocytogenes. *Food Science & Nutrition*, *7*(7), 2252–2260. https://doi.org/10.1002/fsn3.1053
44. Roobab, U., Chacha, J. S., Abida, A., Rashid, S., Madni, G. M., Lorenzo, J. M., Zeng, X., & Aadil, R. M. (2022). Emerging Trends for Nonthermal Decontamination of Raw and Processed Meat: Ozonation, High-Hydrostatic Pressure and Cold Plasma. *Foods*, *11*(15), 2173. https://doi.org/10.3390/foods11152173
45. Rothrock, M. J., Zwirzitz, B., Hakeem, W. G. A., Oladeinde, A., Guard, J. Y., & Li, X. (2024). 16S amplicon-based microbiome biomapping of a commercial broiler hatchery. *Animal Microbiome*, *6*(1), 46. https://doi.org/10.1186/s42523-024-00334-3
46. Royintarat, T., Choi, E. H., Boonyawan, D., Seesuriyachan, P., & Wattanutchariya, W. (2020). Chemical-free and synergistic interaction of ultrasound combined with plasma-activated water (PAW) to enhance microbial inactivation in chicken meat and skin. *Scientific Reports*, *10*(1), 1559. https://doi.org/10.1038/s41598-020-58199-w
47. Sánchez, M., Orts, I., Martillanes, S., Ramírez, R., & Delgado, J. (2026). Chitosan-Based Active Films Enriched with Thyme Essential Oil for Extending the Shelf Life of Refrigerated Chicken Meat. *Foods*, *15*(18), 3347. https://doi.org/10.3390/foods15183347
48. Simões, M., Simões, L. C., & Vieira, M. J. (2010). A review of current and emergent biofilm control strategies. *LWT*, *43*(4), 573–583. https://doi.org/10.1016/j.lwt.2009.12.008
49. Soni, A., Choi, J., & Brightwell, G. (2021). Plasma-Activated Water (PAW) as a Disinfection Technology for Bacterial Inactivation with a Focus on Fruit and Vegetables. *Foods*, *10*(1), 166. https://doi.org/10.3390/foods10010166

50. Traylor, M. J., Pavlovich, M. J., Karim, S., Hait, P., Sakiyama, Y., Clark, D. S., & Graves, D. B. (2011). Long-term antibacterial efficacy of air plasma-activated water. *Journal of Physics D Applied Physics*, *44*(47), 472001. https://doi.org/10.1088/0022-3727/44/47/472001
51. Vaka, M. R., Sone, I., Álvarez, R. G., Walsh, J. L., Prabhu, L., Sivertsvik, M., & Fernández, E. N. (2019). Towards the Next-Generation Disinfectant: Composition, Storability and Preservation Potential of Plasma Activated Water on Baby Spinach Leaves. *Foods*, *8*(12), 692. https://doi.org/10.3390/foods8120692
52. Vyas, H. K. N. (2025). Plasma-activated water: a powerful tool against pesky biofilms. *Microbiology Australia*, *46*(4), 213–217. https://doi.org/10.1071/ma25060
53. Wei, S., Yang, R., Tian, F., Dai, Z., Wang, X., Zhao, Y., Wang, S., & Sun, L. (2026). Plasma-Activated Water as a Novel Irrigation Strategy for Seawater-Immersed Burn Wounds: Antibacterial Activity and Healing Promotion in Rats. *Biomedicines*, *14*(5), 1027. https://doi.org/10.3390/biomedicines14051027
54. Zhang, L., Jiang, Y., Buzdar, J. A., Ahmed, S., Sun, X., Li, F., Li-na, M., Wu, P., & Li, C. (2024). Microalgae: An Exciting Alternative Protein Source and Nutraceutical for the Poultry Sector. *Food Science of Animal Resources*, *45*(1), 243–265. https://doi.org/10.5851/kosfa.2024.e130
55. Zhao, Y., Patange, A., Sun, D., & Tiwari, B. K. (2020). Plasma-activated water: Physicochemical properties, microbial inactivation mechanisms, factors influencing antimicrobial effectiveness, and applications in the food industry. *Comprehensive Reviews in Food Science and Food Safety*, *19*(6), 3951–3979. https://doi.org/10.1111/1541-4337.12644
56. Zhou, R., Zhou, R., Wang, P., Xian, Y., Mai-Prochnow, A., Lu, X., Cullen, P. J., Ostrikov, K., & Bazaka, K. (2020). Plasma-activated water: generation, origin of reactive species and biological applications. *Journal of Physics D Applied Physics*, *53*(30), 303001. https://doi.org/10.1088/1361-6463/ab81cf
57. Σερίδου, Π., & Kalogerakis, N. (2021). Disinfection applications of ozone micro- and nanobubbles. *Environmental Science Nano*, *8*(12), 3493–3510. https://doi.org/10.1039/d1en00700a