Review

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Plasma-activated water production and its application in agriculture

Dingmeng Guo,[a] Hongxia Liu,[a*] Lei Zhou,[b] Jinzhuo Xie[a] and Chi He[a]

Abstract

The use of plasma-activated water (PAW) treatment is a promising technology that has many advantages, such as high efficiency, flexibility, environmental safety, and no residue. Thus, PAW has been applied in the agriculture industry to increase agricultural production. The application of PAW technology in agricultural production should emphasize its systematic nature, controllability, and operability, making it practical. This review systematically illustrates the production of PAW and the factors influencing it. The application of PAW in agriculture and its mechanism are discussed, including the effect on seed germination, the promotion of plant growth, and the control of plant diseases and pests. The implications of PAW for agriculture production and some of the related challenges are discussed. This review provides a deeper understanding of the viability of PAW technology in agriculture production.

Keywords: plasma-activated water; agriculture; seed germination; plant growth; disease and pest control

INTRODUCTION

With the growth in the world population, the demand for agricultural products has increased significantly.[1] Nevertheless, there still exists a contradiction between the total demand for agricultural products and agricultural production.[2,3] Food and Agriculture Organization (FAO) statistics reveal that the yield of agricultural products such as rice, potatoes, and fresh vegetables in China in 2019 decreased compared to 2018.[4] Improving the output of agricultural products has become an urgent problem in agricultural production. At present, the traditional way to improve the output of agricultural products is by applying chemical fertilizers and pesticides. However, the abuse of chemical fertilizers and pesticides is becoming severe, and could destroy the agricultural ecosystem, cause point source or non-point source environmental pollution, and affect seriously the growth and development of crops.[5,6] To solve this problem, researchers have explored many new technologies. In recent years, the application of non-thermal plasma technology in agriculture has attracted more attention.

Plasma is the fourth state of matter, which is the aggregation of high-energy particles (electrons, ions, excited atoms, excited molecules, free radicals, etc.) with special chemical activity. It has super oxidation properties and can reduce the organic matter content. There is no selectivity in the reaction and no residue in the environment. Since the 1970s, cold atmospheric plasma technology has been applied gradually to seed germination, plant growth, sterilization insecticides, virus inhibition, agricultural product preservation, and pesticide residue degradation due to its fast, efficient and pollution-free characteristics.[7–10]

However, non-thermal plasma technology is not flexible enough to treat the plant surface uniformly, and its improper operation may damage the plant surface. Some scholars therefore exposed water to various forms of plasma discharge to generate plasma-activated water (PAW).[11] Compared with traditional plasma treatment technology, PAW has the virtues of flexibility and safety to ensure the effect of plasma treatment and to overcome the limitations of equipment and instruments, and to act directly on plants.[12] In this paper, we considered the generation of PAW and the factors influencing this. The application of PAW in agriculture was analyzed from the viewpoints of seeds germination, plant growth, disease and pest control, and the different mechanisms of action of PAW. Finally, the uses of PAW in agricultural development, and the challenges posed by it, are considered.

THE PHYSICAL AND CHEMICAL PROPERTIES OF PAW

Many studies on PAW indicated that the main active substances of PAW are reactive oxygen species (ROS) and reactive nitrogen species (RNS).[13] The main components of ROS include hydroxyl radicals, hydrogen peroxide, singlet oxygen, superoxide anions, and ozone, whereas RNS mainly includes nitrate, nitrite, peroxynitrite, nitric oxide radical, ammonia, and nitrogen.[14] Among them, the long-lived reactive species are hydrogen peroxide, nitrate, and nitrite. Figure 1 is a schematic diagram of PAW component formation, including the discharge area, gas phase, and reactive species formed inside the liquid.[15] The physical and chemical properties of water, such as conductivity, pH, and redox potential,

* Correspondence to: H Liu, Department of Environmental Science and Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, Shaanxi, P.R. China. E-mail: hxliu72@xjtu.edu.cn

a Department of Environmental Science and Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, P.R. China

b Jiangsu Tester Professional Testing Co., Ltd, Suqian, P.R. China

are affected by plasma activation. The PAW production process, as shown in Fig. 2, indicates the control factors that affect the properties of PAW in each process. We selected the discharge structure, activation method, activation time, storage time, and the working gas species to discuss these controlling factors.

Discharge structure

The discharge structure is a significant factor in producing plasma. The commonly used discharge structures to make plasma include dielectric barrier discharge, plasma jet, glow discharge, spark discharge, corona discharge, and gliding arc discharge (Fig. 3). The PAW produced by spark discharge and microwave discharge mainly contains nitrogen-based chemicals such as nitrates and nitrites. In contrast, the PAW produced by glow discharge and dielectric barrier discharge mostly contain hydrogen peroxide and nitrate. The main reason is that higher plasma temperature is conducive to the gas-phase formation with higher nitrogen dioxide density, resulting in higher nitrate concentration.[16,17] Hoeben *et al.*[18] analyzed the concentrations of nitrites, nitrates, and peroxides in deionized water activated by 150w hot arc plasma. As a result, the generating efficiency for nitrite, nitrate, and peroxide are 23 nmol $NO_2^-\cdot J^{-1}$, 9 nmol $NO_3^-\cdot J^{-1}$ and 2 nmol $H_2O_2\cdot J^{-1}$, respectively. Different discharge structures will form different reactive compositions, resulting in different physical and chemical properties of PAW. Sliding arc discharge will cause significant water acidification, whereas spark discharge will lead to a neutral or higher pH value.[19] Darmanin *et al.*[20] produced two different PAW types by plasma discharge on the surface of the anode side and the cathode side of the copper sheet. Anode side PAW is rich in nitrate, pointing that the amount of ionic conducting species is further than cathode side PAW which is rich in nitrite.

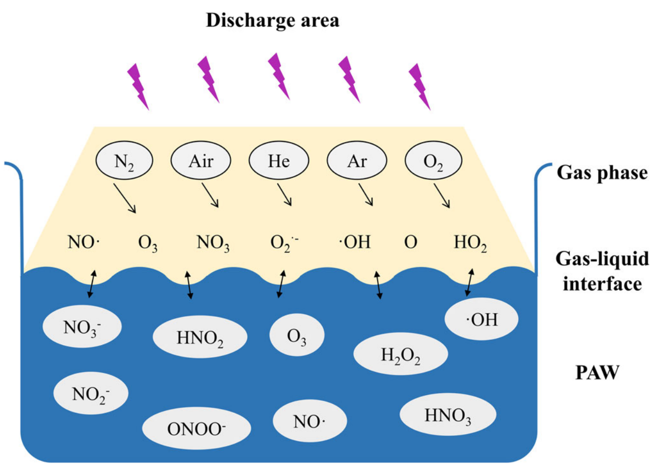

Figure 1. Schematic diagram of the formation of PAW components.

Finally, some researchers studied the optimization of the form of the reactor to obtain better performance from PAW. Nedybaliuk *et al.*[21] developed a plasma-liquid discharge system based on rotating sliding discharge of a single liquid electrode. Compared with other single-electrode rotary sliding discharge, it can be used to manufacture a long-life plasma generator due to its small electrode ablation. Wu *et al.*[22] strengthened the dissolution of ROS and RNS in the water by bonding plasma and microbubble technology. It could improve the concentrations of nitrite, nitrate, and ozone in this water at least twice as much as conventional PAW.

Activation method

The PAW pathways include plasma activation of water above (PAW-A) and below (PAW-B) water surface. Properties of PAW generated by different activation methods are also different. Plasma radiation initiate changes in water composition in PAW-A treatment at the plasma gas-water surface.[23] When discharged below the water surface, the water becomes part of the discharge response, making the reaction more fierce and producing more active species.

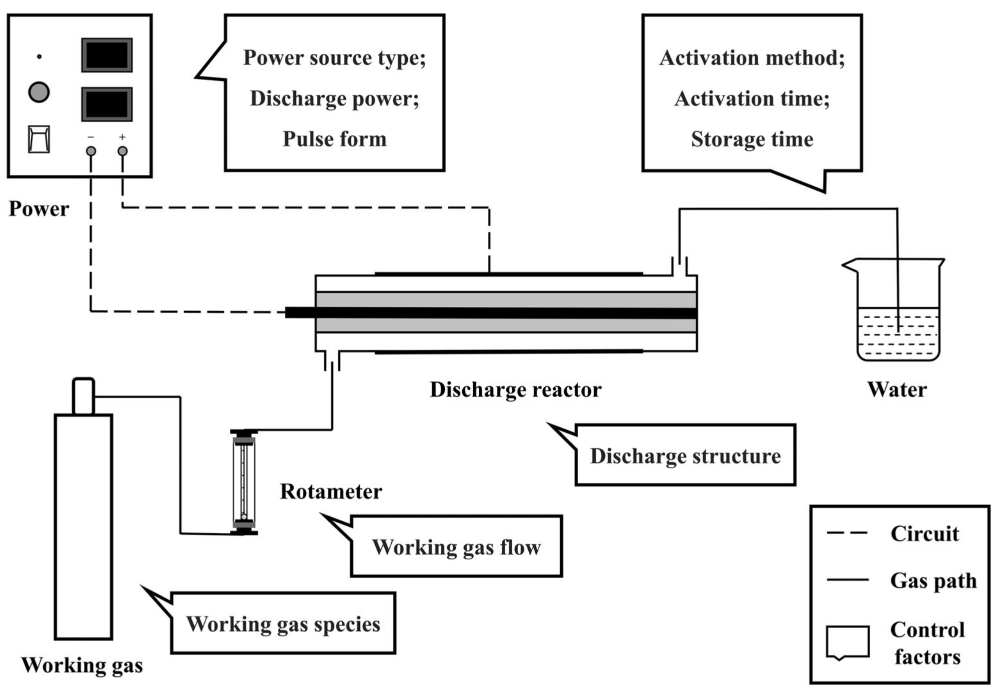

Figure 2. PAW production process and control factors.

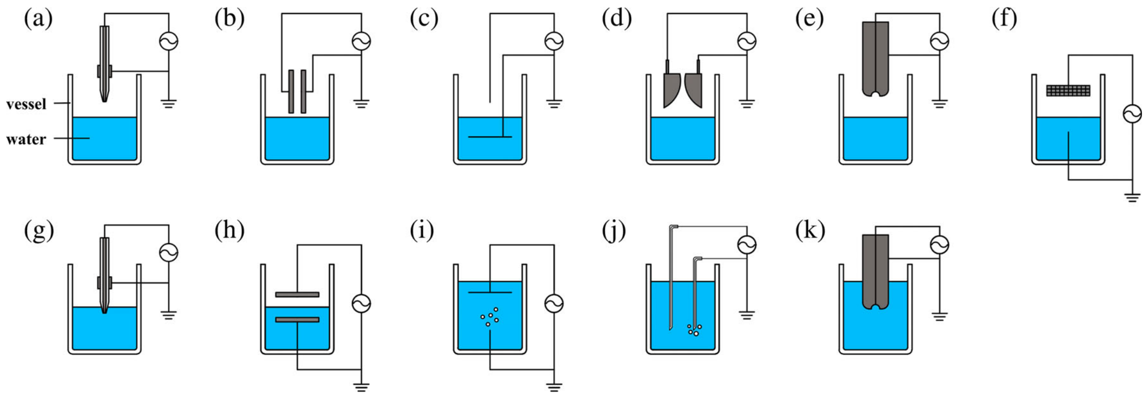

Figure 3. Various discharge structures activation of water above (a-f) and below (g-k) water surface are used for PAW generation. (a) plasma jet, (b) dielectric barrier discharge, (c) glow discharge, (d) gliding arc discharge, (e) spark discharge, (f) gas-phase pulsed electrical discharge, (g) plasma jet, (h) dielectric barrier discharge, (i) point-to-plate/mesh electrode discharge, (j) bubble discharge, (k) gliding arc discharge.

For PAW-A, the effects of mass transfer were crucial in the PAW system. Nevertheless, there are barriers to mass transfer from gas to water. Optimizing the reactor to mix gas and water violently can solve this problem. Some scholars used a peristaltic pump to refresh the page and increased the contact area between plasma and water.[24] Others pass plasma through the tube to the bottom of the reservoir to enhance contact time between plasma and water. Sysolyatina *et al.*[25] proposed a novel method to produce PAW, which was procured using a plasma producer by two-way mass transfer between moist air and fine water spray. Kovačević *et al.*[26] used precipitation membrane dielectric barrier discharge (DBD) to generate PAW. The principle is that the solution flows through the discharge area in a thin film state from the top, adding the contact region between solution and plasma, thus improving the mass transfer efficiency. Adjusting the plasma distance from the water surface can also selectively produce reactive oxygen and nitrogen species (RONS) in the water.[27]

For PAW-B, the oxygen content in water is higher than that in the air at constant volume. Therefore, PAW-B generates more oxygen-containing groups after the impact of plasma reactants and water and is more likely to turn out ROS and free electrons.[28] Liu *et al.*[24] compared the PAW components when water was used as a positive pole and water as a negative pole and reported that a water cathode performed much better than a water anode in producing hydrogen peroxide past plasma water interactions. When water acts as the cathode, the hydrogen peroxide was combined with deliquesced hydroxyl radicals. The dissolution of gaseous hydrogen peroxide had no noticeable effect on the concentration of hydrogen peroxide.[29] When water acts as the anode, the low hydrogen peroxide productivity in this system was due to quenching the deliquesced hydroxyl radicals through aqueous electrons. Alkalization in the plasma directly influenced the water zone.[30] Besides, energy expenditure for activating water by plasma radiation is less than producing the plasma.[31]

Activation time

Activation time refers to the time for the plasma to activate the water. In the current study, the activation time is mostly 5–30 min. An increase in the activation time will lead to more plasma in contact with the water, thus producing more RONS. Furthermore, the activation time will affect the physical and chemical properties of PAW.[32] Laurita *et al.*[33] found that longer treatment times led to a greater concentration of nitrate and hydrogen peroxide. But with the extension of treatment time, nitrite in PAW was unstable in an acid environment ($pH < 3.5$) and showed a downward trend.[34] Ma *et al.*[35] reported that the electrical conductivity, temperature, and oxidation–reduction potential (ORP) of PAW increased over the plasma activation time. Still, the pH of PAW dropped during the first 10 min activation and reached a steady-state of around 3 after 20 min activation. Kucerova *et al.*[36] discovered that, due to a natural hydrocarbon buffer system, the pH value of plasma-activated tap water (PATW) remains quite stable (pH 7.5). The change is very mild with the activation time of tap water. Park *et al.*[19] presented the results of water analysis after treatment with a transfer arc. The pH value increased by 30 s after treatment and decreased steadily with the passage of treatment time.

Storage time

As time goes by, the properties of the PAW will also change. Prolonged storage time will influence the content of RONS in PAW. Zhao *et al.*[37] used a 15 kV atmospheric cold plasma jet for 5 min to produce PAW. The concentration of hydrogen peroxide decreased from 16.25 $\mu mol \cdot L^{-1}$ to 3.74 $\mu mol \cdot L^{-1}$ after 48 h storage. In the process of cold storage, the content of nitrite decreased. After treatment, nitrite was 17.28 $\mu mol \cdot L^{-1}$ immediately, 13.61 $\mu mol \cdot L^{-1}$ after 24 h, and 11.08 $\mu mol \cdot L^{-1}$ after 48 h. The redox potential of treated water is 553 ± 5 mV. From day 4 to day 9, the potential increased to 630 ± 10 mV. Andreev *et al.*[38] prepared PAW using electrode-microwave discharge plasma and found that the hydrogen peroxide content was 3×10^{-3} mol L^{-1}, which could be stable for more than 7 days. Vlad *et al.*[16] assessed the time evolution of the PAW and proved that properties of the PAW were steady for more than 21 days. Moreover, Kutasi *et al.*[39] indicated that wave microwave discharge can change the recombination pathway of hydrogen peroxide and prolong the storage time of the nitrite radical.

The working gas species

Different working gases lead to different kinds and concentrations of reactive species and electrons in the plasma, and the physicochemical properties of PAW are also different. Figure 4 showed the effects of working gas on the formation of major species in water. Above all, in the case of helium or oxygen discharge, with the extension of plasma treatment time, the pH value shows an alkaline condition. Besides, in the case of nitrogen and air, the reactive nitrogen oxide formed by nitrogen and oxygen reaction

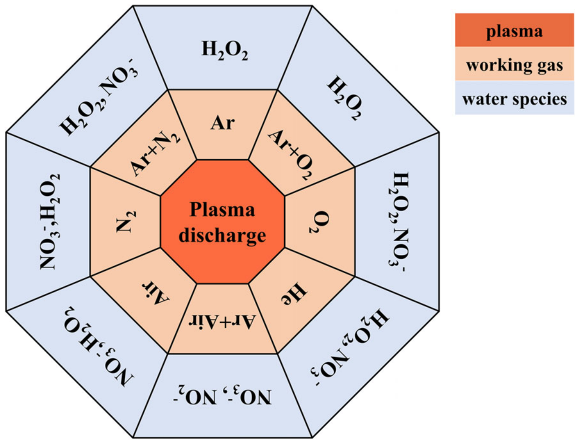

Figure 4. Effects of working gas on formation of major species in water.

during discharge interacts with water, resulting in the activated water's acidic tendency.[40] The RNS in activated water comes from the dissolution of nitrogen-containing substances. The RNS content is therefore higher when air and nitrogen are used as the working gas while working gas oxygen and argon are conducive to the formation of ROS, such as hydrogen peroxide. Zhang *et al.*[41] compared the concentration of hydroxyl radical in PAW produced by the argon, nitrogen, air, and oxygen as working gas. The results indicated that when the activation time is 10 min, the concentration of hydroxyl radical oxygen-PAW and air-PAW was 0.8906 and 1.0633 mmol·L^{-1}, respectively. Moreover, when the argon was mixed with 1% air or nitrogen as working gas, the nitrate and nitrite content in PAW increased sharply, while the pH and content of hydrogen peroxide decreased. Thus, it is clear that the existence of a nitrogen atom in the working gas is essential for the generation of nitrate and nitrite.[42]

Furthermore, the working gas flow rate also affects PAW properties. When the working gas flow rate is low, the gas stays in the plasma discharge area for a long time, and the plasma density is high. When the gas flow rate is high, more plasma will be produced per unit time. Uchida *et al.*[43] demonstrated the remarkable effect of gas velocity on the emission characteristics near the water surface. The area of plasma irradiation on the water surface increases with an increase in gas velocity, which leads to a rise in the total number of charged particles transported to water.

THE APPLICATION OF PAW IN AGRICULTURE

PAW affects seeds germination

Many publications have provided exhaustive reports about the use of PAW on seeds to increase the germination rate, and have indicated that PAW is highly efficient in seed germination. All of this research were shown in Table 1. For instance, Naumova *et al.*[50] produced PAW to treat rye seeds: PAW treatment of rye seeds for 5 min increased the germination rate by 50%. Kucerova *et al.*[36] applied spark discharge generating plasma-activated deionized water (PADW) and PATW to dispose wheat seeds. The germination rate increased by 26% and 103%, respectively. Judee *et al.*[45] prepared PATW to treat lentil seeds, and the results showed that the maximum germination rate of lentil seeds treated by PATW was up to 99%. Chiara *et al.*[47] also found that PAW could promote the germination of soybean seeds, and the germination rate could reach 100% on the third day. Furthermore, Sajib *et al.*[44] investigated the impact of PAW on the black gram and revealed that the germination rate of black gram seeds increased significantly, by 10–15%. Andreev *et al.*[38] found that PAW could improve radish and other crop seeds' drought resistance and improve the seed germination rate under drought conditions. This is consistent with the result obtained by Loganathan *et al.*,[48] and the germination rate of radish seeds reached 100%.

According to literature reports, the mechanism of PAW treatment on seed germination promotion mainly includes the following three aspects. First, the ROS induced by PAW might cause seed coat cracking and make the seed coat thin, which improves its assimilation of water and nutrients, resulting in enhanced germination rate, germination index, and vigor index.[51] Chen *et al.*[52] reported that hydrogen peroxide in the ROS helps to crack hard seeds, letting them absorb moisture. Second, RNS in PAW can be used as the nutrient for seed germination. As a nutrient, nitrate was taken up by the seed, reduced by nitrate reductase to become nitrite, and then further reduced by nitrite reductase to become the ammonium ion, last incorporated into amino acids.[53] Finally, reactive oxygen and nitrogen species (RONS), especially hydrogen peroxide and nitrate in the PAW, may act as the signaling molecule to stimulate seed germination, involving changes at proteomic, transcriptomic, and hormonal levels.[54] Abscisic acid (ABA) is a plant hormone that inhibits growth and plays an essential role in seed dormancy.[55] The RONS can activate the mitogen-activated protein kinase (MAPK) cascade mechanism, leading to the expression of the PsMAPK2 gene, affecting the level of plant hormones, resulting in decreased ABA and jasmonic acid (JA) content in seeds, thereby promoting seed germination.[56] Hydrogen peroxide can also impair ABA's transport and induce the reduction of ABA by directly or indirectly acting on the embryo. Protein carbonylation is a useful biomarker of oxidative stress and can reduce seed dormancy. Hydrogen peroxide can induce carbonylation of seed storage proteins and stimulate seed germination. Some glycolytic enzymes stimulate the pentose phosphate pathway (PPP) during storage protein carbonylation. The PPP activation can provide nicotinamide adenine dinucleotide phosphate (NADPH) to the thioredoxin system, which promotes seed germination.[57] For instance, nitric oxide can diffuse through cell membranes that may participate in the ABA catabolism or GA biosynthesis processes, thereby enhancing the germination of seeds.[58] But the H^+ ions harm the germination of seeds.[59]

PAW promotes plants growth

Plasma-activated water can also improve plant growth. This research is shown in Table 2. Maniruzzaman *et al.*[60] used air as the working gas to produce PAW and treated the wheat seedlings with pot culture for 28 days; the biomass of the seedlings was 87% higher than the control group. Beyond that, PAW can also promote the growth of vegetable and fruit plants. Iwata *et al.*[66] treated radish buds with PAW, which doubled their length. Takahata *et al.*[62] also reported that the height of radish buds increased by 53% by PAW treatment. Takaki *et al.*[65] prepared PAW to improve cabbages' growth rate. The results showed that dry weight of cabbages treated with PAW-10 (PAW with activation time of 10 min) and PAW-20 (PAW with activation time of 20 min) increased by 0.044 g and 0.076 g, respectively, 3.9 times and 6.6 times that of the control group. Lindsay *et al.*[61] used PAW prepared by coaxial glow discharge under atmospheric pressure to irrigate marigold, tomato, and carrot branches, and its mass

Table 1. Main research results of the application of PAW to promote seed germination

Seed	Plasma devices	Voltage/ power	Working gas	Activation time (min mL^{-1})	Mode of activation	Storage time	Treatment time	Germination rate	Ref.
Wheat	Spark discharge	6 W	Air	0.5	a	—	Soak 3 h	100%	36
Black gram	High voltage discharge	6 W	O_2	0.12	b	30 min	Soak 24 h	Increased 10–15%	44
Lentil	DBD	12 kV	Air	0.3	a	—	Soak 3 h	99%	45
Mung bean	Plasma jet	30 mA	N_2, He, O_2, Air	0.2	a	—	20 mL per day	90.33–97.33%	46
Soybean	DBD	80 kV	Air	0.25	a	—	2 mL per day	100%	47
Radish	DBD	40 kV	Air	0.12	a	—	1 mL per day	Increased 60%	48
Rapeseed	Arc discharge	30 W	Ar,O_2	0.2	b	30 min	Soak 4 days	Increased 16–18%	49

a: Plasma activation of water above water surface.
b: Plasma activation of water below water surface.

increased by 1.7–2.2 times. Zhang *et al.*[67] also discovered that PAW could significantly improve the germination rate of lentils and promote the stem of lentils' growth better than chemical fertilizer.

The mechanism of PAW for plant growth is considered a synergistic effect many factors. First, nitrate is of great essential content for nitrogen in temperate soils.[68] Hence, the nitrate in the PAW is one of the chief elements for accelerating plant growth.[65] The nitrate-nitrogen can be absorbed from roots and increase the growth of plants.[64] After nitrate-nitrogen enters plant cells, it is reduced step by step by nitrate reductase and nitrite reductase. Eventually, this generates ammonium ions, which enter amino acids to form nutrients to promote plant growth.[56] Besides, the expense of bicarbonate ions during the plasma-activated process also boosts plants' growth.[45] Second, ROS, especially hydrogen peroxide, plays a vital role as a signal molecule in enhancing plant tolerance mechanisms, reducing oxidative plant damage, and maintaining standard plant physiological and metabolic activities. Iseri *et al.*[69] found that the application of low-concentration hydrogen peroxide from external sources can enhance ascorbate peroxidase (APX) activity and proline accumulation in tomato seedlings. That can help maintain osmotic regulation and membrane stability, improve the antioxidant status of tomatoes, and significantly enhance oxidative stress. Stimulus reaction makes tomato seedlings grow better under cold pressure. Ascorbate peroxidase is a plant's non-enzymatic defense system, which can react directly with active oxygen in plant cells to stimulate oxidative defense. Malonaldehyde (MDA) is a product of membrane peroxidation, and it has been taken as a direct indicator of lipid peroxidation and membrane damage.[70] Sayed *et al.*[71] also reported that hydrogen peroxide treatment could reduce hydrogen peroxide and MDA content in pea seedlings through the accumulation of proline and ascorbic acid to reduce the negative effects of cadmium on the growth of pea. Finally, RONS can promote plant growth by affecting plant hormone levels and gene expressions, such as indole acetic acid (IAA) and ABA. Increasing plant cell elongation is the primary physiological function of IAA. The content of IAA in mung bean sprouts increased significantly after plasma treatment.[46] Abscisic acid is a hormone that inhibits plant growth and inhibits cell division and elongation. As explained in the previous section, RONS activates some genes' expression through the MAPK cascade and reduces ABA content, thereby promoting plant growth. Moreover, hydrogen peroxide is significant for accelerating the growth of plants. When hydrogen peroxide concentration was lower than 0.07%, the treatment was very beneficial to plant growth. When the concentration of hydrogen peroxide increased sharply to 0.1% and 0.3%, plants' growth was restrained.[72] In brief, hydrogen peroxide can promote plant growth by inhibiting the growth of undeveloped leaves, reducing bud shedding, and promoting the expression of the flower-related genes.[73]

PAW controls diseases and pests

The research on PAW control of diseases and insect pests is sporadic and experimental. Guo *et al.*[74] treated grapes with PAW prepared by jet corona discharge and found that PAW could reduce the surface yeast 0.51 ± 0.11 log CFU·ml^{-1}. In the meantime, PAW completely inhibited the mycelium growth of *Fusarium graminearum* for 24–36 h. It reduced the germination rate of its conidia, which could be used to control wheat scab.[75] Bertaccini *et al.*[76] reported that PAW could be used as a resistance inducer for plants to induce tomato plants' defense against *Xanthomonas campestris* pv. *vesicatoria* (*Xv*) and grape plants against phytoplasma. On this basis, Perez *et al.*[77] further studied the relative ability of PAW to protect tomato plants against leaf spot disease and reported that the disease severity could be lower when PAW was applied 1 and 24 h before the pathogen inoculation, providing relative protection of 61% and 51%, respectively. The phenylalanine ammonia-lyase (*pal*) gene transcription abundance for tomato plants treated with PAW and then inoculated with *Xv* was significantly greater than that for plants only inoculated with the pathogen. These consequences were bespoke that the *pal* gene may be a major factor in response to PAW stimulation.[78] Adhikari *et al.*[79] illustrated that irrigation of tomato seedlings with PAW resulted in better growth morphology (compared to longer stem and root), oxidation and defense gene expression. Sroykaew *et al.*[80] contrasted line-to-line discharge and plasma-jet discharge to generate PAW in terms of their effectiveness in treating sugarcane leaf disease. The results showed that the line-to-line discharge treatment reduced the incidence of

Table 2. Main research results of the application of PAW to promote plant growth

Plant	Plasma devices	Voltage/ power	Working gas	Activation time (min mL^{-1})	Mode of activation	Storage time	Treatment mode	Results	Ref.
Wheat	Spark discharge	6 W	Air	0.5	a	—	Cultivated for 28 days	The average length increased 6–7%	36
	Point-to-plate/mesh electrode discharge	18 kV	Ar, Air	0.04	b	—	2.5 mL PAW per day	The biomass of shoot increased 17–33%	60
Black gram	High voltage discharge	6 W	O_2	0.24	b	30 min	Cultivated for 7 days	The dry weights of roots treated with PAW-12 provide the highest one of 7.10 mg	44
Lentil	DBD	12 kV	Air	0.3	a	—	100 mL PAW per day	The length increased 28%	45
Mung bean	Plasma jet	30 mA	N_2, He, O_2, Air	0.2	a	—	20 mL PAW per day	Total plant length increased 0.92–5.96 cm (Control 6.05 cm)	46
Soybean	DBD	80 kV	Air	0.05	a	—	5 mL PAW per day	The length increased 75%	47
Radish	DBD	40 kV	Air	0.12	a	—	5 mL PAW per day	The length increased 45%	48
	Atmospheric glow discharge	420 W	Air	≈0.04	a	2 days	Cultivated for 2 weeks	Shoot masses increased 1.7–2.2 times	61
	DBD	93 W	Air	0.06	b	—	Cultivated for 28 days	Dry weight increased 4.0 times	62
	DBD	3.54–9.64 W	Ar, N_2, He, O_2, Air	0.1	a	1 h	Cultivated for 3 days	The maximum of normalized length increased 1.04–1.62 times	63
	DBD	3.54–9.64 W	Ar, N_2, He, O_2, Air	0.1	a	1 days	Cultivated for 3 days	The maximum of normalized length increased 1.08–1.52 times	
Arabidopsis thaliana	Plasma jet	10 kV	He	0.5	b	—	10-30 mL PAW per week	Diameter of the rosette increased 1 cm	64
Rapeseed	Arc discharge	30 W	O_2, Ar	0.2	b	30 min	Cultivated for 4 days	Shoot height increased 2–2.1 cm	49
Chinese cabbage	DBD	30 kV	Air	0.04–0.08	b	—	Cultivated for 28 days	Dry weight increased 0.044–0.076 g	65
Marigold	Atmospheric glow discharge	420 W	Air	≈0.04	a	2 days	Cultivated for 2 weeks	Shoot masses 1.7–2.2 times larger than controls	61
Tomato	Atmospheric glow discharge	420 W	Air	≈0.04	a	2 days	Cultivated for 2 weeks	Shoot masses 1.7–2.2 times larger than controls	
Spinach	DBD	93 W	Air	0.12	b	—	Cultivated for 28 days	Dry weight correspond to 5.8 times that of the control group.	62
Strawberry	DBD	93 W	Air	0.12	b	—	Cultivated for 63 days	Dry weight correspond to 1.6 times that of the control group.	

a: Plasma activation of water above water surface.
b: Plasma activation of water below water surface.

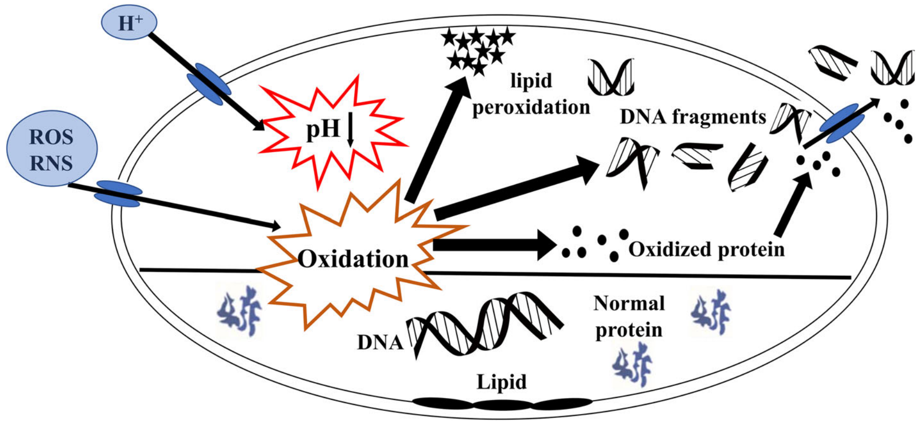

Figure 5. Schematic diagram of PAW killing pathogenic bacteria.

disease by 50%, and the plasma jet discharge treatment reduced the incidence of disease by 40%. In terms of pest control, Sun *et al.*[81] invented a liquid fertilizer containing 60% PAW and revealed that it could reduce grape insect pests.

Control of PAW for plant diseases and insect pests can mainly occur in two ways. The PAW can protect plants from pests and diseases by killing pathogenic bacteria on the plants' surface.[82] Figure 5 is a schematic diagram of PAW killing pathogenic bacteria. The PAW contains RON and ROS, which can enter bacterial cells through the instantaneous pores in the active transport cell membrane. The RNS and ROS in the cell can oxidize DNA, protein, and lipids, break DNA, break down proteins, and trigger lipid peroxidation, thereby causing the contents to flow out of the bacteria and die.[83] In RNS and ROS, ozone and peroxynitrite dominate the sterilization matrix.[84–87] Many researchers also speculate that the acidity and active substances in PAW are interrelated. The lower the pH, the easier the bacteria will die. First, the presence of hydrogen ions reduces the resistance of bacteria to acidic environments.[35] The ROS and RNS will react with the lipids and carbohydrates of DNA proteins in cells, lower the pH level of cells, and cause physiological dysfunction and cell death. Besides, PAW can serve as a resistance inducer for plants, triggering their defenses against pests and diseases. Hydrogen peroxide and nitric oxide in PAW both induce the expression of pathogenesis-related (PR) proteins, antioxidant enzyme activity, salicylic acid (SA), and JA pathway enzymes via MAPK signaling pathways; these defense proteins and phytohormones strengthen the plant pathogen defense pathway.[63]

CONCLUSION AND FUTURE PERSPECTIVES

The unique physicochemical properties of PAW and its unusual biochemical activities are attracting increasing attention in academic and agriculture communities. This review summarizes the PAW way of production and describes how the application of PAW promotes seed germination, affecting plant growth, and prevents diseases and insect pests. In the agricultural field, research into the application of PAW so far has faced many challenges: (i) Existing research into the properties of PAW is insufficient – there has been a lack of comprehensive quantitative analysis and research on the change of PAW properties with storage time; (ii) most of the mechanisms are concentrated in long-living active species such as hydrogen peroxide, nitrates, and nitrites, and there is a lack of research on the effects of other active substances; and (iii) the research direction of literature mostly focuses on seed germination and the plant growth stage, while there is less attention to disease and pest control research.

Future research directions mainly focus on the following aspects:

(1) The conditions of PAW production should be optimized to make the PAW more controllable, which includes improving the PAW production equipment and the search for ways to control the physical and chemical properties of the PAW. For example, the axial magnetic field concentration of the plasma can be found as a tool for the axial manipulation of the plasma jet. The chemical composition of PAW will also change with time, so it is important to explore the physical and chemical properties change trend in actual production.
(2) Many liquids such as phosphate buffer saline, ionic liquids, and hydrogen peroxide have also been activated by plasma to obtain plasma-activated liquids with more stable properties, stronger reaction, and better effect. It is indispensable to research the properties of different media and liquid, to select the appropriate liquid type according to the target and the desired impact in practical applications.
(3) At present, studies on the control of diseases and pests with PAW are in the sporadic and scattered experimental stage. However, this application is essential for the agricultural industry. We should therefore pay more attention to the mechanism of the PAW in diseases and pests control, and combine the findings with the other two applications. It has important scientific significance and application prospects in the agricultural field to find the optimal condition or interval.

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