Plasma-Activated Water

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Plasma-activated water (PAW) is generated by treating water with cold atmospheric plasma (CAP) using controllable parameters such as plasma-forming voltage, carrier gas, temperature, pulses, or frequency as required. PAW is reported to have lower pH, higher conductivity, and higher oxidation-reduction potential when compared with untreated water due to the presence of reactive species. PAW has received significant attention from researchers over the last decade due to its non-thermal and non-toxic mode of action, especially for bacterial inactivation. This review summarizes the properties of PAW, the effect of various treatment parameters on its efficiency in bacterial inactivation along with its usage as a standalone technology as well as a hurdle approach with mild thermal treatments.

cold atmospheric plasma   microbes   disinfection

1. Introduction

Food spoilage is defined as a change in any food product that leads to a significant reduction in its sensory qualities, such as color, texture, and overall smell, due to physical damage or chemical changes (e.g., oxidation), and thus rendering it unacceptable by the consumer [1]. These changes are mainly the result of microbial growth and metabolism in the food, which may lead to the production of enzymes that facilitate to reactions resulting in deleterious by-products affecting the food. These by-products vary in different types of food and can lead to adverse sensory properties, including the presence of slime, off-odors, and off-flavors. Bacterial strains associated with spoilage include *Pectobacterium carotovorum* [2][3], *Brochothrix thermosphacta* [4], *Clostridium perfringens* [5], *Bacillus spp.* [6][7], *Pseudomonas fragi* [8], *Pseudomonas fluorescens* [9], *Shewanella putrefaciens* [10], *Serratia liquefaciens* [11] and *Hafnia alvei* [12]. Food spoilage is a primary concern for food industries due to susceptible loss of shelf life and hence the economic losses followed by a long-term impact on consumer preferences. Nevertheless, food spoilage is also a threat to the environment as it leads to excessive wastage that end ups in the landfill, which does not contribute to sustainable living. This is supported by a survey conducted in 2018, which indicated that 30–50% of the total food produced exclusively by one country in a year ends up in the landfill, with the contribution from households, processing industries, food services, primary production sector and retails being 53%, 19%, 12%, 11%, 5%, respectively [13]. Minimizing food spoilage by employing multiple interventions might help not only the food industries but also the environment.

Another concern for the food processing industries and the regulatory authorities is food poisoning due to bacterial growth in food. Some bacterial strains are capable of producing toxins under certain conditions either in the food itself or inside the human body once live bacterial cells are ingested, while others are enteropathogenic and enteroinvasive pathogens [14]. Few examples of foodborne pathogens include *Clostridium botulinum* [15][16], *B. cereus* [17], *Staphylococcus aureus* [18][19], *Listeria monocytogenes* [20], *Salmonella enterica* serovar typhimurium [21], *Salmonella* spp. [22], *E. coli* O157:H7 [23], *C. perfringens* [24], *Shigella* spp. [25], *Yersina* spp. [26] and *Campylobacter jejuni* [27]. Food poisoning has been a major public health concern, particularly regarding outbreaks affecting immunocompromised individuals and infants and thus may lead to adverse social and economic effects. Although many food-poisoning cases go under-reported due to quick recovery and almost minimum effect on healthy individuals, some still have adverse effects on immunocompromised individuals and infants [28]. Alternate disinfection technologies that do not employ thermal treatments or harmful chemicals could be valuable options for minimizing contamination and growth of microbial contaminants leading to either spoilage or food poisoning. Such sustainable technologies are of great importance to the vast ever-growing population with increasing demand of food across the globe.

Recently, the application of advanced oxidation processes (AOPs) for the decontamination of fruit and vegetables has been widely investigated. These technologies include electrolyzed water [29][30], gaseous ozone [3][31], UV light [32][33], and cold plasma [33][34]. One of these oxidation technologies is plasma-activated water (PAW), which is generated by treating water with cold atmospheric plasma (CAP) using controllable parameters such as plasma-forming voltage, carrier gas, temperature, pulses, or frequency as required. Plasma has been recognized as the fourth state of matter. It is the ionized gas usually produced when gas molecules are exposed to the electric field, forming reactive species and ions [35]. PAW has received significant attention from researchers over the last decade due to its non-thermal and non-toxic mode of action, which is mainly due to the reactive species that could react with the bacterial structural components and later organelles, leading to death [36].

2. Systems for PAW Generation

The fundamental method of generation of PAW involves operating a plasma generator inside the water to generate the ions, which lead to reactive species for bacterial inactivation. There are various combinations and models in the literature leading to difference in the final outputs; these are outlined in Table 1.

Table 1. The effect of different generation conditions and the characteristics of PAW**.**

Gas and Additional Features	Gap (Between Water Surface and the Upper Electrode)	AC Voltage and Frequency	Quantitative Changes after Generation Time	References
Grounded copper electrode (diameter 0.5	10 mM	3–6 kV, 3–10 kHz	pH changed from 6.75 to 3.77 and NO_2^- concentration	[41]

mM) on top and a capillary tube to generate bubbles			changed from 3.77 µM to 8.686 µM in 15 min of activation	
Plasma jet unit coaxial tungsten electrode and a quartz tube (diameter of 700 µM)	nil	6–10 kV, 7.0 kHz	Not determined	[42]
Plasma jet with RD1004 rotating nozzle	8.1-cM	voltage (295 V), air pressure (1990 mBar), and frequency (22.5 kHz)	pH changed from 6.5 to 3.1 and Oxidation-reduction potential (ORP) increased from 376.54 to 534.52 RmV in 5 mins	[43]
Atmospheric pressure plasma jet (patent atmospheric pressure plasma jet (APPJ))	0 mM	3.0 kV and 16 kHz	pH reduced from 7 to 3.2 in 20 mins and the ORP increased from 310 to 510 mV.	[40]
1. DC-driven streamer corona. 2. Transient spark discharge	10 mM	(~10 mA) with a 5–20 kHz repetition rate, 10 kV	The pH changed reduced by 4 units.	[44]
Air plasma generator with copper electrodes and quartz dielectric	2 cM	20 kHz, high voltage (not specified)	The pH changed from 6.8 to 2.3, ORP changed from 250 to 540 mV.	[45]
Atmospheric cold plasma jet	7·5 cM	20 kHz, 30 kV	The pH changed from 5.88 to 2.85, ORP changed from 406.1 to 565.40 mV.	[46]

Most studies have indicated an immediate drop in pH and an increase in electrical conductivity and the ORP as a result of the formation of reactive species in the PAW samples (Table 1). However, the increase of change in these properties cannot be directly correlated with a single factor or reason. When PAW is produced, the gaseous species from either the working or the atmospheric gas enters the liquid-gas interface and as a result there are complex reactions leading to the non-equilibrium, hence generation of the ionic moieties [44][47][48]. This process is highly influenced by the electric field and also using bubble implosions which hence the movement as well as dispersion of the phenomenon across the interface [49]. A recent review suggests that the electrical breakdown in water can occur without a phase change such as evaporating liquid and condensing or dissolving vapor [48]. The factors affecting the changes in PAW during activation may depend on multiple factors. For example, increase in discharge power, which is a direct function of applied voltage, would affect the increase in electric conductivity of the PAW [47]. On the other hand, in another study Vlad et al. showed that increase in treatment time would increase bacterial inactivation by PAW [50]. Although these studies reported above (Table 1) have used different set ups for the PAW generation, it could still be concluded that the efficiency can be a combined effect of two or more factors such as PAW activation time, temperature, power used and the aeration or bubbling to improve the formation of reactive oxygen species (ROS) [51].

Physicochemical Properties of PAW

PAW shows lower pH, higher conductivity and higher oxygen reduction potential when compared with untreated water [44][52]. The reduction in pH is due to the formation of acidic chemical species, which result in a steep decrease from pH 7 to pH 3 within 5–10 min of activation, but with little change thereafter [37][53]. Oxidation-reduction potential (ORP) can be defined as the ability of any solution to acquire or loose electrons to an electrode, and this property of PAW is much more prominent as compared with non-activated water. ORP of PAW depends on the strength of activation, which further depends on the applied voltage, carrier gas and other parameters leading to an increase of up to 63% [54]. Conductivity is the ability of any solution to allow current to pass through it and is reported to significantly increase due to plasma activation, primarily because of the generation of ions [45]. With a plasma jet that was operated from a 10 kHz sinusoidal high-voltage power source with 18 kV peak-to-peak AC voltage using pre-mixed oxygen and argon, the pH reduced from 7 to 3, ORP increased from 250 to 550 mV, conductivity rose from 0 to 410 μS/cm and temperature increased from 25 to 30 °C after 15 min of activation [55]. With a similar plasma source, when PAW was produced using 0.40–0.42 kV AC voltage, the conductivity increased from 5 to 20 mS/cm, the ORP value increased from 180 to 250 mV, pH decreased from 7.0 to 6.0, and the temperature increased from 20 to 40 °C [56]. Hence, the change in the reactive species of PAW are measurable as ORP and pH, and these changes directly show their effect on the potential to attack and disrupt the bacterial membranes during inactivation [40].

References

1. Gram, ; Ravn, L.; Rasch, M.; Bruhn, J.B.; Christensen, A.B.; Givskov, M. Food spoilage—interactions between food spoilage bacteria. Int. J. Food Microbiol. 2002, 78, 79–97.

2. Hassenberg, ; Frohling, A.; Geyer, M.; Schluter, O.; Herppich, W. Ozonated wash water for inhibition of Pectobacterium carotovorum on carrots and the effect on the physiological behaviour of produce. Eur. J. Hortic. Sci. 2008, 73, 37.
3. Pinto, ; Yaseen, T.; Caputo, L.; Furiani, C.; Carboni, C.; Baruzzi, F. Application of passive refrigeration and gaseous ozone to reduce postharvest losses on red chicory. In Proceedings of the VI International Conference Postharvest Unlimited 1256, Madrid, Spain, 8 November 2019; pp. 419–426.
4. Greer, G.; Dilts, B.D. Control of Brochothrix thermosphacta spoilage of pork adipose tissue using bacteriophages. J. Food Prot. 2002, 65, 861–863.
5. De Jong, Spoilage of an acid food product by Clostridium perfringens, C. barati and C. butyricum. Int. J. Food Microbiol. 1989, 8, 121–132.
6. Thompson, M.; Dodd, C.E.R.; Waites, W.M. Spoilage of bread by bacillus. Int. Biodeterior. Biodegrad. 1993, 32, 55–66.
7. André, ; Vallaeys, T.; Planchon, S. Spore-forming bacteria responsible for food spoilage. Res. Microbiol. 2017, 168, 379–387,.
8. Miller, ; Scanlan, R.; Lee, J.; Libbey, L. Identification of the volatile compounds produced in sterile fish muscle (Sebastes melanops) by Pseudomonas fragi. Appl. Microbiol. 1973, 25, 952–955.
9. Kumar, ; Franzetti, L.; Kaushal, A.; Kumar, D. Pseudomonas fluorescens: A potential food spoiler and challenges and advances in its detection. Ann. Microbiol. 2019, 69, 873–883.
10. Jørgensen, R.; Huss, H.H. Growth and activity of Shewanella putrefaciens isolated from spoiling fish. Int. J. Food Microbiol. 1989, 9, 51–62.
11. Salgado, A.; Baglinière, F.; Vanetti, M.C.D. Spoilage potential of a heat-stable lipase produced by Serratia liquefaciens isolated from cold raw milk. LWT 2020, 126, 109289.
12. Hanna, ; Smith, G.; Hall, L.; Vanderzant, C. Role of Hafnia alvei and a Lactobacillus species in the spoilage of vacuum-packaged strip loin steaks. J. Food Prot. 1979, 42, 569–571.
13. Racz, ; Vasiljev Marchesi, V.; Crnković, I. Economical, environmental and ethical impact of food wastage in hospitality and other global industries. JAHR 2018, 9, 25–42.
14. Reis, S.d.; Horn, F. Enteropathogenic Escherichia coli, Samonella, Shigella and Yersinia: Cellular aspects of host-bacteria interactions in enteric diseases. Gut Pathog. 2010, 2, 8.
15. Crane, K. Preformed Bacterial Toxins. Clin. Lab. Med. 1999, 19, 583–599.
16. Hennekinne, -A.; De Buyser, M.-L.; Dragacci, S. Staphylococcus aureus and its food poisoning toxins: Characterization and outbreak investigation. Fems Microbiol. Rev. 2012, 36, 815–836.

17. Ceuppens, ; Rajkovic, A.; Heyndrickx, M.; Tsilia, V.; Van De Wiele, T.; Boon, N.; Uyttendaele, M. Regulation of toxin production by Bacillus cereus and its food safety implications. Crit. Rev. Microbiol. 2011, 37, 188–213.
18. Halpin-Dohnalek, I.; Marth, E.H. Staphylococcus aureus: Production of extracellular compounds and behavior in foods-A review. J. Food Prot. 1989, 52, 267–282.
19. Le Loir, ; Baron, F.; Gautier, M. Staphylococcus aureus and food poisoning. Genet Mol Res 2003, 2, 63–76.
20. Farber, ; Peterkin, P. Listeria monocytogenes, a food-borne pathogen. Microbiol. Mol. Biol. Rev. 1991, 55, 476–511.
21. Davies, ; O'neill, P.; Towers, L.; Cooke, M. An outbreak of Salmonella typhimurium DT104 food poisoning associated with eating beef. Commun. Dis. Rep. Cdr. Rev. 1996, 6, R159.
22. Smith, ; Alao, F.; Goodluck, H.; Fowora, M.; Bamidele, M.; Omonigbehin, E.; Coker, A. Prevalence of Salmonella typhi among food handlers from bukkas in Nigeria. Br. J. Biomed. Sci. 2008, 65, 158–160.
23. Doyle, P. Escherichia coli O157: H7 and its significance in foods. Int. J. Food Microbiol. 1991, 12, 289–301.
24. García, ; Heredia, N. Clostridium perfringens: A dynamic foodborne pathogen. Food. Bioprocess Technol. 2011, 4, 624–630.
25. Warren, ; Parish, M.; Schneider, K. Shigella as a foodborne pathogen and current methods for detection in food. Crit. Rev. Food Sci. Nutr. 2006, 46, 551–567.
26. Zadernowska, ; Chajęcka-Wierzchowska, W.; Łaniewska-Trokenheim, Ł. Yersinia enterocolitica: A dangerous, but often ignored, foodborne pathogen. Food Rev. Int. 2014, 30, 53–70.
27. Altekruse, F.; Stern, N.J.; Fields, P.I.; Swerdlow, D.L. Campylobacter jejuni—an emerging foodborne pathogen. Emerg. Infect. Dis. 1999, 5, 28.
28. Al-Kharousi, S.; Guizani, N.; Al-Sadi, A.M.; Al-Bulushi, I.M.; Shaharoona, B. Hiding in fresh fruits and vegetables: Opportunistic pathogens may cross geographical barriers. Int. J. Microbiol. 2016, 2016, doi:10.1155/2016/4292417.
29. Pinto, ; Ippolito, A.; Baruzzi, F. Control of spoiler Pseudomonas spp. on fresh cut vegetables by neutral electrolyzed water. Food Microbiol. 2015, 50, 102–108.
30. Pinto, ; Baruzzi, F.; Ippolito, A. Recent advances to control spoilage microorganisms in washing water of fruits and vegetables: The use of electrolyzed water. In Proceedings of III International Symposium on Postharvest Pathology: Using Science to Increase Food Availability 1144, Bari, Italy, 7 November 2016; pp. 379–384.

31. Pinto, ; Caputo, L.; Quintieri, L.; de Candia, S.; Baruzzi, F. Efficacy of gaseous ozone to counteract postharvest table grape sour rot. Food Microbiol. 2017, 66, 190–198.
32. Fan, ; Huang, R.; Chen, H. Application of ultraviolet C technology for surface decontamination of fresh produce. Trends Food Sci. Technol. 2017, 70, 9–19.
33. Pinto, ; Baruzzi, F.; Cocolin, L.; Malfeito-Ferreira, M. Emerging technologies to control Brettanomyces spp. in wine: Recent advances and future trends. Trends Food Sci. Technol. 2020, 99, 88–100.
34. Wang, ; Nian, W.; Wu, H.; Feng, H.; Zhang, K.; Zhang, J.; Zhu, W.; Becker, K.; Fang, J. Atmospheric-pressure cold plasma treatment of contaminated fresh fruit and vegetable slices: Inactivation and physiochemical properties evaluation. Eur. Phys. J. D 2012, 66, 276.
35. Lackmann, -W.; Bandow, J.E. Inactivation of microbes and macromolecules by atmospheric-pressure plasma jets. Appl. Microbiol. Biotechnol. 2014, 98, 6205–6213.
36. Royintarat, ; Choi, E.H.; Boonyawan, D.; Seesuriyachan, P.; Wattanutchariya, W. Chemical-free and synergistic interaction of ultrasound combined with plasma-activated water (PAW) to enhance microbial inactivation in chicken meat and skin. Sci. Rep. 2020, 10, 1–14.
37. Thirumdas, ; Kothakota, A.; Annapure, U.; Siliveru, K.; Blundell, R.; Gatt, R.; Valdramidis, V.P. Plasma activated water (PAW): Chemistry, physico-chemical properties, applications in food and agriculture. Trends Food Sci. Technol. 2018, 77, 21–31.
38. Choi, J.; Park, H.W.; Kim, S.B.; Ryu, S.; Lim, J.; Hong, E.J.; Byeon, Y.S.; Chun, H.H. Sequential application of plasma-activated water and mild heating improves microbiological quality of ready-to-use shredded salted kimchi cabbage (Brassica pekinensis L.). Food Control 2019, 98, 501–509.
39. Xu, ; Tian, Y.; Ma, R.; Liu, Q.; Zhang, J. Effect of plasma activated water on the postharvest quality of button mushrooms, Agaricus bisporus. Food Chem. 2016, 197, 436–444.
40. Lin, -M.; Chu, Y.-C.; Hsiao, C.-P.; Wu, J.-S.; Hsieh, C.-W.; Hou, C.-Y. The optimization of plasma-activated water treatments to inactivate Salmonella enteritidis (ATCC 13076) on shell eggs. Foods 2019, 8, 520.
41. Sajib, S.A.; Billah, M.; Mahmud, S.; Miah, M.; Hossain, F.; Omar, F.B.; Roy, N.C.; Hoque, K.M.F.; Talukder, M.R.; Kabir, A.H.; et al. Plasma activated water: The next generation eco-friendly stimulant for enhancing plant seed germination, vigor and increased enzyme activity, a study on black gram (Vigna mungo L.). Plasma Chem. Plasma Process. 2020, 40, 119–143.
42. Liu, C.; Chen, C.; Jiang, A.; Sun, X.; Guan, Q.; Hu, W. Effects of plasma-activated water on microbial growth and storage quality of fresh-cut apple. Innov. Food Sci. Emerg. Technol. 2020, 59, 102256.

43. Joshi, I.; Salvi, D.; Schaffner, D.W.; Karwe, M.V. Characterization of Microbial Inactivation Using Plasma-Activated Water and Plasma-Activated Acidified Buffer. J. Food Prot. 2018, 81, 1472–1480.
44. Machala, Z.; Tarabová, B.; Sersenová, D.; Janda, M.; Hensel, K. Chemical and antibacterial effects of plasma activated water: Correlation with gaseous and aqueous reactive oxygen and nitrogen species, plasma sources and air flow conditions. J Phys. D 2018, 52, 034002.
45. Shen, J.; Tian, Y.; Li, Y.; Ma, R.; Zhang, Q.; Zhang, J.; Fang, J. Bactericidal Effects against S. aureus and Physicochemical Properties of Plasma Activated Water stored at different temperatures. Sci. Rep. 2016, 6, 28505.
46. Zhao, Y.-M.; Ojha, S.; Burgess, C.M.; Sun, D.-W.; Tiwari, B.K. Inactivation efficacy and mechanisms of plasma activated water on bacteria in planktonic state. J. Appl. Microbiol. 2020, 129, 1248–1260.
47. Anderson, C.E.; Cha, N.R.; Lindsay, A.D.; Clark, D.S.; Graves, D.B. The Role of Interfacial Reactions in Determining Plasma–Liquid Chemistry. Plasma Chem. Plasma Process. 2016, 36, 1393–1415.
48. Bruggeman, P.J.; Kushner, M.J.; Locke, B.R.; Gardeniers, J.G.E.; Graham, W.G.; Graves, D.B.; Hofman-Caris, R.C.H.M.; Maric, D.; Reid, J.P.; Ceriani, E.; et al. Plasma-liquid interactions: A review and roadmap. Plasma Sources Sci. Technol. 2016, 25, 053002.
49. Zhao, Y.-M.; Patange, A.; Sun, D.-W.; Tiwari, B. Plasma-activated water: Physicochemical properties, microbial inactivation mechanisms, factors influencing antimicrobial effectiveness, and applications in the food industry. Compr. Rev. Food Sci. Food Saf. 2020, 19, 3951–3979.
50. Vlad, I.; Martin, C.; Toth, A.; Papp, J.; Anghel, S. Bacterial inhibition effect of plasma activated water. Rom. Rep. Phys. 2019, 71, 602.
51. Zhou, R.; Zhou, R.; Wang, P.; Xian, Y.; Mai-Prochnow, A.; Lu, X.; Cullen, P.; Ostrikov, K.K.; Bazaka, K. Plasma-activated water: Generation, origin of reactive species and biological applications. J. Phys. D 2020, 53, 303001.
52. Lu, P.; Boehm, D.; Bourke, P.; Cullen, P.J. Achieving reactive species specificity within plasma-activated water through selective generation using air spark and glow discharges. Plasma Process. Polym. 2017, 14, 1600207.
53. Thirumdas, R.; Sarangapani, C.; Annapure, U.S. Cold Plasma: A novel Non-Thermal Technology for Food Processing. Food Biophys. 2015, 10, 1–11.
54. Zhang, Q.; Ma, R.; Tian, Y.; Su, B.; Wang, K.; Yu, S.; Zhang, J.; Fang, J. Sterilization Efficiency of a Novel Electrochemical Disinfectant against Staphylococcus aureus. Environ. Sci. Technol. 2016, 50, 3184–3192.

55. Ma, R.; Wang, G.; Tian, Y.; Wang, K.; Zhang, J.; Fang, J. Non-thermal plasma-activated water inactivation of food-borne pathogen on fresh produce. J. Hazard. Mater. 2015, 300, 643–651.

56. Tian, Y.; Ma, R.; Zhang, Q.; Feng, H.; Liang, Y.; Zhang, J.; Fang, J. Assessment of the Physicochemical Properties and Biological Effects of Water Activated by Non-thermal Plasma Above and Beneath the Water Surface. Plasma Process. Polym. 2015, 12, 439–449.

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