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Review

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PLASMA-ACTIVATED WATER: A CUTTING-EDGE TECHNOLOGY DRIVING INNOVATION IN THE FOOD INDUSTRY

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Abstract

Innovation regarding food production and processing is required to meet the emerging challenges of ensuring worldwide food security and meeting consumer demands for high-quality, safe and nutritious food products. This review provides insights into the current state-of-the-art of the emerging applications of Plasma Activated Water (PAW) in the food industry. PAW antimicrobial properties, inactivation mechanisms and the critical factors determining the lethal effect, as well as the bases for other technological applications are discussed. Overall, this review article describes the degree of success achieved by PAW technology in different applications and illustrates its feasibility and applicability in the food-processing industry.

Keywords: Plasma Activated Water, antimicrobial activity, emerging applications, food industry, food production, promising technology

1. Introduction

The current consumers´ demands for foods of high nutritional and sensory quality, with characteristics similar to those of the fresh product and free of additives, have led to the development of new processing and preservation technologies. These technologies have been considered as an alternative to other traditional methods that are more aggressive for the organoleptic, nutritive and functional properties of foods. Among them, Non-Thermal Atmospheric Plasma (NTAP) has acquired special relevance. NTAP is generated, at room temperature and atmospheric pressure, by applying an electrical discharge to a gas, which causes ionization, dissociation and excitation of its atoms and molecules. NTAP is composed by electrons and positive and negative ions, free radicals, atoms and molecules in the excited or non-excited state, and ultraviolet photons. Additionally, reactive oxygen and nitrogen species (ROS and RNS, respectively), such as ozone, superoxide, hydrogen peroxide, hydroxyl and peroxyl radicals, singlet oxygen, atomic oxygen, nitric oxide or nitrogen dioxide can be present and interact with microorganisms, causing their inactivation (López et al., 2019). Compared to other non-thermal microbial inactivation technologies, NTAP presents various advantages, such as its low application cost, the use of short treatment times, and the possibility of treating a wide variety of food products, including packaged foods. Moreover, it is considered an environmentally sustainable technique. Therefore, it is considered a very promising technology to improve the microbiological quality of food and to decontaminate packaging materials and food contact surfaces (López et al., 2019).

It has been observed that the direct exposure of water to the action of NTAP leads to the production of the so-called “Plasma Activated Water” (PAW), with relevant antimicrobial properties that persist for long periods of time (Ercan et al., 2013; Shen et

al., 2016). This is due to the ability of the chemical species generated in the plasma to diffuse and interact with each other or with water molecules, promoting the formation of new chemical species (Figure 1). The presence of ROS and RNS, including hydroxyl radicals, singlet oxygen, superoxide anion, hydrogen peroxide, as well as nitric oxide and its derivatives formed through reaction with water, such as nitrates, nitrites and peroxynitrites, has been determined in various studies (Shen et al., 2016; Khan & Kim, 2019; Qian et al., 2019; Tarabova et al., 2019; Xiang et al., 2020a). In addition, several authors have verified that the treatment of water and other aqueous solutions with NTAP increases their electrical conductivity and oxidation-reduction potential, and reduces their pH, to values close to 3 (Ma et al., 2015; Guo et al., 2017; Joshi, Salvi, Schaffner & Karwe, 2018; Qian et al., 2019; Frías et al., 2020; Xiang et al., 2020a). This interesting phenomenon represents a completely new approach in the application of NTAP, through the activation of water which will be then used for the treatment or processing of food (Herianto, Hou, Lin & Chen, 2020; Xiang et al., 2020b). It is noteworthy that PAW provides a series of additional advantages when compared to the direct treatment of foods with NTAP, including its straightforward generation and application, as well as its aptitude to be stored. This is leading to an increasing number of research groups around the world who are developing innovations related to the application of PAW in the food industry.

The potential of PAW to improve the microbiological quality of food was revealed for the first time by Ma et al. (2015). The authors studied the efficacy of PAW on strawberries, that due to their complex surface structure are difficult to decontaminate. A water treated with NTAP for 10 min in which the strawberries were introduced led to reductions of *Staphylococcus aureus* of between 1.7 and 2.5 log units, depending on the

exposure time. These results demonstrated a bactericidal effect comparable to that of treatments using sodium hypochlorite solutions (Issa-Zacharia, Kamitani, Muhimbula & Iwasaki, 2010), while no changes in color and firmness of strawberries were observed.

Apart from the demonstrated ability of PAW to improve the microbiological quality of food and decontaminate food contact surfaces, its potential for other applications in the food industry has been also evidenced. Indeed, PAW has been recently used for curing meat products without the need of adding synthetic nitrites, to stimulate seed germination, to degrade pesticides used in agriculture and to modify the structure of starch and myofibrillar protein gels (Figure 2).

2. Chemical composition and physicochemical properties of PAW

Plasma treated solutions, including PAW, present a different chemical composition and physicochemical properties when compared with their untreated counterparts (Zhao, Patange, Sun & Tiwari, 2020a). They contain ROS and RNS, are acidic and show changes in the oxidation-reduction potential and conductivity (Table 1, Figure 1).

Neutral reactive chemical species with long life, such as ozone, atomic oxygen, hydrogen peroxide and nitrogen oxides (NO_2, N_2O_3, N_2O_5, N_2O_4), as opposed to reactive charged species generated in NTAP, with short-live, have the ability not only to diffuse through the liquid but also to subsequently interact with each other or with water molecules, leading to the formation of new reactive species. For example, the coexistence of ozone and hydrogen peroxide in water promotes the generation of highly reactive species, such as hydroperoxide and hydroxyl radicals (Zhou et al., 2015). Atomic oxygen, when reacting with water, can generate hydroxyl radicals and singlet oxygen (Surowsky, Fröhling, Gottschalk, Schlüter & Knorr, 2014). On the other hand, the interaction of nitric

oxide and superoxide produces peroxynitrite, a highly reactive compound that can easily diffuse through cell membranes (Ercan, Smith, Ji, Brooks & Josh, 2016). The presence in PAW of ROS and RNS, including hydroxyl radicals, singlet oxygen, superoxide anion, hydrogen peroxide, ozone, as well as nitric oxide and its derivatives formed with water, such as nitrates, nitrites and peroxynitrites, has been confirmed using various analytical techniques (Tian et al., 2015; Zhang et al., 2016; Choi et al., 2019; Khan & Kim, 2019; Vaka et al., 2019; Xiang et al., 2020a; Xu et al., 2020a; Hou et al., 2021).

It has been repeatedly reported that NTAP treatment of water causes an increase in both electrical conductivity and oxidation-reduction potential (Ma et al., 2015, 2016; Tian et al., 2015; Xu, Tian, Ma, Liu & Zhang, 2016; Joshi et al., 2018; Choi et al., 2019; Wang, Han, Liao & Ding, 2021). For example, an increase in the oxidation-reduction potential of treated water from 270 mV to 450 and 550 mV and in the electrical conductivity, reaching values of 350 and 450 µS/cm after 10 and 20 min of treatment, respectively, has been observed (Ma et al., 2015). Likewise, several authors have observed the rapid acidification of PAW during its generation, mainly due to the dissociation of water caused by NTAP treatment, and to the formation of nitric acid and nitrous acid, if nitrogen is available, either from ambient air or from the working gas itself. This pH decrease has been described in various studies (Ma et al., 2015; Joshi et al., 2018; Lin et al., 2019; Zhao et al., 2019; Xiang et al., 2020a; Machado-Moreira, Tiwari, Richards, Abram & Burgess, 2021), where it has been shown that PAW pH gradually decreased as treatment times increased, reaching pH values of up to 2.4.

3. PAW as a microbial decontamination technique

The effectiveness of PAW against a wide variety of pathogenic and spoilage microorganisms, including bacteria, molds, yeasts, spores, and viruses has been repeatedly demonstrated (Ma et al., 2015; Guo et al., 2018; Choi et al., 2019; Lin et al., 2019; Bai et al., 2020; Machado-Moreira et al., 2021).

3.1. Mechanisms of microbial inactivation by PAW

Although PAW has been shown in numerous studies to be a very effective strategy for microbial inactivation, the mechanism responsible for its lethal effect has not yet been elucidated. However, there seems to be an agreement that RONS present in PAW are the main agents responsible for microbial inactivation. The role of RNS, such as nitric oxide and its by-products (nitrates, nitrites and peroxynitrite), have been shown to have a direct role in microbial inactivation by PAW. In the study conducted by Naïtali, Kamgang-Youbi, Herry, Bellon-Fontaine & Brisset (2010) the synergistic effect of nitrates, nitrites, and hydrogen peroxide in an acidic environment is the primarily responsible for the lethal effects of PAW on *Hafnia alvei*. Nevertheless, other authors have described that the bactericidal power of PAW is higher than that of defined cocktails containing these main RONS at equal concentrations, suggesting that other reactive species with short life may also play an important role (Zhou et al., 2018). Although the mechanisms of microbial inactivation through RNS such as nitrate and nitrite has been less characterized than that of ROS, it has been observed that peroxynitrite and/or peroxynitrous acid also play an important role in the antimicrobial ability of PAW (Zhou et al., 2018; Tarabova et al., 2019) caused by oxidizing, nitrating, and hydroxylating biomolecules (Szabó, Ischiropoulos & Radi, 2007). These compounds can be produced in the presence of hydrogen peroxide and nitrite and, also through the

reaction of nitric oxide and superoxide, nitrites and hydroxyl radicals, nitric oxide and hydrogen dioxide. The cell envelopes represent the first barrier for the contact with reactive chemical species, which would cause a loss of their functionality and/or integrity derived from an oxidative damage. The reactive chemical species can exert a powerful oxidative effect on all cell membrane components, especially on the polyunsaturated fatty acids of the phospholipids (Laroussi & Leipold, 2004), since they are very susceptible to oxidative agents, especially to free radicals, which lead to a lipid peroxidation phenomenon. Thus, the cell viability could be compromised due to modifications in the properties of the membranes, with reductions in their fluidity and alterations in their permeability and integrity (Xu et al., 2020a). Lipid peroxidation is a chain reaction that begins with the attack of ROS (or any reactive species) to an unsaturated fatty acid, extracting a hydrogen atom from a methylene group ($-CH_2$), giving rise to the formation of a lipid radical (L*) that can react rapidly with an oxygen molecule to give a peroxyl radical (LOO*). These radicals can extract hydrogen atoms from other lipids and become hydroperoxides (LOOH), which undergo degradative chemical phenomena to form highly toxic degradation compounds (alkoxyl radicals (LO*), peroxyl and hydroxyl and highly reactive aldehydes, including malondialdehyde and 4-hydroxynonenal). In fact, malondialdehyde is commonly used as a biological marker of oxidative stress, and the increase of this compound has been confirmed during the exposure of *Saccharomyces cerevisiae* to the action of PAW (Xu et al., 2020a). These intermediate reactive compounds could behave as secondary toxic messengers of the reactive species present in PAW, thus transferring their activity across the cell membrane and amplifying their lethal damage within the cell (Joshi et al., 2011). In addition, many of these compounds have greater stability than many of the reactive

species present in PAW and, consequently, show a much longer cytotoxic action, having the ability to diffuse from their place of production to more distant molecules in the membrane (Yost & Joshi, 2015). Moreover, they can also interact with nucleotides and induce important modifications in the nucleic acids by forming adducts and cross-links (del Río, Stewart & Pellegrini, 2005), hindering cell growth and DNA repair (Alkawareek, Gorman, Graham & Gilmore, 2014). Furthermore, some of the aldehydes generated in the peroxidation process, including malondialdehyde, are capable of forming crosslinks in the polypeptide chains of proteins, affecting the activity of membrane-associated enzymes and proteins (Xu et al., 2020a).

The occurrence of damages in the cell envelopes of various microorganisms, including *S. aureus*, *Salmonella* Enteritidis, *Escherichia coli* O157:H7, *Pseudomonas deceptionensis*, *S. cerevisae* and *Aspergillus flavus* spores, has been evidenced from the information obtained through different analytical techniques. Different morphological alterations in microbial cells, such as decrease in size, rounding, appearance of rough surfaces, presence of ridges and pores in the membranes, or completely broken envelopes, have been observed upon exposure to PAW (Tian et al., 2015; Shen et al., 2016; Zhang et al., 2016; Xiang et al., 2018; Lin et al., 2019; Los, Ziuzina, Boehm, Cullen & Bourke, 2020; Qian, Wang, Zhuang, Zhang & Yan, 2020; Liu et al., 2021a). However, the cell envelopes are not considered the only target structure, since an increase in the intracellular content of ROS has been also documented during microbial exposure to PAW (Tian et al., 2015; Qian et al., 2020; Xu et al., 2020a; Liu et al., 2021a). These chemical species are capable of interacting with all intracellular components, especially with DNA and proteins. The damage caused to these structures would affect the microbial metabolism and physiological functions, thus compromising cell viability

(Zhang et al., 2016). In fact, the exposure of *S. aureus* and *S. cerevisiae* to PAW has been shown to cause a significant degradation of DNA (Zhang et al., 2016; Xu et al., 2020a). Despite the extreme acidic pH values of PAW, several authors have demonstrated that the exposure of various microorganisms to water acidified to achieve the same pH values reached in PAW barely had a lethal effect after the same treatment times (Chen, Lee & Chang, 2009; Ercan et al., 2013; Frías et al., 2020). For instance, Frías et al. (2020) verified that PAW generated by using an air-based plasma for 10 min presented a pH value of 3.8 and achieved 0.6 log units of inactivation for *Listeria monocytogenes* on tofu. However, the immersion of this product inoculated with the same pathogen in water acidified with hydrochloric acid (pH 3.8) did not show any bactericidal effect. Therefore, it has been suggested that acidification is not the main cause of microbial inactivation by PAW (Chen et al., 2009; Ercan et al., 2013; Frías et al., 2020). Nevertheless, it has been speculated that the low pH values could contribute to the stabilization of some reactive chemical species present in PAW (Julák, Scholtz, Kotucova & Janouskova, 2012; Yost & Joshi, 2015) or to the formation of new antimicrobial compounds (Naïtali et al., 2010). Additionally, a possible synergistic effect of acid pH and these reactive species can contribute to the microbial inactivation, as acid pH could facilitate the penetration of the reactive species through the cell walls or the presence of these reactive species could make the microorganisms more vulnerable to the acidic environments prevailing in PAW (Oehmigen et al., 2010).

3.2. Factors affecting the antimicrobial effectiveness of PAW

3.2.1. Critical factors during PAW generation

PAW can be obtained from various sources of NTAP that apply different types of electrical discharge (glow discharge, spark discharge, corona discharge, arc discharge, gliding arc discharge, dielectric barrier discharge (DBD)) to cause the ionization of the precursor gas. In addition, among the different plasma systems, plasma jet Ma et al., 2015, 2016; Xu et al., 2016; Zhao et al., 2019; Chen et al., 2019; Kang et al., 2019; Lin et al., 2019; Muhammad et al., 2019; Qian et al., 2019; Frías et al., 2020; Liu et al., 2020; Xiang et al., 2019, 2020a) and DBD-based configurations (Vaka et al., 2019; Han et al., 2020; Wang et al., 2021) are the most widely used in food research, due to their ease of construction and operation. The activation of water can be carried out by two different procedures, i.e., applying the discharge of plasma above the water surface, which is the approach most widely used in food decontamination studies (Ma et al., 2015, 2016; Guo et al., 2017; Joshi et al., 2018; Choi et al., 2019; Muhammad et al., 2019; Xiang et al., 2019, 2020a), or carrying out the discharge of plasma beneath the water surface (Fröhling, Ehlbeck & Schlüter, 2018; Chen et al., 2019; Lin et al., 2019; Liu et al., 2020; Royintarat, Choi, Boonyawan, Seesuriyachan & Wattanutchariya, 2020; Zhao, Wang & Ma, 2021a). However, it has been reported that different plasma discharge, plasma sources and exposure mode can give rise to PAW with very distinct chemical characteristics and, consequently, with different antimicrobial properties (Tian et al., 2015; Lu, Boehm, Bourke & Cullen, 2017; Tsoukou, Delit, Treint, Bourke & Boehm, 2021). Tsoukou et al. (2021) studied the influence of two different types of electrical discharge configuration, spark and glow, on the resulting PAWs chemistry. The authors found that PAW generated by spark discharge contained hydrogen peroxide and nitrates, while glow discharge resulted in PAW with nitrates and nitrites, and a lower pH value (2.7 *vs* 3.0). In addition, other authors reported comparative studies on the different RONS

profiles through water exposure to a microwave (MW) and DBD sources. For example, Niquet et al. (2018) observed that nitrogen-based compounds were mostly present in PAW-MW with high concentrations of nitrous acid generating nitrite and nitrate, whereas hydrogen peroxide and nitrate were dominant in PAW-DBD. On the other hand, Tian et al. (2015) found, using the same NTAP generation source, that PAW obtained by applying the plasma discharge in the water exhibited higher values of oxidation-reduction potential and electrical conductivity, as well as a greater effectiveness in the inactivation of *S. aureus* (5.0 vs 1.2 log cycles), in comparison to that obtained by supplying the plasma superficially. This phenomenon was attributed to the higher intracellular content in ROS.

The energy input to ionize a gas at atmospheric pressure is determined by voltage, frequency and power, which will define the species generated and their concentration, thus affecting the antimicrobial properties of the resulting PAW. PAW obtained by increasing the discharge power from 16 to 36 W (Vaka et al., 2019) and from 50 to 60 W (Lin et al., 2019) allowed to reduce, after 2 min of exposure, the bacterial populations naturally present in spinach leaves and the population of *S.* Enteritidis superficially inoculated on eggs in 0.4 and 1.2 additional log units, respectively. In these studies, it was observed that the increase in the power of the discharge led to a more significant drop of pH and higher concentration of reactive chemical species with long life and, specifically, of hydrogen peroxide, nitrates and nitrites, which could be directly correlated with the level of bacterial inactivation achieved.

It has also been demonstrated that, when keeping the discharge power constant, an increase in the discharge voltage used for the activation of the water, from 6 to 8 kV (Chen et al., 2019; Liu et al., 2020), enhanced the antimicrobial properties of PAW when

applied to decontaminate cut apple and pear. This effect could result from the increase in the levels of reactive chemical species generated in the PAW. For example, when the voltage increased from 6 to 8 kV, the lethal effect achieved against total aerobic bacteria, molds and yeasts in cut pear increased by 0.4, 0.2 and 0.4 log units, respectively, after a 5-min treatment and subsequent storage at 4 ^{o}C for 12 days (Chen et al., 2019). However, a further increment in voltage (up to 10 kV) resulted in a reduction in the antimicrobial activity (Chen et al., 2019; Liu et al., 2020). In fact, the inactivation rates achieved for the microbial groups tested were practically similar to those obtained with the lowest power tested (6 kV). This lower effectiveness observed using high voltages in the electrical discharge could be due to the generation of less reactive chemical species and/or to their greater degradation (Chen et al., 2019; Liu et al., 2020).

Another variable to consider in the antimicrobial effectiveness of PAW for food decontamination is the type of carrier gas used to generate NTAP. Various gases have been used, including nitrogen (Zhou, Li, Zhou, Zhang & Yang, 2019), oxygen (Zhou et al., 2019), noble gases, such as argon (Royintarat et al., 2020) and helium (Zhou et al., 2019), and mixtures of different gases (Ma et al., 2015; Xu et al., 2016). For economic and logistic reasons, air (Ma et al., 2016; Joshi et al., 2018; Chen et al., 2019; Vaka et al., 2019; Xiang et al., 2019; Zhao et al., 2019, 2021a, b; Liu et al., 2020; Hou et al., 2021) is the most widely used. Many studies have confirmed that all of them are effective for obtaining PAW with antimicrobial properties. Nevertheless, it is still unknown which working gas provides the greatest decontamination capacity to PAW. To the best of our knowledge, there is only one study in the literature in which the effect exerted by the composition of the working gas (nitrogen, helium, oxygen and air) used in the generation

of PAW on its subsequent effectiveness for microbial inactivation on food has been assessed (Zhou et al., 2019). These authors observed that, under the same water activation conditions, PAW obtained from air plasma was the most effective for decontaminating mung bean sprouts, reaching a microbial inactivation of 5.2 log units as compared to 4.3, 2.8 and 2.0 log cycles achieved with PAW activated with oxygen, helium and nitrogen plasmas, respectively. The obtained results were attributed to the fact that PAW-air showed the highest values of oxidation-reduction potential (650 mV) and the lowest pH (3.5) values, as well as the highest levels of ROS and RNS (up to 4.3 mM).

Besides the type of carrier gas, the gas flow rate has been identified as another parameter that can also influence the effectiveness of PAW treatments. It is thought that the concentration of reactive species can increase as the gas flow rate also increases, although their average energy decreases and, therefore, the likelihood of each reactive species interacting with microbial cells and, consequently, their antimicrobial efficacy, might decrease. Hou et al. (2021) studied the ability of PAW generated for 20 min using air flow rates of 6 or 10 slm to decontaminate tomatoes inoculated with *S.* Typhimurium, *E. coli*, or *L. monocytogenes*. These authors reported that increasing gas flow rate enhances antimicrobial effectiveness against *E. coli* and *L. monocytogenes* after 30 s and 150 s of exposure, respectively, with population reductions of 0.5 and 1.0 log cfu/tomato, respectively. However, in the same study, limited or no impact of higher flow rates on *S.* Typhimurium inactivation was observed.

The activation time to NTAP of water is another factor that markedly determines the effectiveness of PAW as a microbial decontamination strategy. In general, it has been frequently observed that longer activation times lead to important changes in the

physicochemical properties of PAW, including a more acidic pH and an increase in the reactive chemical species concentration (Ma et al., 2015; Choi et al., 2019; Khan & Kim, 2019; Lin et al., 2019; Vaka et al., 2019; Guo et al., 2021; Wang & Salvi, 2021; Wang et al., 2021; Zhao et al., 2021a). Consequently, higher rates of inactivation for different spoilage and pathogenic microorganisms have been achieved in several food products of vegetal origin, such as strawberries, grapes, cabbage, tiger nuts, mushrooms, tomato, kumquat, baby spinach and lettuce leaves with longer exposure times (Ma et al., 2015; Guo et al., 2017; Choi et al., 2019; Khan & Kim, 2019; Muhammad et al., 2019; Vaka et al., 2019; Guo et al., 2021; Wang & Salvi, 2021; Zhao et al., 2021a). For example, it has been observed that the exposure of strawberries for 15 min to a 10-min activated PAW allowed to reduce *S. aureus* populations by 1.5 log units; whereas when a 20 min activation time of PAW was used, a greater lethal effect was achieved (2.2 log cycles) (Ma et al., 2015). Muhammad et al. (2019) increased the activation time of sterile deionized water from 3 to 7 min resulting in a PAW with improved bactericidal properties against *Klebsiella pneumoniae* when applied to tiger nuts, increasing the inactivation rates attained by 1.2 log units. For the same duration of PAW treatment on kumquats, Guo et al. (2021) prolonged plasma activation time from 30 to 60 min and achieved 0.8, 1.3 and 3.3 log reductions for *Penicillium italicum* with PAW30, PAW45 and PAW60, respectively. Similar results have been described for the decontamination of food products of animal origin (Kang et al., 2019; Lin et al., 2019; Wang et al., 2021). Lin et al. (2019) found that an increase in the exposure time of water to air-plasma, from 10 to 20 min, improved the effectiveness of PAW for the inactivation of *S.* Enteritidis on shell eggs by 1.7 log units. Wang et al. (2021) showed a higher lethal effect against *S. aureus* (about 5 times greater inactivation) in chicken breast when a 20-min activated

PAW was used instead of a 5-min activated water. In another study, an increase in the activation time of distilled water of only 30 s (from 30 s to 1 min) improved by 0.3 log units the lethal effect on *P. deceptionensis* on chicken breast (Kang et al., 2019).

Different types of water have been used for the preparation of PAW, including tap water (Fröhling et al., 2018; Lin et al., 2019), reversed osmotic water (Lin et al., 2019) and, especially, distilled (Ma et al., 2015, 2016; Guo et al., 2017; Joshi et al., 2018; Chen et al., 2019; Choi et al., 2019; Bai et al., 2020; Liu et al., 2020; Xiang et al., 2020a) and deionized (Zhao et al., 2019, 2021b; Muhammad et al., 2019; Frías et al., 2020; Royintarat et al., 2020) water. In all cases, the results showed that the generated PAW was effective for microbial surface decontamination of foods. However, its effectiveness is affected by the hardness of the water, the activation volume, as well as by the subsequent storage conditions of PAW. In a recent study, it was found that the physicochemical properties of PAW are closely related to the hardness of the water used in its production (Lin et al., 2019). These authors observed that PAW prepared with hard water showed low oxidation-reduction potential values and high pH values, concluding that these characteristics could reduce its ability to inactivate microorganisms. Bai et al. (2020) also studied the inactivation properties of PAW prepared at different activation volumes (50, 75, 100 mL) against *B. cereus* spores; they found that inactivation rate was affected by PAW activated volumes, reaching maximum inactivation values at the smallest volume. The differences reported might be explained by the ORP decrease, and pH increase with the increase in activation water volumes.

In most studies assessing the potential of PAW as a food decontamination strategy, this agent has been applied to food immediately after its generation. Although in some occasions it has been pointed out that the antimicrobial properties of PAW persist for a

long time, of up to 4 weeks (Julák et al., 2012), it seems that its effectiveness is progressively reduced to an extent that depends on both storage time and temperature. Indeed, Lin et al. (2019) found that the efficacy of freshly prepared PAW was higher than that of PAW stored for 24 h at 4 ºC. After the application of identical treatments, the inactivation rates obtained for *S.* Enteritidis superficially inoculated on eggs were 3.8 log units with freshly prepared PAW and 2.1 log units with 24-h stored PAW. Furthermore, these authors showed that PAW stored under these conditions presented a slight acidification and a significant decrease in the oxidation-reduction potential, with the loss of antibacterial effectiveness observed being maybe related to the degradation of reactive chemical species in PAW over time.

Storage temperature also influences the subsequent antimicrobial activity of PAW. Shen et al. (2016) investigated, for up to 30 days, the effects exerted by storage temperature (25, 4, -20 and -80 ºC), both on the physicochemical characteristics of PAW and on its ability to inactivate *S. aureus*. The results obtained showed that storage caused a decrease in PAW antibacterial activity, which was more marked at the highest storage temperatures. Thus, the application of a 20-min treatment with freshly obtained PAW reduced the population of this pathogen by 5 log units, while the use of PAW stored for 30 days at -80, -20, 4 and 25 ºC caused an inactivation of approximately 3.5, 1.0, 1.0 and 0.8 log cycles, respectively. Furthermore, the concentration of H_2O_2 and NO_2^- present in the solution only decreased significantly at higher storage temperatures (-20, 4 and 25 ºC). Based on these results the authors proposed -80 ºC as the most suitable storage temperature for PAW. The stability of PAW during 48 h was also studied by Wang and Salvi (2021). They reported that freshly prepared PAW, activated for 15 min, showed the highest inactivation effectiveness against *E. coli* and *L. innocua* while refrigerated PAW

(4 °C) presented better inactivation efficacy compared to PAW stored at room temperature (22 °C) due to the delayed dissipation of reactive species.

3.2.2. PAW application conditions

The time of food exposure to PAW also has a great influence on the level of microbial inactivation achieved. Thus, as the exposure time of microorganisms to the action of PAW increases, the effectiveness of this strategy for decontamination also does (Ma et al., 2015, 2016; Kang et al., 2019; Lin et al., 2019; Frías et al., 2020; Royintarat et al., 2020; Hou et al., 2021; Wang et al., 2021). For example, increasing the immersion time from 5 to 15 min (Ma et al., 2015) and from 5 to 20 min (Wang et al., 2021) enhanced the inactivation rates obtained for *S. aureus* from 1.7 to 2.3 and from 0.4 to 2.2 log units on strawberries and chicken breast surfaces, respectively. Similarly, Lin et al. (2019) found that the inactivation of *S.* Enteritidis increased by 3.1 log cycles by extending the exposure time of eggs to PAW from 5 to 15 min.

Agitation is also considered another important factor that can impact significantly on the antimicrobial effectiveness of PAW. In this sense, Wang et al. (2021) have recently shown that the inactivation levels of *S. aureus* on chicken breast were 1.8 log units/g when carrying out a treatment without shaking, while under stirring conditions they obtained a 2.2 log units/g reduction. The application of agitation, as occurs with other decontamination methods, could favor the detachment of microorganisms from the food surface, thus accelerating their inactivation.

Although most of the studies evaluating the effectiveness of PAW as a food decontamination strategy have been carried out at room temperature, it has been recently shown that its effectiveness can be enhanced by increasing the exposure

temperature, even at sublethal levels (Liao et al., 2019). These authors observed that the treatment of rice with PAW for 60 min reduced the population of *B. cereus* spores by 0.7 log units, while by rising the treatment temperature to 40 or 55 ^{o}C the inactivation levels increased 0.8 and 1.4 log cycles, respectively.

3.2.3. Microbial-related factors

The effectiveness of PAW is also determined by the type of microorganism and the microbial load. In general, Gram-positive bacteria are more resistant than Gram-negative bacteria, probably due to the different chemical composition and structural properties of their cell envelopes (Oehmigen et al., 2010; Ercan et al., 2013; Khan & Kim 2019; Zhou et al., 2020). Hou et al. (2021) reported that to achieve the same reduction levels on tomato, the treatment times required for *E. coli* and especially for *L. monocytogenes* were longer than those required for *S.* Typhimurium. Additionally, *L. innocua* showed much higher resistance than *E. coli*, *Aeromonas hydrophila*, *Pseudomonas fluorescens* and *Shewanella putrefaciens* (Zhou et al., 2020). A similar observation was also published by Wang and Salvi (2021), who demonstrated that PAW also had higher effectiveness against *E. coli* than *L. innocua* in planktonic state. PAW activated for 5 min reduced *E. coli* by > 5 log CFU/mL and *L. innocua* by 1.8 log CFU/mL within 5 min of bacterial exposure, increasing PAW activation time for 15 min reduced *E. coli* by > 5 log CFU/mL and *L. innocua* by 3.5 log CFU/mL within 5 min of bacterial exposure. Contradictory results were reported by Schnabel, Sydow, Schlüter, Andrasch & Ehlbeck (2015). In this study, PAW activated for 50 s was used to decontaminate fresh-cut lettuce and fresh mung bean sprouts contaminated with six different bacteria, namely, *E. coli*, two strains of *P. fluorescens*, *P. marginalis*, *Pectobacterium carotovorum*

and *L. innocua.* After 1 min of exposition time, *L. innocua*, *P. marginalis* and *P. carotovorum* showed much lower resistance than *E. coli* and both strains of *P. fluorescens*, achieving reductions on fresh-cut lettuce of around 4-6 log and 2 log units, respectively. This same trend was not observed on fresh sprouts, where similar log reductions were achieved for all bacteria strains.

Microbial inactivation induced by PAW might be influenced by different cells concentration. Bai et al. (2020) evaluated the inactivation potential of a suspension of *B. cereus* spores induced by PAW at different initial spore concentrations (10^5, 10^6, 10^7 spores/mL). They observed that the lower the initial spore load, the higher the inactivation rate values. Similarly, Deng, Shi, Shama & Kong (2005) and Fernández, Shearer, Wilson & Thompson (2012) also found that the inactivation efficacy of direct plasma was related to *B. subtilis* spores and *S.* Typhimurium concentration, respectively. The effect of PAW on bacteria also depends on the mode of growth, planktonic or biofilm. The high heterogenicity of the cells present in biofilm will certainly impact the effectiveness of antimicrobial agents, including PAW treatment. Microbial inactivation of biofilms using PAW as an antimicrobial agent, has been recently well reviewed by Mai-Prochnow et al. (2021).

3.2.4. Food characteristics

There are several studies demonstrating the high effectiveness of PAW against planktonic cells of *E. coli*, *S. aureus*, *P. deceptionensis* and *B. cereus spores,* among others (Traylor et al., 2011; Shen et al., 2016; Xiang et al., 2018; Bai et al., 2020). However, when PAW is used to decontaminate food products, its effectiveness can be significantly reduced. For example, Liu et al. (2021a) observed, after 10 min exposition time, a

reduction of 1.6 log cycles when *E. coli* O157:H7 was inoculated into PAW activated for 60 s. Nevertheless, it was necessary to extend the exposure time up to 30 min to achieve 2.2. log cycles on spinach inoculated with *E. coli* O157:H7.

Some studies suggest that the antimicrobial potential of PAW might be influenced by food constituents, namely, proteins, lipids and polysaccharides (Zhang et al., 2016; Kang et al., 2019). Zhao et al. (2020c) reported that the bactericidal effect of plasma-treated fish homogenates (5, 10 and 20%) against *P. fluorescens* was limited, with reductions of 1.1 and 0.5 log units for 5% and 10% fish homogenate, respectively, and almost no reduction was found for 20% plasma-treated fish homogenate. In addition, also the presence of bovine serum albumin (BSA) decreased the antimicrobial effectiveness of the PAW treatments, achieving a reduction of *S. aureus* from 2.1 to 5.5 log units, when without BSA reached 7.0 log units (Zhang et al., 2016). Furthermore, the food surface characteristics, such as roughness, hydrophobicity, the presence of irregularities or the adsorption of reactive species can also affect the survival of microorganisms. Joshi et al. (2018) evaluated the efficacy of PAW for the inactivation of *Enterobacter aerogenes* on tomato, lime and spiny gourds, when generated and applied under identical experimental conditions. They observed the highest lethal effect on tomato (4.7 log units) and the lowest on spiny gourds (1.0 log units). These differences were attributed to the uneven surface roughness of these products. The authors reported that roughness values were, in fact, higher for spiny gourds (101.5 ± 11.0 μ), followed by lime (18.8 ± 3.0 μ), and finally tomato (5.2 ± 0.5 μ). These factors should also be therefore considered when designing effective PAW treatments.

3.3. Microbial decontamination of foods by PAW

To the best of our knowledge, as previously mentioned, Ma et al. (2015) were the authors who revealed for the first time the potential of PAW as a washing disinfectant for food products, specifically for strawberries. Since then, several studies have been published which confirmed the effectiveness of this strategy to improve the microbiological quality of various food products, both of animal and non-animal origin, raw and processed, without exerting adverse effects on their quality attributes (Table 1).

Microbial decontamination of fruits and vegetables

Ma et al. (2016) observed the effect of PAW on the inactivation of bacteria and molds naturally present in Chinese bayberries at the end of their storage period (3 ^{o}C, 8 days). They found a decrease of 1.1 log cycles/g in the microbial populations as compared to the control treatment (Ma et al., 2016). In addition, the authors observed greater firmness and more intense red color on treated bayberries. Similarly, it was shown that the use of PAW for washing grapes reduced the population of *S. cerevisiae* by 0.4 log units, without affecting their organoleptic, functional or nutritional properties (Guo et al., 2017; Xiang et al., 2020a).

Likewise, the potential of PAW to improve the microbiological quality of fresh cut fruits, such as pears (Chen et al., 2019), kiwis (Zhao et al., 2019), and apples (Liu et al., 2020), without affecting their quality attributes, has been also demonstrated. Chen et al. (2019) demonstrated that washing cut pear with PAW reduced the counts of bacteria and molds and yeasts in around 0.7 and 1.0 log units, respectively, after 12 days of storage at 4 ^{o}C, without exerting an adverse effect in the content in vitamin C. Liu et al. (2020) obtained similar inactivation rates (between 0.6 and 1.1 log units) for aerobic bacteria, molds, yeasts and coliforms in cut apple. Zhao et al. (2019) found that spraying PAW on

the surface of cut kiwis also reduced the population of *S. aureus* in about 1.7 log after storage at 4 ^{o}C for 8 days.

Recently, the ability of PAW to inactivate pathogenic microorganisms such as *S.* Typhimurium, *S. aureus* and *L. monocytogenes* on cabbage (Choi et al., 2019), spinach (Vaka et al., 2019), endives (Schnabel et al., 2021) and lettuce leaves (Khan & Kim, 2019) has been also demonstrated. For example, it has been observed that the immersion of Iceberg and Romaine lettuce leaves for 3 min into PAW, which had been activated through exposure to NTAP for 10 min, reduced the population of *S.* Typhimurium by 3.0 and 2.6 log units, respectively, without compromising the color and flavonoids content (Khan & Kim, 2019). Choi et al. (2019) described that the treatment of cabbage with PAW for 10 min allowed the reduction of mesophilic aerobic bacteria, lactic acid bacteria, coliforms, and molds and yeasts in 1.8, 1.6, 0.7 and 1.2 log cycles, respectively. These authors also reported reductions for *S. aureus* (0.9 log units) and *L. monocytogenes* (1.0 log units) with minimal modifications in sugar content, hardness and color of the end product.

Microbial decontamination of meat, fish and eggs

The ability of PAW to inactivate spoilage and pathogenic microorganisms, including *S.* Enteritidis and *S. aureus*, has also been demonstrated in different types of meat, such as beef and chicken meat (Kang et al., 2019; Qian et al., 2019; Royintarat et al., 2020; Zhao et al., 2020b) and in ready-to-eat meat products (Wang et al., 2021). For example, it has been observed that spraying PAW onto fresh beef reduced the surface bacterial populations by 3.1 log units, which allowed to extend the beef shelf-life, stored under

refrigeration, for 4 to 6 days, without compromising its quality after cooking (Zhao et al., 2020b).

Although there is only one study assessing the potential of PAW on eggs decontamination (Lin et al., 2019), the results obtained are very promising. These authors found that the immersion of eggs into PAW for 2 min (water previously activated through exposure to NTAP for 20 min) can effectively reduce the population of *S.* Enteritidis by 4.7 log units, without modifying the freshness indexes. Therefore, they suggested that PAW could be an effective approach for the decontamination of eggs. On the contrary, the few studies evaluating the potential of PAW to decontaminate fish showed very little effect not only on native microbiota (total mesophilic and psychrotrophic bacteria) but also on inoculated bacteria (*E. coli*, *L. innocua* and *P. fluorescens*), barely achieving 0.4 log after 30 min of exposure time (Zhao, Ojha, Burgess, Sun & Tiwari 2020c; Zhao et al., 2021b).

Microbial decontamination of other foods

The potential of PAW for the decontamination and preservation of some processed and ready-to-eat foods, such as some popular products from Asian countries, made from soybeans (bean curd and tofu) and rice cake (Zhai, Liu, Xiang, Lyu & Shen, 2019; Frías et al., 2020; Han et al., 2020), has been also revealed. Thus, Han et al. (2020) described that the treatment of Korean rice cake with PAW for 20 min allowed to reduce the population of aerobic microorganisms, *Penicillium chrysogenum* and *Candida albicans* in about 2.8, 2.0 and 1.0 log cycles, respectively. In addition, these authors reported the reduction of 2.0 log units of the most important foodborne pathogens (*E. coli* O157:H7,

S. Typhimurium and *L. monocytogenes*) without affecting the main characteristics of the treated product, i.e., texture and color.

PAW as thawing media

Freezing is frequently used as a preservation method in the food industry, especially in the meat and fish sectors. For the subsequent transformation of meat, fish and seafood, it is essential to thaw frozen products. However, conditions prevailing during thawing can allow microbial growth. In a recent study, Liao et al. (2020) evaluated the application of PAW as a novel meat thawing media and compared this thawing strategy with conventional thawing methods (air, water, microwaves). These authors found significant lower counts of aerobic bacteria, molds and yeasts on samples thawed using PAW. Additionally, the use of PAW not only enhanced the microbiological quality of meat, but also it did not produce any adverse effects on its physical-chemical (pH value) and sensory (texture, color and odor) attributes. From the results obtained, the authors suggested that PAW could be used as an active thawing media that would allow to maintain the microbiological safety and quality attributes of frozen foods.

PAW as a covering liquid

PAW also has a great potential, due to the persistence of its antimicrobial properties, to maintain the microbiological quality of those foods that are marketed immersed into an aqueous solution. Its effectiveness was demonstrated on tofu after 28 days of refrigerated storage (Frías et al., 2020). These authors observed that microbial counts for raw tofu stored in PAW were approximately 3.0 log units lower than those found in tofu samples packaged into sterile distilled water. These results show the ability of PAW

to extend the shelf-life of tofu. Although the level of microbial inactivation achieved with PAW was lower than that obtained with the heat treatment currently applied in the industrial processing of tofu, PAW-immersed tofu had better texture properties (i.e., less hard and elastic), with a greater retention of polyphenols, and the color was not affected.

Ice made with PAW for the preservation of fresh fish and seafood

Liao et al. (2018) have proposed the use of ice made with PAW as a promising method to prolong the shelf-life of fresh fish and seafood. In the study carried out by these authors, it was shown that the storage of shrimp in ice generated from PAW (PAW-ice) allowed, in comparison with the use of conventional ice, to extend the shelf-life between 4 and 8 days. This effective strategy was able not only to inhibit the growth of microorganisms naturally present in the food product, but also slowed down the main spoilage reactions (production of volatile basic nitrogen, melanosis, lipid oxidation) involved in quality losses.

PAW in combination with other treatments

There are several studies which have demonstrated that the antimicrobial effectiveness of PAW for food decontamination can be enhanced through its combination with moderate heat treatments (Choi et al., 2019; Liao et al., 2019; Xiang et al., 2020a), ultrasounds (Royintarat et al., 2020), as well as by adding lactic or peracetic acid to the water prior to its treatment by NTAP (Qian et al., 2019, 2020).

Liao et al. (2019) observed that the treatment of rice with PAW for 60 min reduced the population of *B. cereus* spores by 0.7 log units, while when the treatment temperature

was raised to 40 or 55 ºC, the inactivation rates increased to 1.5 and 2.1 log cycles, respectively. A synergistic effect for the inactivation of *S. cerevisiae* has also been described when PAW treatments were carried out at mild heat temperatures of 50, 52.5 and 55 ºC (Xiang et al., 2020a). The exposure of grapes to PAW at 55 ºC for 30 min allowed to reduce the total microbial load by 5.9 log units. This reduction was significantly higher than the one achieved by other treatments carried out at 25 ºC (0.4 log cycles) or in sterile distilled water at 55 ºC (2.4 log cycles). In addition, the authors reported that the combined treatments did not exert adverse effects on the nutritional value, functional properties and sensory attributes of the grapes. Similar results have been obtained in cabbage after the sequential combination of washing treatments with PAW followed by moderate heating at 60 ºC (Choi et al., 2019). These authors found that the individual application of PAW, for 10 min, resulted in a reduction of 1.8, 1.6, 1.2 and 0.7 log units/g for mesophilic aerobic bacteria, lactic acid bacteria, yeasts and molds, and coliforms, respectively. However, the combined treatment was able to reduce the counts of lactic acid bacteria, yeasts and molds, and coliforms to levels below the detection limit, without significantly modifying the quality attributes of the product.

The combination of PAW with ultrasounds also demonstrated a synergistic effect (Royintarat et al., 2020). In fact, the simultaneous application of PAW and ultrasounds for 60 min was able to reduce the population of *E. coli* K12 and *S. aureus* on chicken meat by 1.3 and 0.8 log units, respectively. When PAW was applied individually, the inactivation rates achieved were only 0.5 and 0.3 log cycles for *E. coli* K12 and *S. aureus*, respectively. These results suggest that ultrasonic waves could facilitate the penetration of the chemical species into microbial cells, thus enhancing bacterial inactivation.

Qian et al. (2019, 2020) studied the addition of lactic acid to deionized water prior to its exposure to NTAP. These authors observed that the immersion of beef and chicken wings for 20 s and 10 min into an aqueous solution with 0.2% lactic acid previously activated (80 s) with plasma showed, against *S.* Enteritidis, a higher bactericidal effect than the use of classic PAW (3.5 vs 1.0 log and 1.3 vs 0.5 log inactivation units, respectively), without exerting adverse effects on the quality attributes of the meat. Another approach studied by Liu et al. (2021a) showed that PAW exhibits synergistic antimicrobial activity with propylparaben (PP) in wash water. Nevertheless, when the same treatments were applied on spinach leaves, the synergistic antimicrobial activity of PAW and PP disappeared. The study reported a 2.8-log reduction in *E. coli* O157:H7 cells after a treatment of PAW combined with 4 mmol/L PP for 30 min, while 2.2 and 2.4-log reductions were obtained after PAW and PP treatments applied individually, respectively, under the same conditions. The authors did not notify negative effects after the combined treatment on the quality characteristics of spinach leaves, including color, chlorophyll, total phenolic content, and antioxidant activity.

3.4. Decontamination of surfaces and equipment

Microorganisms, both spoilage and pathogenic, have the ability to adhere to equipment and surfaces, and cause food cross-contamination issues, with significant repercussions for human health and considerable economic losses for industrial operators. There are several studies which have demonstrated the effectiveness of PAW for reducing microbial populations (in planktonic and biofilm state) on materials widely used in the food industry, such as stainless steel, polystyrene and high-density polyethylene (Kamgang-Youbi et al., 2009; Smet et al., 2019; Fernández-Gómez et al., 2020). For

example, Kamgang-Youbi et al. (2009) observed that counts of *S. cerevisiae*, *Hafnia alvei*, *Leuconostoc mesenteroides* and *Staphylococcus epidermidis* adhered to stainless steel decreased by 3.1, 5.4, 4.7 and 6.1 log units, respectively, after exposure to PAW for 30 min. It is worth mentioning that the treatment did not cause corrosion problems on the stainless-steel material. Smet et al. (2019) found that the populations of *L. monocytogenes* and *S.* Typhimurium cells adhered to polystyrene was reduced by up to 3.9 log units after 30 min of exposure to PAW. In the study carried out by Fernández-Gómez et al. (2020), the influence exerted by the time of exposure to PAW on the inactivation attained for a cocktail of three *L. monocytogenes* strains adhered to stainless steel and polystyrene (10^6-10^7 CFU/cm^2) was evaluated. It was found that treatment times of 30 (stainless steel) and 60 (polystyrene) min reduced the microbial counts to values below the limit of detention (lower than 10^2 CFU/cm^2).

Recently, PAW has been tested as a clean-in-place (CIP) agent (Figure 3) for the inactivation and removal of *Enterobacter aerogenes* (a non-pathogenic surrogate of *Salmonella*) biofilms (10^8 CFU/cm^2) attached to the inner surface of a model piping system (Tan & Karwe, 2021). The ability of distilled water, chlorine solution and PAW to inactivate the biofilms were compared by the authors. Distilled water reduced *E. aerogenes* counts on the surface by 0.4, 0.2, and 0.2 log CFU/cm^2 on the tees, elbows, and tubing, respectively, while PAW reduced the concentration of bacteria in the pipe inner surfaces by about 3.5 log CFU/cm^2, presenting a similar antibacterial effect as a 100-ppm chlorine solution.

4. Other applications of PAW in the food industry

4.1. PAW as a curing agent of meat products

Nitrites play a very important role in the processing of cured meat products by contributing to the development of their characteristic color and aroma, inhibiting lipid oxidation, and controlling the growth of spoilage and pathogenic microorganisms, including *Clostridium botulinum*. PAW, as already mentioned, contains nitrates and nitrites (Oehmigen et al., 2010). Based on this, Jung et al. (2015) elaborated Frankfurt-type sausages substituting the nitrites of the curing salts with PAW (water with 1% sodium pyrophosphate treated by NTAP, which presented a content of 782 and 358 ppm of nitrites and nitrates, respectively). The authors did not detect differences between traditional- and PAW-processed products after 28 days of storage. They assessed changes in the total aerobic bacterial counts and some quality parameters, including color, aroma, flavor, juiciness and elasticity. Additionally, PAW-treated sausages presented the advantage of showing a residual nitrite content 30% lower than that of traditionally made products. This is an interesting fact from a health point of view, since there is a concern expressed by health authorities related to the occurrence of high contents of nitrites in food products due to their transformation into nitrosamines and carcinogenic derivatives. Subsequent studies have also demonstrated the potential of NTAP-treated brines for curing loin (Yong et al., 2017) and beef jerky (Inguglia, Oliveira, Burgess, Kerry & Tiwari, 2020).

The results obtained in these studies suggest that PAW, or brines treated by NTAP, could constitute an innovative, effective and safer alternative to curing salts currently used in the meat industry.

4.2. PAW in sprouts production

The consumption of sprouts of cereal and pulse seeds has a strong tradition in East Asian countries and their demand by Western consumers has increased considerably in recent years. This is mainly due to the fact that the germination process improves the nutritional value of the seeds, increases the content in bioactive compounds, such as vitamin C and polyphenols, and reduces the levels of antinutritional factors, which has driven the development of industries dedicated to their production (Mir et al., 2021). Seeds germination is a slow process that requires exposing the seeds for a long time to warm temperatures (20-25 ^{o}C) and high humidity environments, which provide suitable conditions for microbial growth, including of some pathogens, such as *Salmonella* spp., *E. coli* and *L. monocytogenes*. The consumption of contaminated sprout products is of concern given the fact that sprouts are considered ready-to-eat foods. In fact, sprouts have been implicated in food poisoning events, such as in the case of the German outbreak caused by a Shiga toxin-producing strain of *E. coli* O104:H4, which occurred in 2011, affecting about 4,000 people and causing several deaths, which resulted in a major health alert (Frank et al., 2011).

It has been reported in several studies (Sivachandiran & Khacef, 2017; Zhang, Rousseau & Dufour, 2017; Lo Porto et al., 2018; Xiang et al., 2019; Zhou et al., 2019; Machado-Moreira et al., 2021) that the irrigation of seeds with PAW stimulates their germination and subsequent growth, thus shortening the productive process. For example, Zhou et al. (2019) described that the use of PAW as irrigation water was capable of decreasing the germination time of mung bean seeds, from 72 h to 36 h, increasing by 6% the final germination percentage. Similarly, Zhang et al. (2017) obtained improved results when using this strategy to produce sprouts of lentils. These authors observed that seed germination using PAW increased stems development and produced higher percentages

of germinated seeds (80% compared to 30% obtained when using tap water). Although the mechanism responsible for the boost in germination obtained using PAW is yet unknown, it is considered that the presence of ROS and RNS plays an important role, especially H_2O_2 and NO_3^- (Zhang et al., 2017). Also, the increase in the surface wettability of the seed caused by oxidation (Sivachandiran & Khacef, 2017) and the initiation of cellular metabolic activity in response to the oxidative stress induced by PAW (Zhang et al., 2017) are to be considered.

In addition to the increase of germination percentages, reduction of the time required for germination, and enhancement of the growth of the shoots, PAW also reduces the microbial load in the final product (Zhou et al., 2019). Thus, the total mesophilic counts in sprouts produced with tap water reached values of 6.2 log CFU/g, while in the sprouts watered with PAW the counts were approximately of 1.0 log CFU/g. Similarly, Machado-Moreira et al. (2021) evaluated the activity of PAW as a disinfecting agent for alfalfa (*Medicago sativa*) and mung bean (*Vigna radiata*) seeds, during seed soaking. The authors reported reductions of up to 1.7 log cfu/g in alfalfa seeds inoculated with *E. coli* O104, and a reduction of 1.8 log cfu/g for mung bean seeds inoculated with *E. coli* O157. Additionally, the combination of PAW with ultrasound resulted in increased reduction levels of 3.5 log cfu/g of *S.* Montevideo in mung bean seeds.

In summary, the set of advantages offered by PAW for the production of sprouts makes this technology appealing and with potential for its application in this industrial sector.

4.3. PAW as a coadjuvant agent for the modification of starch and flour structure

Recently, starch and wheat flour modification using PAW and heat-moisture treatment (HMT) has gain considerable attention. Wheat flour is composed of starch and other

ingredients, and their interaction determines the functional characteristics of the dough, and consequently, the quality of the products.

Starch is the most important carbohydrate in human diet and is widely used in the food industry given its ability to regulate and stabilize the texture of foods and its thickening and gelling properties. However, the native structure of starch is problematic under certain processing conditions, as it is insoluble in water and tends to easily undergo retrogradation and syneresis phenomena, giving rise to unstable pastes and gels. These limitations can be mitigated by applying physical, chemical, enzymatic or biotechnological processes which allow to obtain different types of modified starches according to the specific conditions required for each food. Starches are characterized depending on the rate of digestion as follows, rapidly digested starch (RDS), slowly digested starch (SDS) and resistant starch (RS). The treatment of native starch under conditions of heat and moisture is one of the approaches followed for starch modification. This method consists of a thermal agitation, at temperatures lower than the gelatinization temperature, of the starch granules for a long time and with a restricted moisture content of 10-35% (Zavareze & Dias, 2011). To improve its effectiveness, this treatment can be combined with other modification technologies, such as enzymatic and acid hydrolysis, as well as esterification (Hung, Vien & Phi, 2016; Xie, Li, Chen & Zhang 2019; Zhang, Li, Xie & Chen, 2019). Recently, it has been shown that the use of PAW instead of distilled water (DW) during the modification treatment of corn starch increased not only its solubility but also the RS content (Yan, Feng, Shi, Cui & Liu, 2020). The results of that study showed that the incorporation of PAW during this process could result in a new method to modify the structure of starch, reducing its digestibility by increasing the content of the resistant fraction of starch, with the

additional advantage of avoiding the use of acids or enzymes. Similarly, Shi, Wang, Ji, Yan & Liu (2021) observed that PAW-HMT offers a novel, sustainable method for modifying flour and dough. These authors reported that the grain sizes in flour treated by PAW-HMT were lower than those treated by DW-HMT, reducing the viscoelasticity in the dough. In this case, the RS content of PAW-HMT flour was also slightly increased.

4.4. Use of PAW to induce the formation of protein gels

Many efforts have been done to understand the basis of myofibrillar proteins (MPs) gel formation, to improve and broadening their functional performance in the food industry. The functional characteristics of proteins are directly correlated with their molecular structure and also, their spatial conformations are closely related to the protein functionalities (Xu et al., 2020b). In this regard, MPs are frequently used as multifunctional ingredients for food processing due to their capacity to improve texture, yield and organoleptic characteristics of final meat products (Xu & Xu, 2021). Therefore, many approaches have been used to modify molecular structures and functional properties of proteins, including the use of additives, oxidation treatments, and novel food processing technologies. These approaches can modify the structure of proteins, and consequently, improve the strength of the protein gels. Chicken myofibrillar protein (CMP) is known for its poor gel strength and microbial contamination, limiting its application for food processing. To overcome these limitations, Qian et al. (2021) used PAW instead of deionized water to improve the CMP gel attributes in the absence of any additives. These authors studied the effect of PAW on the rheological properties, particle size, zeta potential and aromatic amino acid residues of CMP. Additionally, its antimicrobial effectiveness against *S.* Enteritidis and *S. aureus* was assessed. The findings

indicated that PAW enhanced the aggregation and strength of CMPs, as well as the water holding ability of the gels (Figure 4). Another important finding was that the resulting CMP gels showed antimicrobial activity against the bacteria tested (Qian et al., 2021). The results found in this recent study highlight the possibility of obtaining CMP with enhanced functionality and value-added muscle-based products, and, consequently, of applying it as a novel meat ingredient in the food industry.

4.5. PAW as a technique for the degradation of pesticides

It has been reported that PAW also has great potential to reduce the content of pesticides, which are widely used in intensive agriculture to protect crops from insects, weeds and diseases. The presence of pesticides in food constitutes a great risk to consumers health due to their toxicological effects, associated, among others, with neurological problems, cancer, hormonal and nervous system disorders and asthma (Lee & Choi, 2020).

Zheng et al. (2019) observed that the immersion of grapes in PAW for 10 min caused a reduction of 73.6% in the residues of foxim, a commonly used organophosphate insecticide, without significantly affecting the quality attributes of the fruit. In addition, applying analytical HPLC-MS chromatography techniques, the authors detected after treatment the presence of two intermediates of the degradation of the pesticide, 2-hydroxyimino-2-phenylacetonitrile and O-diethyl O- (alpha-cyano benzylideneamino) phosphonate, suggesting that the reduction of the pesticide was related to its degradation. Similarly, Gracy, Gupta & Mahendran (2019) found a reduction of up to 52% in the concentration of the pesticide chlorpyrifos on tomatoes after a 15-min

exposure to the action of PAW, resulting in a much higher reduction than that obtained by immersion in distilled water (0.1-0.6%).

Ali, Cheng & Sun (2021) studied the effect of PAW and an activated buffer solution (PABS) on fungicide (chlorothalonil (CTL) and thiram (THM)) degradation on tomato fruit. Using atmospheric air as the feed gas to activate the liquids (PAW and PABS), CTL residues were decreased to 85.3% and 74.2% and THM residues decreased to 79.5 and 72.2% after immersion of the samples in PAW and PABS for 10 min, respectively. The authors did not observe notable negative impacts on the selected quality parameters (total soluble solids, pH, titratable acidity, colour, lycopene content, ascorbic acid, total phenolic content and texture) of tomato fruits.

The results obtained from the previous studies showed that the capacity of PAW to reduce pesticides strongly depends on the energy applied to ionize the gas, the type of gas and the flow rate of the plasma during the generation of PAW (Ali et al., 2021; Gracy et al., 2019), as well as on the time of exposure of food to PAW (Ali, Sun, Cheng & Esua, 2022; Gracy et al., 2019; Zheng et al., 2019), the activation time (Ali et al., 2021, 2022) and the combination with ultrasound treatment (Ali et al., 2022). On the other hand, it is considered that the ROS and RNS present in PAW, including ozone and the hydroxyl radical, are responsible for the degradation of the pesticides due to their ability to interact with them. However, it has been suggested that the coexistence of acidic conditions (pH <3) and oxidants (oxidation-reduction potential >500 mV) play an important role in the degradation process of foxim (Zheng et al., 2019).

Although the results obtained in this field are promising to reduce pesticide residues on fruits and vegetables, it has not yet been possible to demonstrate the ability of PAW to completely eliminate them. Moreover, it is also important to evaluate the possible side

effects of the intermediate and final products generated during the pesticides´ degradation.

5. Conclusions and future prospective

This review summarizes a great number of the most recent works using PAW for food related applications. Although PAW effectiveness as a bactericidal agent could be demonstrated in those studies, there are still many gaps that need to be filled by the scientific community in order for this technology to be implemented in the food industry. Therefore, researchers and stakeholders world-wide seek to further explore optimization of PAW treatments for specific food applications and to overcome the existing challenges regarding regulatory/legislative approval.

It is necessary to address research needs, with coordinated activities within research groups, in order to better tackle this challenge. Five main topics can be identified where research is especially needed: i) recognize the key food applications; ii) establish the key parameters and standard procedures to evaluate treatment efficacy; iii) identify the key parameters to evaluate the safety and quality of PAW treated products; iv) optimize pilot plant prototypes mimicking large scale systems in the food industry; v) undertake studies on life cycle assessment associated with the key food applications.

Despite the numerous studies showing the potential of PAW, the toxicity aspects of this technology are still not fully studied. So far, just few studies have investigated the possible formation of toxic compounds when PAW interacts with food components. It will be useful to undertake more studies on the minimal concentration threshold of reactive species and exposure time of food to PAW, thus avoiding any potential toxic or mutagenic effects. Furthermore, the safety risk assessments regarding potential adverse

effects on human health will facilitate the process of receiving regulatory approval for this technology to be used in the food industry.

Another point that needs to be considered is the possible chemical changes to food compounds leading to potential changes in food quality caused by the generation of reactive species and their interaction. As an example, the oxidation of lipids can result in the formation of aldehydes and keto acids, generating unpleasant odors and off-flavors. The synergistic effect between different preservation technologies, including ultrasounds and/or mild temperatures, should be further studied to enhance PAW effectiveness with minimum impact on organoleptic, nutritive and functional properties of foods. Hence, a complete diagnostic of PAW reactive species should be accomplished in order to optimize treatment conditions in particular food products, which can improve PAW effectiveness and outline the application of reactive species for specific purposes.

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Conflict of Interest Statement

The authors report no commercial or proprietary interest in any product or concept discussed in this article.

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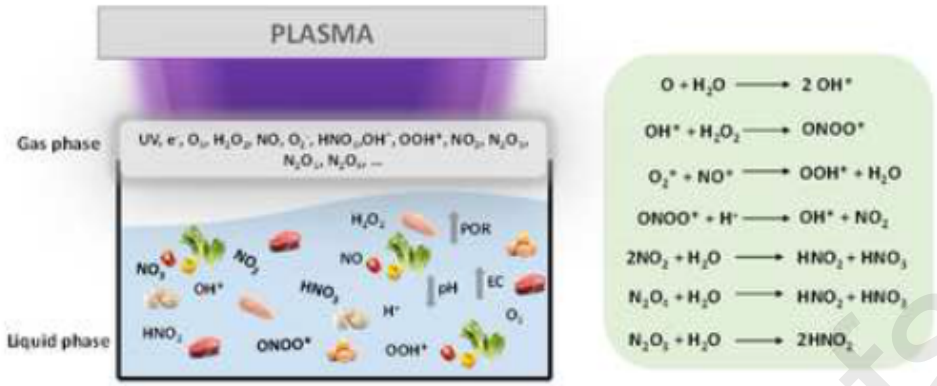

Figure 1.

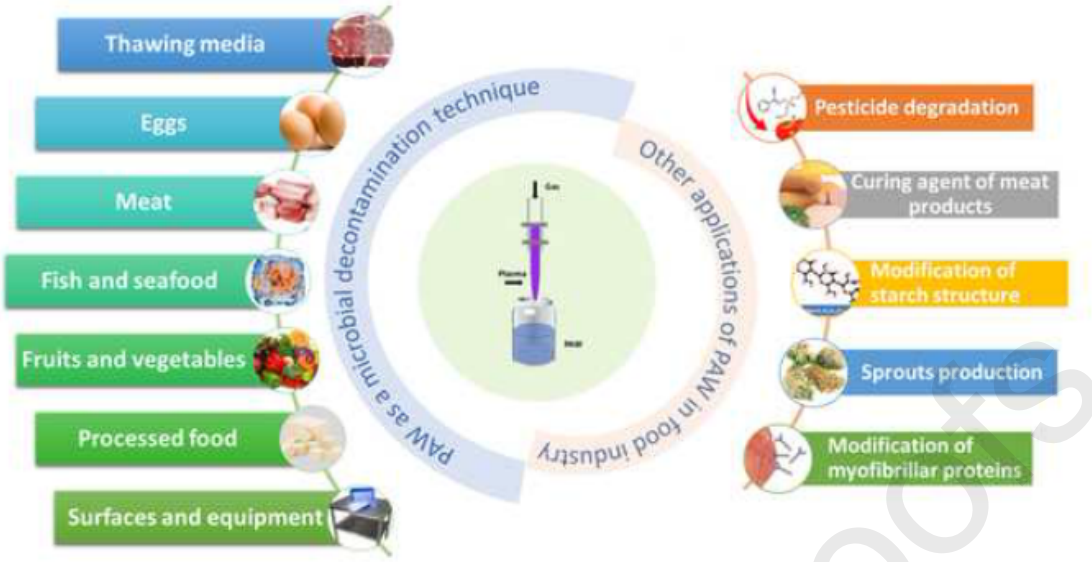

Figure 2.

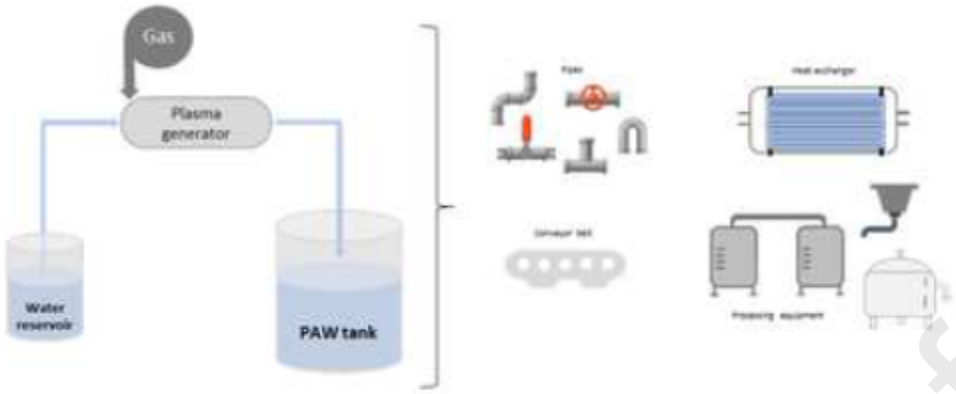

Figure 3.

Physical properties	Control	PAW 100 s
Gel strenght (N)	0.34a	0.6Sb
Water Holding Capacity (%)	48.78a	54.95b
Whiteness	89.06a	89.72a

Figure 4.

Table 1.- Summary of major research articles assessing the level of microbial inactivation achieved and the quality changes occurring in foods subjected to plasma-activated water (PAW).

Food product	Conditions of PAW generation	Chemical composition and physicochemical properties of PAW	Maximum log reduction	Impact on quality attributes	References
Fruits and vegetables					
Strawberries	Plasma jet, 18 kV, 10 kHz, 98% Ar+2% O_2 (5 L/min), 2 cm distance, SDW, 20 min	pH: 3 ORP: 550 mV EC: 450 µS/cm	*Staphylococcus aureus* ~ 2.5 log in 15 min	No significant changes in pH value, firmness and color	Ma et al. 2015
Chinese bayberry	Plasma jet, 20 kHz, air (260 L/h), 3 cm distance, SDW, 25 min	pH: 3.53 ORP: 511 mV EC: 125 µS/cm	Total aerobic bacteria ~ 1.1 log Total fungi ~ 1.1 log In 30 s and 8 d storage at 3 °C	Firmness and total soluble solids were maintained. Decay incidence decreased	Ma et al. 2016
Grapes	Plasma jet, 8.2 kV, air (1.2 L/min), 1.5 mm distance, SDW, 60 min	pH: 4.18 ORP: 442	*Saccharomyces cerevisiae* ~ 0.4 log in 30 min	No change in color and total anthocyanin content	Guo et al. 2017
	Plasma jet, 5 kV, 40 kHz, 750 W, air (30 L/min), SDW, 90 s	pH: 3.17 ORP: 550 mV H_2O_2: 37.91 µmol/L NO_2^-: 37.91 µmol/L NO_3^-: 37.91 µmol/L	*S. cerevisiae* ~ 0.4 log in 30 min	No influences on total soluble solids, total phenolics, vitamin C, antioxidant propertied, firmness and color	Xiang et al. 2020a
Limes	Plasma jet, 295 V, 22.5 kHz, air, 8.1 cm distance, SDW, 5 min	pH: 3.1 ORP: 534.52 mV EC: 324.19 µS/cm	*Enterobacter aerogenes* ~ 3.2 log in 3 min	Not assessed	Joshi et al. 2018

Kumquat	Dielectric barrier discharge, 20 kHz, 4.5 kV, air (5 L/min), 50 mm distance, SDW, 60 min	pH: 4.19 ORP: 400 mV EC: 194.98 µS/cm NO_2^-: 0.929 mg/L NO_3^-: 164.372 mg/L	*Penicillium italicum* ~ 3.3 log in 30 min	No significant changes in surface color and no reductions in ascorbic acid, total flavonoid, and carotenoids content	Guo et al. 2021
Fresh-cut pear	Microplasma jet array, 8 kV, 9 kHz, air (1 slm), DW, 10 min		Total aerobic bacteria ~ 0.7 log Molds ~ 0.8 log Yeast ~ 1.0 log In 5 min and 12 d storage at 4 °C	No adverse impact on vitamin C content	Chen et al. 2019
Fresh-cut apple	Microplasma jet array, 8 kV, 7 kHz, air (1 slm), DW, 10 min		Total aerobic bacteria ~ 1.1 log Molds ~ 0.6 log Yeast ~ 1.0 log Coliforms ~ 0.9 log In 5 min and 12 d storage at 4 °C	Reduction of superficial browning, without affecting firmness and titratable acidity. No changes in the content of total polyphenols and ascorbic acid	Liu et al. 2020
Fresh-cut kiwifruit	Microplasma jet array, 10 kV, 8 kHz, air (1 slm), DW, 30 min	pH: 2.8 H_2O_2: 0.05 mmol/L	*S. aureus* ~ 1.7 log in 8 d storage at a 4 °C of sprayed samples with PAW	Firmness and *b** value were well maintained	Zhao et al. 2019
Grape tomato	Plasma jet, 295 V, 22.5 kHz, air, 8.1 cm distance, SDW, 5 min	pH: 3.1 ORP: 534.52 mV EC: 324.19 µS/cm	*E. aerogenes* ~ 4.7 log in 3 min	Not assessed	Joshi et al. 2018
Tomato	2 Plasma jet, 60 W, 3.0 kV, 16 kHz, air (10 slm), ROW, 20 min	pH: 2.59- 2.62 ORP: 570.02-597.40 mV EC: 941.50- 1220.5 µS/cm O_3: 0.57-0.84 ppm NO_2^-: 97.83-144.67 ppm NO_3^-: 6.39-19.57 ppm	*S.* Typhimurium ~ >5 log in 30 s *E. coli* ~ >5 log in 180 s *L. monocytogenes* ~ >5 log in 210 s	Not assessed	Hou et al. 2021

		H_2O_2: 21.65-31.32 ppm			
Spiny gourds	Plasma jet, 295 V, 22.5 kHz, air, 8.1 cm distance, SDW, 5 min	pH: 3.1 ORP: 534.52 mV EC: 324.19 µS/cm	*E. aerogenes* ~ 1.0 log	Not assessed	Joshi et al. 2018
Salted kimchi cabbage	18 kV, 14.3 kHz, SDW, 120 min	pH: 2.4 ORP: 798.33 mV EC: 2022.0 µS/cm H_2O_2: nd NO_2^-: 88.66 ppm NO_3^-: 394.28 ppm	Mesophilic aerobic bacteria ~ 1.8 log Lactic acid bacteria ~ 1.6 log Yeast and moulds ~ 1.2 log Coliforms ~ 0.7 log *Listeria monocytogenes* ~ 1.0 log *S. aureus* ~ 0.9 log In 10 min	Minimal changes in moisture content, reducing sugar content, instrumental hardness, and CIE colour values	Choi et al. 2019
Fresh-cut baby spinach leaves	Surface barrier discharge, 11 kV, 12 kHz, 36 W, air, 44.8 mm distance, DW, 20 min	pH: 2.4 H_2O_2: nd NO_2^-: 320 mg/L NO_3^-: 7 mg/L	Total aerobic bacteria ~ 1.0 log in 2 min and 8 d storage at 4 °C	Adequate color retention	Vaka et al. 2019
	Plasma jet, 750 W, 5 kV, 40 kHz, air (30 L/min), 5 mm distance, SDW, 60 s		*Escherichia coli* O157:H7 ~ 0.7 log in 30 min	No significant changes in color, chlorophyll, total phenolic content, and antioxidant activity	Liu et al. 2021a
Fresh-cut Iceberg lettuce leaves	Glow plasma, O_2 or air, 10 min	NO radical: 5×10^{-5} M OH radical ~ 90×10^{-4} M O_3: 0.5 ppm H_2O_2: 1.8×10−6 M	*Salmonella* Typhimurium ~ 3.0 log in 3 min	No significant changes in flavonoids (kaempferol and quercetin) content and color	Khan et al. 2019
Fresh-cut Iceberg lettuce	Microwave-plasma source, 1.1 kV, 2.45 GHz, air (18 slm), DW, 50 s	pH: 1.3	*E. coli* ~ 2.0 log *P. fluorescens* ~ 1.5 log *P. marginalis* ~ 6.0 log *Pectobacterium carotovorum* ~ 6.0 log	After 8 days of storage, little changes in the texture and the appearance	Schnabel et al. 2015

			L. innocua ~ 4.0 log In 1 min		
Fresh-cut Romaine lettuce leaves	Glow plasma, O_2 or air, 10 min	NO radical: 5×10^{-5} M OH radical ~ 90×10^{-4} M O_3: 0.5 ppm H_2O_2: 1.8×10^{-6} M	*S.* Typhimurium ~ 2.6 log in 3 min	No significant changes in flavonoids (kaempferol and quercetin) content and color	Khan and Kim 2019
Rocket leaves	Dielectric barrier discharge, 9 kV, 5 kHz, air, 5 mm distance, DW, 4 min	pH: 3.3 EC: 200 µS/cm H_2O_2: 4.5 mg/L NO_2^-: 30.4 mg/L NO_3^-: 90.4 mg/L O_3: 0.3 mg/L	Mesophilic aerobic bacteria ~ 2.5 log Psychrotrophic bacteria ~ 3.0 log Enterobacteriaceae ~ 1.5 log In 5 min	No significant changes in pH and total flavonoid content. Slight changes in colour and total phenolic content	Laurita et al. 2021
Rocket leaves	Surface dielectric barrier discharge jet, 7 kV, 80 kHz, He (1 L/min), 5 mm distance, DIW, 15 min	pH: 4.1 EC: 41 µS/cm H_2O_2: 285 mM NO_2^-: 153 mM NO_3^-: 1.34 mM	Total viable count ~ 1.6 log *Pseudomonas spp.* ~ 2.3 log Yeasts and molds ~ 1.0 log Lactic acid bacteria ~ 1.0 log In 15 min	No significant changes in pH, color and Firmness. Extension of shelf-life from ~ 3 days to ~ 7.5 days upon storage at 5 °C	Dimitrakellis et al. 2021
Fresh-cut endive	2-stage microwave plasma torch, 2.45 GHz, 4.3 kW, 72 slm, air, DW	H_2O_2: 5.61 mg/L NO_2^-: 315.83 mg/L NO_3^-: 472.8 mg/L	Total bacteria ~ >5 log in multiple application (3-step-PFW-application)	Not assessed	Schnabel et al. 2021
Tiger nuts	Plasma jet, 650 W, air (39 L/min), 5 cm distance, SDW, 10 min	pH: 2.71 ORP: 575.67 mV H_2O_2: 0.0172 ng/L NO_2^-: 54.83 mg/L NO_3^-: 116.54 mg/L	Total bacteria ~ 3.2 log *Klebsiella pneumoniae* ~ 3.5 log In 15 min	No significant changes in total phenolic and flavonoid contents, antioxidant activity and sensory characteristics (color, appearance, aroma and overall acceptability)	Muhammad et al. 2019

Seeds					
Alfalfa	Plasma jet, 10 kV, 20 kHz, air (11 L/min), SDW, 10 min	pH: 2.93	*Escherichia coli* O104:H4 ~ 1.7 log in 180 min	No adverse impact on the germination and growth rate of alfalfa sprouts	Machado-Moreira et al. 2021
Mung bean	Plasma jet, 10 kV, 20 kHz, air (11 L/min), SDW, 10 min	pH: 2.93	*E. coli* O157 ~ 1.8 log *Salmonella* Montevideo ~ 1.6 log In 180 min	No adverse impact on the germination and growth rate of mung bean sprouts	Machado-Moreira et al. 2021
Sprouts					
Mung bean sprouts	Microwave-plasma source, 1.1 kV, 2.45 GHz, air (18 slm), DW, 50 s	pH: 1.3	*E. coli* ~ 2.5 log *P. fluorescens* ~ 3.0 log *P. marginalis* ~ 3.0 log *Pectobacterium carotovorum* ~ 3.0 log *L. innocua* ~ 2.0 log In 1 min	After 8 days of storage, little changes in texture and appearance	Schnabel et al. 2015
Mung bean sprouts	Plasma jet, 750 W, 5 kV, 40 kHz, air (30 L/min), 5 mm distance, SDW, 30 s	pH: 3.35 ORP: 550.67 mV EC: 307.00 µS/cm H_2O_2: 20.17 µmol/L NO_2^-: 669.89 µmol/L NO_3^-: 644.33 µmol/L	Total aerobic bacteria ~ 2.3 log Molds and yeasts ~ 2.8 log In 30 min	No significant changes in the antioxidant potential, total phenolic and flavonoid contents and sensory characteristics (color, flavour, texture, appearance, overall acceptance)	Xiang et al. 2019
Meat and meat products					
Fresh beef	Microplasma jet array, 10 kV, 8 kHz, air (1 slm), DW, 30 min	pH: 2.5 H_2O_2: 116.2 mg/L NO_2^-: 2.6 µmol/L NO_3^-: 90.4 mg/L O_3: 0.11 mmol/L	Total bacteria ~ 3.1 log in 24 h storage at 4 °C of sprayed samples with PAW. Extension of shelf-life by 4 to 6 d	No adverse effects on surface color, texture, and pH	Zhao et al. 2020b
	Plasma jet, 19.2 kV, 0.46 W, 0.024 mA, air		*Salmonella* Enteritidis ~ 1.0 log in 20 s	No noticeable effects on pH, odor and color. Lipid oxidation was not	Qian et al. 2019

	(22.5 L/min), 10 mm distance, DIW, 80 s			observed	
Chicken meat	Plasma jet, 6.8 kV, 1.5 kHz, Ar (1 slm), DIW, 6.5 min	pH: 5.5 ORP: 490 mV EC: 8.5 µS/cm H_2O_2: 2.9 ppm OH radical: 60 ppm	*E. coli* K12 ~ 0.5 log *S. aureus* ~ 0.3 log In 60 min	Minor changes in hardness, protein and lipid contents and sensory characteristics (appearance, color, texture acceptability)	Royintarat et al. 2020
Chicken breast	Plasma jet, 750 W, 5 kV, 40 kHz, air (30 L/min), 5 mm distance, SDW, 1 min		*Pseudomonas deceptionensis* ~ 1.1 log in 12 min	Significant reductions in cohesiveness, gumminess, odor and color. No significant changes in hardness and springiness (mm)	Tian et al. 2015
Chicken wings	Plasma jet, 19.2 kV, 0.45 W, 20 kHz, air (22.5 L/min), 10 mm distance, DIW, 80 s		*S.* Enteritidis ~ 0,5 log in 10 min	No adverse effects on the color, pH and lipid oxidation	Qian et al. 2020
Cooked chicken breast	Dielectric barrier discharge, 42 W, 5 mm distance, 20 min	pH: 2.56 ORP: 514.67 mV EC: 470.33 µS/cm	*S. aureus* ~ 2.2 log in 20 min	No adverse effects on the color	Wang et al. 2021
Fish					
Mackerel cubes	Plasma jet, 30 kV, air, 8 cm distance, SDIW, 15 min		*P. fluorescens* ~ 0.4 log In 30 min	Not assessed	Zhao et al. 2020c
Mackerel fillets	Plasma jet, 300 W, 20 kHz, air (11 L/min), SDIW, 10 min	pH: 3.11 ORP: 561.0 mV EC: 365.0 µS/cm H_2O_2: 13.43 µM NO_2^-: 420.0 µM NO_3^-: 300.0 µM	Mesophilic aerobic bacteria ~ 0.2 log Psychrotrophic bacteria ~ 0.2 log *E. coli* ~ 0.2 log *L. innocua* ~ 0.2 log *P. fluorescens* ~ 0.3 log In 10 min	No noticeable changes in color. Lipid oxidation was induced	Zhao et al. 2021b

Carp fillets	Plasma jet, 750 W, 5 kV, air (30 L/min), 5 mm distance, SDIW, 2 min		*Shewanella putrefaciens* ~ 1.0 log In 6 min	No significant changes in pH, hardness, springiness and cohesiveness. Sensory attributes were affected. Lipid oxidation was induced	Liu et al. 2021b
Eggs					
Shell eggs	Plasma jet, 60 W, 3 kV, 16 kHz, air (5 L/min), ROW, 20 min	pH: 3.13 ORP: 567.5 mV	*S.* Enteritidis ~ 5.5 log in 2 min	No adverse effects on freshness indexes	Lin et al. 2019
Other food products					
Button mushroom	Plasma jet, 18 kV, 98% Ar+2% O_2 (5 L/min), 10 mm distance, SDW, 20 min		Total aerobic bacteria ~ 1.5 log Total fungi ~ 0.5 log In 10 min and 7 d storage at 20 °C	The softening was delayed. No significant changes in the color, pH and antioxidant properties	Xu et al. 2016
	Dielectric barrier discharge, 2.8 kV, 10 kHz, air (2.5 L/min), DW, 25 min	pH: 3.08 ORP: 257.24 mV EC: 48 µS/cm H_2O_2: 1.35 mmol/L O_3: 0.51 mmol/L	*E. coli* ~ 1.32 log in 10 min	Delayed the browning process and extended the shelf life	Zhao et al. 2021a
Bean curd	Plasma jet, 750 W, 5 kV, 40 kHz, air (30 L/min), 3.5 cm distance, SDW, 90 s		Total aerobic bacteria ~ 1.3 log Total yeasts and molds ~ 0.9 log In 30 min	Total isoflavone content, sensory characteristics (appearance, flavour, brittleness, overall acceptance), springiness, cohesiveness, chewiness and resilience were well maintained. Significant changes in hardness and color parameters	Zhai et al. 2019

Tofu	Plasma jet, 1 W, 2 kV, 1 kHz, air (10 L/min), DIW, 10 min	pH: 3.82 ORP: 364 mV EC: 140 µS/cm	*E. coli* O157:H7 ~ 0.5 log *S.* Typhimurium ~ 0.8 log *S.* Enteritidis ~ 0.6 log *L. monocytogenes* ~ 0.6 log In 24 h immersion	Not assessed	Frías et al. 2020
Korean rice cake	Surface dielectric barrier discharge, 51.7 W, 8 kV, 14.4 kHz, air, DW, 20 min	pH: 2.48 ORP: 507.23 mV EC: 910.24 µS/cm	*E. coli* O157:H7 ~ 2.0 log *S.* Typhimurium ~ 2.0 log *L. monocytogenes* ~ 2.0 log Total aerobics ~ 2.8 log *Candida albicans* ~ 1.0 log *Penicillium chrysogenum* ~ 2.0 log In 20 min	No adverse effects on the color, texture, or pH	Han et al. 2020

SWD, sterile distilled water; DW, distilled water; SDIW, sterile deionized water; DIW, deionized water; ROW, reverse osmotic water

slm, standard liters per minute

nd, not detected

Conflict of Interest Statement

The authors report no commercial or proprietary interest in any product or concept discussed in this article.

Highlights

- New insights into the current state-of-the-art of the applications of PAW
- Decontamination effects and other technological applications of PAW
- Overview on the critical factors determining PAW effectiveness
- A contribution on PAW feasibility and applicability in the food-processing industry