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Review

Properties of Water Activated with Low-Temperature Plasma in the Context of Microbial Activity

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Abstract: The low-temperature plasma process is an advanced technology that has recently enjoyed great popularity due to its eco-friendly nature and antibacterial efficacy. Plasma-activated water (PAW)—a product of non-thermal plasma reaction with water, containing a rich variety of highly reactive oxygen and nitrogen species (RONS), is a green prospective solution for decontamination of microorganisms in a wide range of biotechnology aspect. Here, we present a succinct review of the formation of PAW and its properties in the context of inactivation of microorganisms. Among the wide range of articles on plasma-activated water, there is no comprehensive overview of the mechanism of microbial inactivation, the influence of reactive oxygen and nitrogen species on cell components, or the role of growth phases in PAW effectiveness in inactivation. This review aims to summarize the results of research in this area, taking into account the directions of potential applications of PAW in the field of medical sciences and food technology, indicating the species or strains of inactivated microorganisms.

Keywords: plasma; plasma-activated water; reactive species; microbial inactivation; decontamination

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1. Introduction

Plasma is commonly known as the fourth state of matter. Its state of aggregation resembles a gas with unique properties, in which a significant part of the particles is ionized [1,2]. There are thermal (hot) and non-thermal (cold) plasma based on the thermodynamic temperature equilibrium of the constituents [3]. In the case of cold plasma, the temperature of heavy molecules (ions and neutral particles) ranges from 25–100 °C, whereas the electron temperature is much higher and amounts to between 5000 °C and 10^5 °C. The degree of ionization in such plasma is below 0.1% and its gas temperatures are relatively low, typically less than 100 °C. The pressure of non-thermal plasma does not exceed 133 mbar [4]. Cold plasma consists of several excited atomic, molecular, ionic and radical forms, coexisting with many reactive forms—free radicals, reactive oxygen species (ROS) and reactive nitrogen species (RNS), and quanta of electromagnetic radiation—UV photons and visible light (VIS) [5,6].

Cold plasma can be obtained through a variety of electrical discharges, including micro-hollow cathode discharge, corona discharge, gliding arc discharge, dielectric barrier discharge, plasma needle, and atmospheric pressure plasma jet. The method of plasma generation influences its composition (type and number of chemical individuals), and also, indirectly, its technological application [1,7]. In the field of biotechnology, biology, medicine, pharmacy, and environmental sciences, the most commonly used are cold plasma produced by dielectric barrier discharge (DBD) and atmospheric-pressure plasma jet (APPJ) [1,8]. The unique properties of cold plasma make it widely used, among others in surface modification of polymeric materials [9], production and treatment of nanoparticles [10,11],

decontamination of surfaces in contact with food [12,13], wastewater treatment [14], air purification [15], or the production of plasma-activated water (PAW) [16,17].

2. Generation of Plasma-Activated Water and Its Properties

Plasma activated water is water treated with plasma, which is produced above the water column, in water or gas bubbles present in water [18]. Reactive molecules formed in the gas phase penetrate the plasma-liquid interface into water (Figure 1), inducing secondary reactive species in solution. The transfer of reactive species from plasma to the liquid consists of numerous physical and chemical processes, including mass transfer, molecules collision, liquid evaporation, sputtering, and ultra-violet radiation [19].

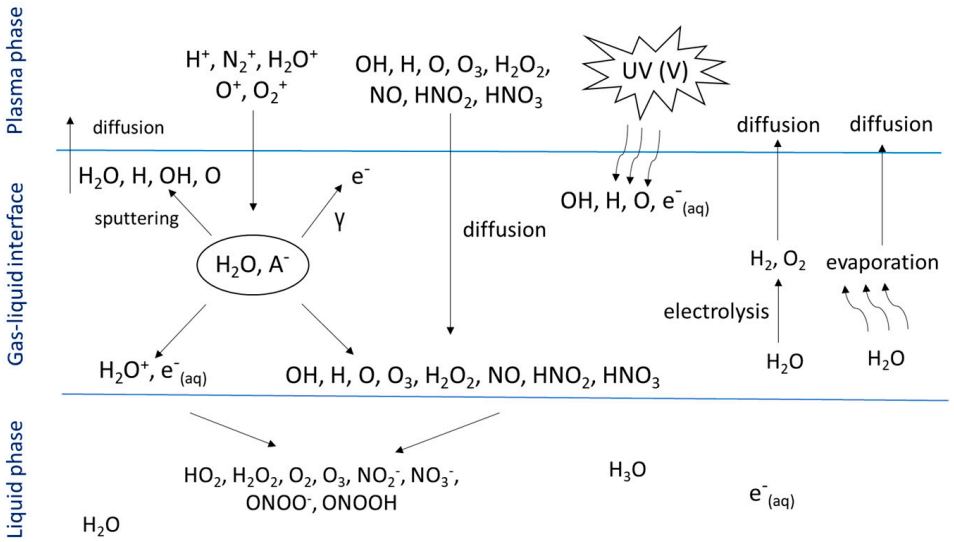

Figure 1. Scheme of migration of reactive oxygen and nitrogen species between phases during plasma water treatment. Adapted from Bruggeman et al. [19].

Small volumes (from 1 mL to 1000 mL) of deionized water, distilled water, filtered water, or drinking water from the tap are subjected to plasmas [19–22]. The type and concentration of the reactive species that are present in PAW depend on the type of gas used to generate the plasma as well as on the type of plasma liquid. The source of the plasma, electrode configuration, applied voltage, treatment time or the distance between the liquid, and the plasma trail are also very important [22]. According to Lamichhane et al. [23], the formation of various reactive molecules as a result of collisions is also mostly regulated by the temperature of the electrons. In order to observe the influence of the abovementioned parameters on the PAW properties, Table 1 lists several examples of different methods of generating plasma and various gases used in this process, with an indication of differences in the physicochemical properties of water.

Table 1. Differences in physical properties of water, depending on plasma devices, working gas and activation time.

			Physical Properties of PAW			
Plasma Generating Equipment	**Working Gas**	**Time of Activation (min)**	**pH**	**Conductivity (μS/cm)**	**Redox Potential (mV)**	**References**
Plasma microjet	Air Ar/O_2	20 20	2.3 6.1	- 18.8	540 250	[24] [25]
Plasma jet	Ar/O_2	15	3.0 3.7	450 218	550 467	[26] [27]
Low frequency plasma jet	He	5	4.2	-	-	[28]

Table 1. *Cont.*

			Physical Properties of PAW			
Plasma Generating Equipment	**Working Gas**	**Time of Activation (min)**	**pH**	**Conductivity (μS/cm)**	**Redox Potential (mV)**	**References**
Gliding arc	Air	15	2.8	1100	-	[29]
	O_2		3.2	300	-	[29]
	N_2		3.0	500	-	[29]
	Ar		3.6–3.7	50–70	-	[30]
DBD micro discharge	Air	15	2.7	-	-	[31]
DBD	Air	20	2.1	-	-	[32]
	O_2		2.2	-	-	[32]
DBD with hallow electrodes	Air	10	1.9	2000	550	[33]

The high-energy electrons generated by a plasma discharge collide with water, causing a series of complex processes such as excitation, dissociation and ionization. A large amount of active particles is produced. Among the reactive species produced by the commonly used plasma sources, the following are distinguished active forms of oxygen molecules and atoms, that is, reactive oxygen species: atomic oxygen O, singlet oxygen $^1O_2$, superoxide anion O_2^- and ozone O_3; reactive nitrogen species, such as atomic nitrogen N, excited nitrogen N_2, nitric oxide NO•; NO_2^- (nitrites), NO_3^- (nitrates), $ONOO^-$ (peroxynitrites), H_3O^+, OH^- anion, and OH• radical or H_2O_2 are also generated [1,19,22]. Chemical reactions between the reactive molecules created by the action of the plasma and those present in the water affect the properties of PAW. The pH, redox potential, conductivity, and surface tension are modified.

2.1. pH

The pH value of plasma-activated water is usually lower than that of traditional water, which is due to the production of nitric acid (derived from NO generated in PAW), peroxynitrous acid, and hydrogen peroxides [22]. According to the patent description of Pemen et al. [34] with the right combination of non-thermal and thermal plasmas in PAW generation, the pH value can be controlled. The results of research on the treatment of water with plasma showed that a significant decrease in pH takes place in the initial period of plasma operation. According to Ma et al. [26], the first 10 min of plasma stream operation was crucial when the pH dropped from 7 to 3.2, using Ar/O_2 as the working gas. A decrease in the pH value to 3.7 after 5 min of plasma treatment of the water was observed in the studies by Xu et al. [27]. In addition, Abuzairi et al. [35] indicate a drop in water pH from 7.03 to 3.52 within 3 min of treatment, which is explained by the presence of nitrites (NO_2^-) and nitrate (NO_3^-) ions. Shen et al. [24] draw attention to the acidity stability of plasma-activated water. The team studied the pH of the water during 30 days of storage at various temperatures—positive (4 °C, 25 °C) and negative (−20 °C, −80 °C). The pH was shown to drop from 6.8 to 2.3 after 20 min of plasma treatment, after which it did not change over the controlled monthly period. Slightly different results were obtained by Bialopiotrowicz et al. [36], treating distilled water with low-temperature low-frequency glow plasma (LPGP) for 5 to 90 min. During the process, the pH of the water changed slightly, in a non-linear manner, in relation to the extension of the plasma exposure time. The initial pH at 5.56 increased to 6.41 after 1 h of plasma treatment, then stabilized at 5.83 after 90 min.

According to Bruggeman and Leys [37] and Tian et al. [25], the level of change in the pH value depends on the type of reactor and the feed gas used to generate the plasma. This is confirmed by the data collected in Table 1.

2.2. Oxidation-Reduction Potential

Treatment of water with plasma significantly influences its oxidation-reduction potential (ORP). Among the reactive oxygen species that are formed, the most important

factor for the redox potential is hydrogen peroxide, which can act as both an oxidant and a reducing agent [22]. Zhang et al. [33] observed an approx. 63.3% increase in the redox potential of distilled water after 20 min of plasma treatment with the Ar/O_2 mixture. Xu et al. [27], for the production of PAW, used a plasma stream at atmospheric pressure, and also in the mixture environment (Ar 98% and O_2 2%), and observed an increase in the redox potential from 146 mV to 314 mV within 5 min of treatment. When the activation time was extended to 15 min, an oxidation-reduction potential of approx. 467 mV was obtained. An increase in water ORP, from the level of 236 mV to 359 mV, was also noted during the 3-min plasma treatment at atmospheric pressure [35]. Similar results were also obtained in the latest studies [38,39]. According to the authors, longer duration of plasma activation in the air atmosphere results in a greater amount of reactive oxygen species generated in PAW and an increase of the ORP value. The oxidation-reduction potential of PAW depends on the activation strength, which additionally depends on both the carrier gas, the applied voltage, and other parameters leading to an increase in ORP to 63% [33].

2.3. Conductivity

Parameters that are modified during plasma treatment also include electrical conductivity, which indicates the concentrations of free ions present in an electrolytic solution and expresses the ability of water to pass a current through it. Distilled water has a conductivity ranging from 0.5 to 3 µS/cm. The amount of additional ions in the water has a significant influence on its conductivity. The reactive forms of RONS produced during plasma processing dissolve easily in water, which contributes to an increase in conductivity. Brisset et al. [40] described the higher PAW conductivity caused by the generation of NO_X species using gliding arc plasma. After 20 min of water activation with Ar/O_2 gas plasma, the conductivity value was 450 µS/cm [26]. In the case of using a plasma microjet, the increase in conductivity reached the level of 18.8 µS/cm [25]. This significant difference in the obtained increases in conductivity may result from the value of the applied voltage. An increase in the conductivity of plasma-treated water is attributed to the predominance of peroxynitrite over the oxonium ion chemistry [40]. Thirumdas et al. [22] mentions different values of plasma-activated water conductivity resulting from the use of different plasma devices (DBD, jets, etc.) and different gas carriers. Xu et al. [27] emphasize that conductivity is also dependent on plasma systems that are used for production of plasma-activated water. The conductivity of PAW obtained by generating discharges directly in the water is greater compared to PAW, where the discharges are generated above the water surface.

3. Influence of Plasma-Activated Water on Microorganisms

Plasma-activated water shows antimicrobial effectiveness, which is associated, among others, with the presence of reactive oxygen species, reactive nitrogen species, and hydrogen peroxide [41]. The formation of countless numbers of these active chemical compounds, combined with physical factors (low pH, high redox potential), has an antimicrobial effect. The destructive effect of PAW in relation to microorganisms is explained by the mechanisms taking place in various areas of the cell—damage to the cell wall, cytoplasmic membrane, DNA and enzyme apparatus (Figure 2). Observations in the scanning electron microscope(SEM) indicate that the action of plasma-activated water on cells damages their external structures. Changes in bacterial morphology after PAW treatment have been observed in SEM images by many authors [42–44]. The smooth surfaces of the cells distort, shrink, and rupture. The surface structures—the cell wall and membrane—are disintegrated. Reactive forms present in the PAW collide with microorganisms, causing serious and difficult to repair damage to the cell membrane. As a consequence, they may lead to a break in its continuity. This effect may also result from the accumulation of electric charge on the outer surface of the cell membrane. In this process, according to the authors, atomic oxygen and hydroxyl radicals have the greatest lethal effect [45]. A similar effect is obtained as a result of electroporation, otherwise known as electropermeabilization. This process involves the electrically induced formation of new microspores in the cell mem-

brane and the growth of existing ones. The destructive action of this mechanism, described on the example of *Salmonella enterica* and *Listeria monocytogenes*, consists in increasing the permeability of the cell's cytoplasmic membrane. This directly affects the transmembrane potential of cells and their ability to regulate intracellular pH [46].

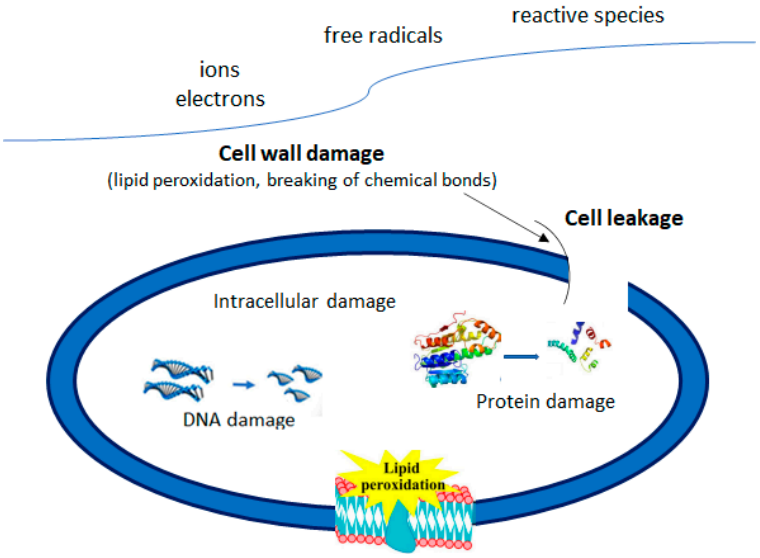

Figure 2. Schematic diagram of the PAW induced inactivation of microbial cells. Adapted from Mandal et al. [12].

3.1. Role of Reactive Oxygen Species

Among the reactive oxygen species produced in PAW, hydroxyl radical (OH•), hydrogen peroxide (H_2O_2), and ozone (O_3) are compounds with the strongest antimicrobial potential [22].

An important role in the inactivation of microorganisms is played by hydroxyl radicals, which mainly affect the outer part of the cell membrane. They are responsible for the peroxidation of fatty acids present in the cells of microorganisms [47]. Dolezalova and Lukes [48] report that OH• radicals initiate the lipid oxidation reaction, cleaving hydrogen from unsaturated bonds in fatty acids. Ultimately, they contribute to the formation of malondialdehyde (MDA), which is a marker of lipid oxidation. MDA has cytotoxic properties. It also inhibits enzymes related to the cell's defense against oxidative stress. Malondialdehyde in microbial cells causes DNA damage and, consequently, cell death [49]. The negative effect of hydroxyl radicals penetrating from PAW into microbial cells and causing internal damage through DNA breakdown, destruction of proteins and internal cell components is described by Lukes et al. [18]. The same authors emphasize that OH• radicals participate in breaking the intramolecular bonds of the peptidoglycan, which may lead to the breakdown of the cell wall. The team of Tian et al. [25] studied the release of components from inside the bacterial cells by the action of PAW. The level of DNA/RNA leakage from cells was analyzed as a function of plasma operating time. It was observed that after 20 min of plasma activation, the DNA/RNA leakage rate increased by approx. 42% due to the destruction of the cell membrane integrity. Similar observations are made for the plasma treatment of yeast cells with *Saccharomyces cerevisiae* ATCC 4126. In case of these microorganisms, during multiplication, the cell cycle was arrested in the G1 phase, which was a consequence of DNA damage. Reactive oxygen species caused the activation of superoxide dismutases and catalase [50]. The key role of the hydroxyl radical in the elimination of microorganisms is also emphasized by Weiyuan et al. [51]. They investigated the effect of atmospheric pressure plasma treatment on *E. coli*. The process was effective in inactivating bacteria, and the cause of this effect was believed to be oxygen-containing reactive compounds that were able to destroy the C-C or C-H bonds present in the cell, and thus contribute to the degradation of organic compounds.

Hydrogen peroxide is one of the longest-lived reactive compounds in PAW and exhibits multifunctional activity in redox cell signaling pathways and oxidative stress [52]. The antimicrobial mechanism of H_2O_2 results from the generation of the intracellular hydroxyl radical OH• in the presence of transition metals. Furthermore, the interaction between H_2O_2 and the superoxide ion causes the formation of OH• radicals, which through the Fenton or Haber–Weiss reactions contribute to oxidative damage, stimulating the breakdown of the DNA double helix [53,54].

Additionally, singlet oxygen generated in PAW, due to its high activity, easily reacts with various biological molecules, including DNA and proteins [55–57]. Singlet oxygen can react with cysteine to contribute to the formation of R-cys-S-S-cys-R, which may result in cell interaction and aggregation. Davies [55] emphasizes that singlet oxygen can also selectively react with tyrosine, tryptophan, and histidine to form hydroperoxides that can inhibit enzyme activity. In the case of DNA, singlet oxygen can also oxidize guanine and induce cross-links between guanine and lysine, resulting in the formation of large complexes formed by genomic DNA [58].

Ozone dissolved in aqueous solutions is considered a strong antimicrobial oxidizing agent [18]. It has the highest oxidation-reduction potential, at the level of E_0 = 2.07 V, among other typical oxidants: hydrogen peroxide (E_0 = 1.77 V), chlorine (E_0 = 1.36 V), and chlorine dioxide (E_0 = 1.50 V) [59]. Reactions involving ozone are selective and proceed with participation to unsaturated aromatic and aliphatic compounds [41,60]. Ozone participates in the oxidation of sulfhydryl groups, which are quite abundant in enzymatic proteins of microorganisms, which explains the rapid inactivation of microorganisms and bacterial spores by ozone [61].

3.2. Role of Reactive Nitrogen Species

Among the reactive nitrogen species, formed in plasma activated water, an important role in the inactivation of microorganisms is played by the nitric oxide radical (NO•), nitric oxide (NO), nitrite (NO_2^-), nitrate (NO_3^-), and peroxynitrite (ONOO−). It is difficult to ascribe specific antimicrobial activities to individual molecular species. Reactive nitrogen species trigger a wide range of interacting mediator molecules in phagocytic microbial cells, making it difficult to assign specific antimicrobial effects to individual chemical molecules. The antimicrobial activity of RNS is presumed to be more complex than that of reactive oxygen species and depends on the local redox environment [62].

RNS can interact with numerous targets in a microbial cell, including protein ty-rosines, metal centers, thiols [62]. The presence of reactive forms of nitrogen can damage almost all classes of biomolecules: lipids, proteins, and DNA [63]. Nitric oxide (NO) as a signaling molecule can relatively easily penetrate into cells, causing the enhancement of intracellular RONS, damage to organelles and, consequently, cell apoptosis [64]. In the presence of oxidizing compounds in water, nitric oxide (NO) has a short lifetime, reacting to the formation of other RNS. NO can inhibit cell respiration, contributing to put microorganisms into a dormant state. It was observed, inter alia, in case of *Mycobacterium tuberculosis*. Moreover, it is believed that in the presence in PAW the H_2O_2, the inhibition of respiration by NO may exacerbate oxidative damage by promoting Fenton's reactions and reducing flavin [65,66].

In the case of NO• radical, Schapiro et al. [67] indicate that this radical and *S*-nitrosothiols, which contribute to nitrosative stress, may inhibit bacterial DNA replication. According to Lepoivre [68], the NO• radical can interact with tyrosyl radicals, which results in the inhibition of ribonucleotide reductase and indirectly affects the availability of precursors for the synthesis and repair of DNA.

Nitrite (NO_2^-), nitrate (NO_3^-), and peroxynitrite (ONOO−) are involved in the formation of acids, which reduces the pH of the water. Moreover, it is commonly believed that these acids have antimicrobial properties [69]. The antimicrobial activity of peroxynitrite (ONOO−) is due to its ability to diffuse through the cell wall and cause cell damage, e.g., by initiating lipid peroxidation. The peroxynitrous acid, conjugated with it, is also considered

a strong oxidant, showing the ability to react with biological molecules [70]. Peroxynitrile ions can also react with dissolved carbon dioxide to form ONO_2CO_2—which is subsequently transformed into the $\bullet CO_3$ radical with oxidizing properties. It is presumed to be able to oxidize several critical amino acids in proteins even in the presence of antioxidants that are normally present in biological fluids [71].

Many publications emphasize that reactive nitrogen species damage numerous components of the cell, including DNA, RNA, membrane components (lipids), and proteins. Aerobic microorganisms (yeasts, bacteria) naturally encountering RNS under aerobic conditions have developed a number of protective systems to help cells survive. Bacteria synthesize enzymes, or small proteins such as thioredoxin and glutaredoxin and other molecules, such as glutathione, neutralize RNS [31,72]. The production of enzymes, including catalase, peroxidase, and superoxide dismutase, allows for transforming harmful RNS in the cell, before they cause damage [73]. In *Saccharomyces* and *Candida* yeast cells, the counteracting of nitrosative stresses is based on the active detoxification of NO by flavohemoglobins, the antioxidant system for scavenging NO via GSH or trehalose and the up-regulation of repair systems to counteract the caused damage [74–76].

It is worth emphasizing the role of the *oxyR* or *soxS* genes in the cell's response to the action of PAW. The *SoxS* protein is a regulator controlling genes mainly responsible for the detoxification of peroxides and nitric oxides, while the *oxyR* gene is a regulator of transcriptional processes occurring during gene activation in response to oxidative stress. Therefore, mutants with the missing *SoxS* gene are sensitive to destruction by peroxides and nitrogen oxides, while bacteria with the missing *oxyR* gene are sensitive to reactive oxygen species [62,77].

In conclusion, it is worth paying attention to the fact that inhibition of microbial growth by PAW is related not only to the action of the above-mentioned radicals; it also occurs in the environment of ionized noble gases. It is a complex process, the effects of which depend on many elements.

Despite the complexity of the process of microbial inactivation by PAW, the latest research trends in this area indicate that it is possible to partially regulate the level of impact on microbes. The concentration of reactive oxygen and nitrogen species in PAW (including their ratio to one another) can be controlled by modifying the length of the plasma stream. The level of microbial inhibition by PAW can also be influenced indirectly by controlling and regulating the electrons temperature, which mainly determines the formation of RNS. The level of PAW interactions on cells is also determined by the size of the plasma–liquid interface [23,78].

4. The Role of Physiological Factors in the Inactivation of Microorganisms by PAW

When analyzing the effect of plasma-activated water on different species of microorganisms, it was observed that Gram-positive bacteria are more resistant to plasma than Gram-negative cells. This is probably partly due to the difference in the structure of the peptidoglycan (its much thicker layer) and the degree of its acetylation. In the case of direct treatment with cold plasma, this layer constitutes a kind of protective shield. In the operation of PAW, the role of the peptidoglycan layer may be reduced because the physical digestive effect is limited, and the antimicrobial effect is mainly based on the interactions of reactive oxygen and nitrogen species [79]. Smet et al. [80], by conducting research on the use of plasma-activated water on *Listeria monocytogenes* (Gram-positive) and *Salmonella typhimurium* (Gram-negative) cells, achieved a much better inactivation effect of the Gram-negative species. Inhibition was seen in both single colonies and biofilm. Souskova et al. [81], conducting studies involving fungi and bacteria, showed that the effectiveness of PAW inactivation of fungi is much lower than that of bacteria, mainly due to the more complex cellular structure of eukaryotes (the cell wall structure and specialized cellular organelles, such as mitochondria and ribosomes). The cell wall of fungi consists of chitin, which is more rigid than the peptidoglycan of bacterial cell walls.

Considering the influence of PAW on microbial cells from the point of view of their growth phase, it is assumed that bacterial cells in a phase of exponential growth may be more susceptible to inactivation compared to the stationary phase [41]. In *Escherichia coli* culture, significantly higher logarithmic cell reductions by PAW occurred in the exponential growth phase [82]. However, this was not confirmed by studies with *Salmonella enterica*—in the case of these microorganisms, the growth phase had no effect on the level of cell inactivation by PAW [83]. The authors suggest that the effects of PAW at different stages of growth may be different, depending on the species and factors important in the subsequent growth stages. This is especially true in case of bacterial biofilms, the characteristic feature of which is cell heterogeneity (e.g., differences in metabolic potential). This cellular heterogeneity significantly influences the differences in susceptibility to the effects of PAW [84].

5. The Use of Plasma-Activated Water in Inhibiting the Growth of Microorganisms

The properties of plasma-activated water, especially those related to the inactivation of microorganisms, make it more and more appreciated and used in medicine or food processing. Numerous scientific studies conducted in the last decade have shown that PAW inhibits the growth of bacteria, viruses and fungi, destroys cancer cells, allows for maintaining the quality of fruit and vegetables after harvest, and inactivates foodborne microbes on food [85–89].

In the field of medical science, plasma-activated water is tested for the effectiveness of sterilization. Dental and medical tools are constantly exposed to the action of various microorganisms during treatments, and they constitute a reservoir of pathogens, being a source of potential infection of patients. The possibility of disinfecting the device by means of simple washing seems to be much easier compared to the multiple exposures of the surfaces to the direct action of the plasma stream [35]. Plasma-activated water was used, among others, in the decontamination of dental unit waterline system tubes (DUWLs). Its effectiveness in inactivating of *Enterococcus faecalis* biofilms created in DUWL was analyzed [90]. For this purpose, the activation of the distilled water was carried out for 3 min using a continuous plasma jet of compressed air. Significant reduction in the number of viable cells was observed already after 1–3 min of plasma treatment. The 5-min process led to a complete reduction of microorganisms. Moreover, a 3-min contact of microorganisms with PAW gave a comparable effect as the use of common disinfectants—1% H_2O_2 solution or 10 mg/L NaOCl solution. Using plasma-activated water obtained by gliding electric discharges, sterilization of medical instruments made of stainless steel, and polyethylene was carried out [42]. After 30 min of exposure to PAW, a reduction in both single yeast colonies (approx. 3 log) and bacterial biofilms (approx. 5 log) was observed. An interesting path of PAW application is its use in the treatment of infectious diseases of the oral cavity [91]. Plasma-activated water is a rich source of reactive oxygen and nitrogen species (RONS), which play an important role in cancer therapies. Mahdikia et al. [92] studied the induction of apoptosis in melanoma cancer cells in-vitro. The source of the cold plasma was a helium (He) plasma stream, operating with a dissipation power of 0.75 W and 20 kHz. Test results confirmed that the application of cold atmospheric plasma (CAP) enables the achievement of a specific concentration of anti-cancer agents in water and induces apoptosis in melanoma cancer cells due to RONS via activating the caspase pathway. Plasma-activated water is also effective in inactivating viruses: rotaviruses, noroviruses, adenoviruses, astroviruses, and hepatitis A and E viruses [88]. Guo et al. [93] reported that PAW efficiently inactivated bacteriophages T4, U174, and MS2 in a time-dependent manner. DNA and protein analysis revealed that the reactive species generated in water by plasma damaged both nucleic acids and proteins. PAW after 30 min of contact could completely inactivate Newcastle disease virus (NDV) [94].

Many studies conducted in recent years show the effectiveness of PAW in the decontamination of food—both products of plant and animal origin [88]. Plasma-activated water was used, among others, in in the reduction of *Staphylococcus aureus* bacteria on the surface

of strawberries [26]. After 20 min of water activation with single electrode nonthermal APPJ, it reduced the bacteria count by about 3.4 log CFU/g. The use of PAW successfully reduced both bacteria and fungi from the surface of Chinese bayberries [95]. Bayberries were treated by PAW at different times (0.5, 2 or 5 min) and then stored for 8 days at 3 °C. The results of the experiment showed that all PAW variants reduced fruit spoilage by approx. 50% compared to the control sample, and the maximum reduction of microorganisms reached the level of approx. 1.1 log CFU/g.

PAW was applied on grapes, observing a reduction of yeast *Saccharomyces cerevisiae* on the level 0.38–0.53 log CFU/mL, without any deterioration in the quality of the grapes [96]. The water activated by two plasma jets was effective in reducing bacteria from the surface of tomatoes. The study reported more than 5 log reductions of *E. coli*, *L. monocytogenes*, and *S. typhimurium* [97]. PAW is also used for the preservation of fresh-cut fruits, such as pears [98], kiwifruits [99], and apples [100]. Liu et al. [100] showed that PAW is effective in inactivating microorganisms on the surface of fresh-cut apples, immersed in PAW for 5 min. The reduction level was 0.86 log CFU/g, 1.04 log CFU/g, and 0.64 log CFU/g, for *E. coli*, molds and yeast, respectively.

In the case of vegetables, plasma-activated water was used, among others, to minimize microorganisms on the surface of baby spinach leaves [101]. Washing in PAW reduced the bacteria on the surface of the spinach by about 1 log CFU/g. Microwave plasma-activated water is also effective for decontaminating fresh-cut lettuce from *Escherichia coli* K12, *Pseudomonas fluorescens* DSMZ, *Pseudomonas fluorescens* RIPAC, *Pseudomonas marginalis*, *Pseudomonas carotovorum*, and *Listeria innocua* [102]. Berardinelli et al. [103] demonstrated that treating fresh-cut radicchio and celery with PAW can effectively reduce *Listeria monocytogenes* and *E. coli* populations.

In the research, PAW was also tested on edible mushrooms, such as button mushrooms and shiitake mushrooms. It was shown that after the process of immersion of mushrooms in PAW and storage for one week at 20 °C, the number of fungi and bacteria on the surface decreased by 0.5 log and 1.5 log CFU/g, respectively [27].

Apart from plant products and fungi, plasma-activated water is used in the decontamination of animal products. Zhao et al. [104] used PAW in bacterial inactivation of fresh beef. From the surface of beef, they managed to reduce approx. 3.1 log CFU in conversion to gram of meet. The total number of aerobic bacteria in beef was reduced from 3.1 to 2.4 and 2.3 log CFU/g after water immersion using a non-thermal atmospheric pressure plasma jet [105]. The use of plasma treated water was also tested in chickens. The water treated by gliding arc plasma has been successful in a reduction of about 1.05 log CFU/g *P. deceptionensis* CM2 on chicken breast [106]. Royintarat et al. [107] analyzed the effectiveness of PAW in inactivating *Escherichia coli* and *Staphylococcus aureus* on chicken surfaces. PAW treatment for 60 min reduced *E. coli* K12 and *S. aureus* by 0.46 log CFU/mL and 0.33 log CFU/mL, respectively. PAW was also used to inactivate methicillin-resistant *S. aureus* (MRSA) and methicillin-susceptible *S. aureus* (MSSA) on cooked chicken breast. Chicken breasts soaked for 20 min in PAW showed a reduction of about 2.09 log CFU/g for MSSA and 2.29 log CFU/g for MRSA [108].

Plasma-activated water also effectively inactivates microorganisms on egg shells. It has been proven that the removal of bacteria by washing with PAW was three times higher than washing with traditional water. The 2-min PAW effect on the egg shell reduced *Salmonella enteritidis* by approx. 5.51 CFU/egg [109]. Using two plasma streams and application of more water, a 60 s treatment reduced the *S. enteritidis* population from 7.92 log CFU/egg to 2.84 CFU/egg [110].

PAW is also used in the partial decontamination of seafood, i.e., oysters, salmon, or shrimps. Solid state-activated plasma water was used in the preservation of fresh Metapenaeus ensis. Compared to traditional ice, PAW-ice showed a significant advantage in inhibiting the growth of microorganisms [111]. PAW-ice was also used in the preservation of fresh portions of salmon [112]. The level of *L. monocytogenes* on the surface of the salmon patches after treatment with PAW-ice and stored at 4 °C for 5 days was approximately

3.6 log CFU/mL compared to approximately 5.1 log CFU/mL for the controls. PAW-ice also reduced the number of *P. fluorescens* colonies on fresh mackerel fillets by about 0.4 log [113]. PAW application on grass carp was also effective. It was possible to reduce *S. typhimurium* and *L. monocytogenes* up to 1.44 and 1.21 log [114]. Research on the Yellow River carp fillets also showed that PAW is effective in the reduction of *Shewanella putrefaciens* bacteria—showing a decrease in the number of bacteria by 1.03 log CFU/g [115].

6. Conclusions

In recent years, plasma-activated water has received a lot of attention as a decontamination method. The unique physio-chemical properties of this water and its excellent biochemical and biological activities have attracted growing attention in academic and industrial communities. The article presents the fundamentals of PAW properties in relation to microorganisms. An attempt was made to determine the role of reactive oxygen and nitrogen species in the inactivation of microorganisms, also in the context of different phases of their growth. However, research in this area is limited. The review presents the latest application possibilities of PAW in reducing the amount of microorganisms in the field of medical sciences and foods sciences. In the perspective of further research involving PAW, the mechanisms of the antimicrobial action of water should be further elucidated, using technologies of proteomics, metabolomics, or transcriptomics. It seems interesting to analyze the positive aspects of increased oxygen or nitrogen content in PAW (water treatment with plasma in an atmosphere of oxygen or nitrogen) in the context of the growth and metabolic activity of beneficial microorganisms.

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