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COMPREHENSIVE REVIEW

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Recent advances in activated water systems for the postharvest management of quality and safety of fresh fruits and vegetables

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Abstract

Over the last three decades, decontamination management of fresh fruits and vegetables (FFVs) in the packhouses and along the supply chains has been heavily dependent on chemical-based wash. This has resulted in the emergence of resistant foodborne pathogens and often the deposition of disinfectant byproducts on FFVs, rendering them unacceptable to consumers. The management of foodborne pathogens, microbial contaminants, and quality of FFVs are a major concern for the horticultural industries and public health. Activated water systems (AWS), such as electrolyzed water, plasma-activated water, and micro–nano bubbles, have gained significant attention from researchers over the last decade due to their nonthermal and nontoxic mode of action for microbial inactivation and preservation of FFVs quality. The aim of this review is to provide a comprehensive summary of recent progress on the application of AWS and their effects on quality attributes and microbial safety of FFVs. An overview of the different types of AWS and their properties is provided. Furthermore, the review highlights the chemistry behind generation of reactive species and the impact of AWS on the quality attributes of FFVs and on the inactivation/reduction of spoilage and pathogenic microbes (in vivo or in vitro). The mechanisms of action of microorganism inactivation are discussed. Finally, this work highlights challenges and limitations for commercialization and safety and regulation issues of AWS. The synergistic prospect on combining AWS for maximum microorganism inactivation effectiveness is also considered. AWS offers a potential alternative as nonchemical interventions to maintain quality attributes, inactivate spoilage and pathogenic microorganisms, and extend the shelf-life for FFVs.

KEYWORDS
electrolyzed water, food quality and safety, fruits and vegetables, micro–nano bubbles, plasma activated water

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1 | INTRODUCTION

Fresh fruits and vegetables (FFVs) consumption improves human health due to their essential vitamins, minerals, and plant chemicals. Nevertheless, FFVs are susceptible to rapid senescence, microbial contamination, and decay along the postharvest supply chain (Fan, 2021). Therefore, postharvest washing (PW) is an important practice during processing and storage of FFVs. PW ensures safety of FFVs by removing residual soil, metals, pesticides, and microorganisms (Chinchkar et al., 2022). For fresh cut FFVs, it is important to rewash after cutting to clean/remove the exudates from shredded tissues, which alleviates microbial contamination and quality deterioration. According to Kamarudin et al. (2018), washing with contaminated water will add foodborne pathogens to the FFVs, resulting in varying degrees of human illnesses (Aiyedun et al., 2021).

Commonly, a chlorine-based solution (sodium or calcium hypochlorite) is used for washing FFVs (Chinchkar et al., 2022). However, studies have demonstrated that chlorine is ineffective against spores and viruses (Gerba et al., 2002). The effectiveness of chlorine is influenced by pH, temperature, FFVs type, and initial microflora population (Chinchkar et al., 2022). Additionally, FFVs washed with 100–200 mg L^{-1} of chlorine are rejected by European markets because of health and environmental concerns (Deng et al., 2020). On the other hand, the United States Food and Drug Administration imposed a maximum residue limit of 0.2% of mixing chlorine in water and cleaning FFVs. Thus, chlorine for washing of FFVs (50–200 mg L^{-1}) for 1–2 min is recommended (Deng et al., 2020). Therefore, based on the disadvantages of chlorine-based solutions, chlorine solutions must be substituted/replaced with eco-friendly, nonhazardous, and sustainable PW techniques.

Activated water systems (AWS) have become of interest in recent times as alternatives PW techniques to sanitize FFVs and for quality management (Wang et al., 2022). Among those AWS, electrolyzed water (EW), plasma-activated water (PAW), and micro–nano bubbles (MNBs) have demonstrated excellent potential for microbial inactivation, removing pesticide residues, and prolonging shelf-life of FFVs during processing (Li, Liu et al., 2023; Liu, Yu, et al., 2021; Liu, Zhang, et al., 2021; Liu, Wang, et al., 2021; Shiroodi et al., 2021; Wang et al., 2022,). Moreover, AWS presents a green prospective for a wide range of biotechnology applications with minimal effect on composition, scent, and flavor of FFVs (Herianto et al., 2021; Sun, Chen, et al., 2022; Sun, Jiang, et al., 2022). The antimicrobial efficacy of the abovementioned AWS has been reported. EW was tested on fresh cut "Tommy Atkins" mangoes; the treatment maintained the mold and yeasts population below 10 CFU g^{-1} and complete elimination of *Salmonella* spp. up to the 6th day of storage (Lopes et al., 2021). Around 6 log CFU/g reduction in *Escherichia coli* populations was observed in PAW treatment (Perinban et al., 2022), and populations of *E. coli* and *Salmonella* on coriander, peppermint, asparagus, okra, ginger, and lemongrass were decreased by more than 1 log reduction after washing with MNB (Mahakarnchanakul et al., 2015). Furthermore, various studies demonstrated the effects of AWS to maintain the quality of melons (Le Nguyen et al., 2019), cherry tomato (Kasih et al., 2022), and carambola fruit (Zhang et al., 2023).

Most review articles related to the application of AWS in FFVs have mostly focused on the specific technology with emphasis on their basic principles, microbial inactivation and safety, and biochemical processes in FFVs (Foudas et al., 2023; Lu et al., 2022; Phan et al., 2021; Rebezov et al., 2022; Soni et al., 2021; Shan et al., 2022; Xiang et al., 2022; Zhang, Wang et al., 2023). Similarly, Heng et al. (2022) investigated the synergistic application of acidic EW and PAW against bacterial suspension (*E. coli*) biofilms (*Bacillus subtilis*). It was demonstrated that the plasma-activated acidic electrolyzed water (PA-AEW) was significantly efficient as a fast disinfectant. For instances, treatment with PA-AEW for 10 s resulted in killing logarithm (KL) of 2.33 $\log_{10}$ CFU mL^{-1} against *B. subtilis* suspension, which was significantly higher than acidic EW and PAW with KL of 0.58 and 0.98 $\log_{10}$ CFU mL^{-1}, respectively ($p < .01$). The strong disinfectant effect could be attributed by the interaction between reactive chlorine species and reactive oxygen and nitrogen species in PA-AEW. Wang et al. (2022) provided a comprehensive review on the impacts of EW and PAW on the development and effects on the chemical compositions, microbiological safety, and postharvest quality of sprouts. The authors established that EW was effective as a powerful tool in developing functional sprouts, whereas PAW was positioned as a potential pretreatment with the capability of improving seed germination (12%) and seedling length sprout yield (growth/seed germination) and controlling associated foodborne microorganisms (Ahmed et al., 2018). Nonetheless, there are no comprehensive reviews focused on the application of all AWS and their impacts on whole and fresh cut fruit and vegetables. To date and based on literature search, no review has explored the comprehensive and comparative study on the application of these functionalized waters EW, PAW, and MNBs in terms of their: (i) possible microbial inactivation mechanisms, particularly that of MNB is poorly understood, (ii) impact on the physical and biochemical quality attributes, and (iii) enhancement of bioactive compounds of FFVs. Therefore, this article provides a comprehensive overview on the generation of AWS (EW, PAW, and MNB). The applications of these AWS and their impacts on physiological

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activities, physical and biochemical, and bioactive compounds of FFVs are discussed. Furthermore, the mechanism of actions of these AWS in the inactivation of microorganisms and their antimicrobial efficacy is provided. This review highlights other emerging AWS such as the plasma bubble activated water and the hydrogen-rich water. The aim of this work is to advocate to all role players, including packhouse managers, policymakers, and academics, for a paradigm shift from chlorine-based pretreatments to the application of these AWS for washing fresh fruit and vegetables.

2 | ACTIVATED WATER SYSTEMS: AN OVERVIEW

Over the last decade, there have been numerous advancements in the application of AWS for the disinfection of food contact surfaces and surfaces of fresh and ready-to-eat FFVs. This article takes into consideration that there are extensive individual reports/articles available on each of these AWS, this includes on EW (Zhao, Li, et al., 2021; Li, Jia, et al., 2023; Yu et al., 2023;), on PAW (Cheng et al., 2023; Wang et al., 2023; Zhang et al., 2023), and MNB (Shi et al., 2023; Shan et al., 2023).

2.1 | Electrolyzed water

EW is produced by electrolysis of dilute salt solution in an electrolysis chamber consisting of a diaphragm that separates the anode and cathode (Rahman et al., 2016). As shown in Figure 1, EW can be classified as acidic (AEW), alkaline (ALEW), neutral (NEW), slightly acidic (SAEW), and slightly alkaline (SALEW), depending on the production conditions, physicochemical properties (pH, oxidation reduction potential (ORP), available chlorine concentration (ACC), electrolyte solution, and the devices used) (Abadias et al., 2008; Issa-Zacharia et al., 2010; Rahman et al., 2010; Rao, Xue et al., 2022). At the anode side, AEW is produced with hypochlorous acid (HOCl) and hypochlorite ion (OCl^-). The strong sanitization properties, deodorizing, antimicrobial efficiency, and FFV preservation are the synergistic effects of low pH, high ORP, and ACC ranging from 20 to 60 mg L^{-1} (Rebezov et al., 2022). Although higher antimicrobial efficacy of AEW is important for FFVs sanitization, undesirable changes in quality and nutritive properties caused by AEW have been reported (Chen et al., 2020). In addition, the acidic pH of AEW increases susceptibility of metal surfaces to corrosion. SAEW is extensively used in sanitization due to its high efficiency on a broad spectrum of microorganisms and ease of production owing to its production in a membrane-less EW reactor (Sheng et al., 2018). Similarly, NEW is also generated using a membrane-less reactor or produced from anode with a partial mix of hydroxide ions (OH^-). The active constituent of SAEW and NEW is HOCl, and these EWs are preferred over acidic EW because they are less corrosive due to their pH and have a longer shelf-life (Ampiaw et al., 2021). At the cathode side, ALEW with a high pH, low ORP is produced. At this chamber outlet, Na^+ reacts with hydroxide ion (OH^-) to form sodium hydroxide (NaOH). The NaOH and negative ORP result to a detergent-like characteristics and bacterial inactivation functionality (Athayde et al., 2018). A more recent EW is SALEW that is produced in a single cell chamber. SALEW is not significantly researched as compared to other EW types. However, Nyamende et al. (2021) findings showed the curative efficacy of SALEW against *Botrytis cinerea* on "Granny Smith" apple. In general, recent application of EW in FFVs has been on sanitization and quality management.

2.2 | Plasma activated water

Plasma activated water is generated by discharging plasma inside the water in two broad categories: (i) plasma discharge in the gas phase over the liquid or solution and (ii) plasma direct discharge within the liquid (Schnabel et al., 2015; Schnabel et al., 2020). Common plasma sources and devices used to produce PAW include plasma jet, gliding arc discharge, dielectric barrier discharge (DBD), and corona-discharge (Figure 2). However, it should be noted that each plasma source and device have its own merits and demerits. For example, DBD has a larger electrode surface area and can effectively distribute desired species/plasma into water, with up to 4 weeks life span of reactive species (Subramanian et al., 2021); however, the electric field applied to the gas must be high enough to produce high-energy electrons to generate plasma (Hadinoto et al., 2023). Water interaction with atmospheric plasma exhibits acidified solution containing various reactive oxygen nitrogen species (RONS). Reactive species, such as hydroxyl radicals ($^{\bullet}OH$), singlet oxygen ($^1O_2$), super-oxide ($O_2{}^-$), peroxynitrite ($ONOO^-$), nitric oxide ($^{\bullet}NO$), and peroxynitric ($OONO^-{}_3$), are short-lived RONS in PAW (Gorbanev et al., 2021). RONS with a longer life span includes nitrate ($NO^-{}_3$), hydrogen peroxide (H_2O_2), nitrite ($NO_2{}^-$), and ozone (O_3) (Zhou et al., 2019). These RONS are essential for FFVs sanitization. Nevertheless, the physicochemical properties, such as concentration of RONS, gases, treatment time, pH, and ORP, are considered to play a dominant role in sanitization of FFVs. In addition, the efficacy of PAW is influenced by processing factors (power, voltage, frequency, plasma treatment time, working gas, gas flow

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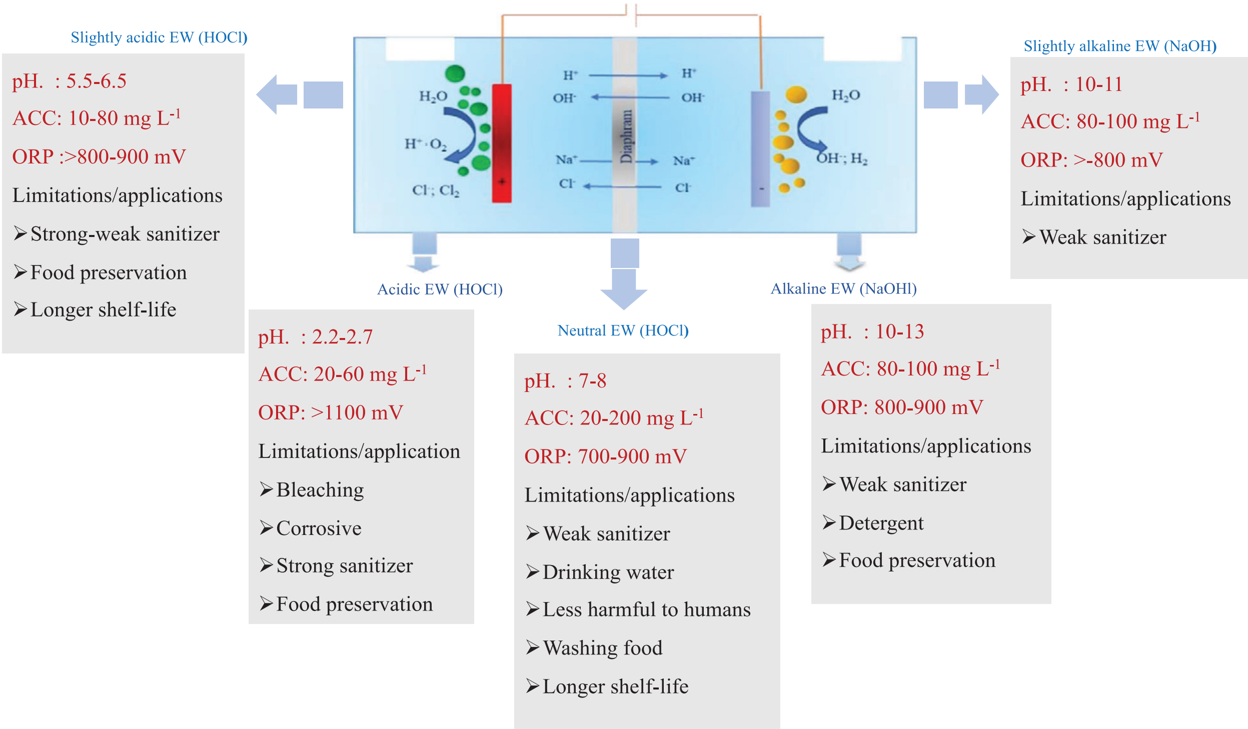

FIGURE 1 Summary of the different electrolyzed water systems, their physicochemical characteristics, and application and limitations. ACC, available chlorine concentration; EW, electrolyzed water; ORP, oxidation-reduction potential.

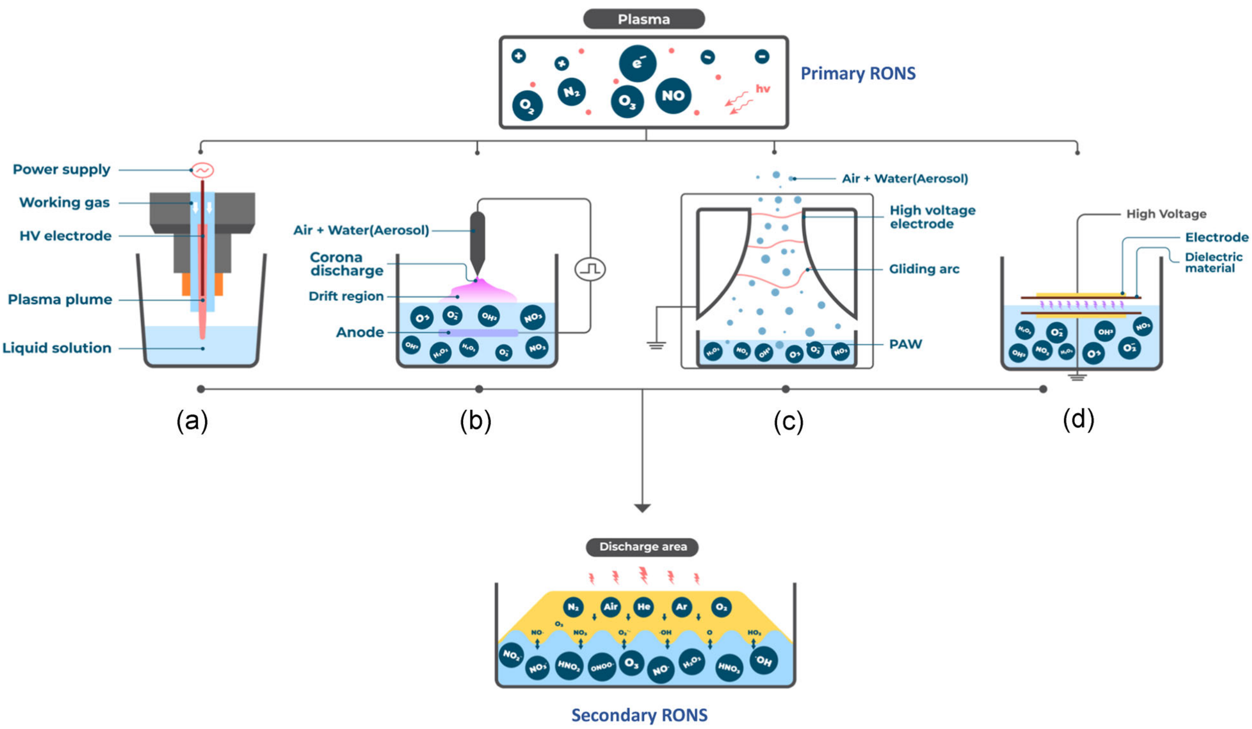

FIGURE 2 Schematic of plasma activated water generation with different plasma discharge sources and devices: (A) plasma jet; (B) corona discharge; (C) gliding arc; and (D) dielectric barrier discharge. HV, high voltage; PAW, plasma activated water; RONS, reactive oxygen-nitrogen species.

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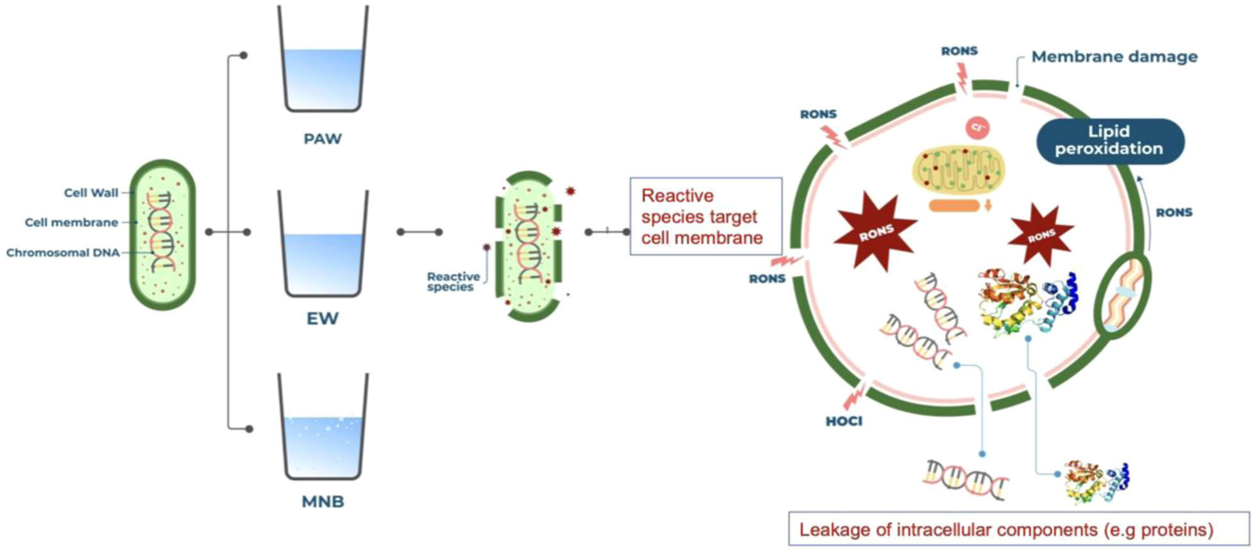

FIGURE 3 Schematic diagram of activated water systems (plasma activated water, electrolyzed water, and micro–nano bubbles) induced cell destruction through different mechanism (membrane damage, lipid peroxidation, and leakage of intracellular components). EW, electrolyzed water; HOCl, hypochlorous acid; MNB, micro-nano bubbles; PAW, plasma activated water; RONS, reactive oxygen–nitrogen species.

rate, storage temperature, storage time, water type, liquid temperature, and water conductivity), type of microorganism, and their initial concentration (Zhao et al., 2020, 2023). These critical factors should be considered by producers, PAW operators, and FFVs packhouse personnel at the industrial scale.

2.3 | Micro–nano bubbles

MNBs generally refer to ultrafine bubbles, usually less than 100 μm in diameter (Zhang et al., 2023; Zhu et al., 2016). MNB can be produced by chemical- and physical-based techniques. Chemical approach includes: (i) electrolysis—where H_2 and O_2 produced at the cathode and anode, respectively, resulting to gas saturation, bubble nucleation, and formation of MNB and (ii) chemical reaction between Na_2CO_3 and HCl (Bai et al., 2020). Physical methods involve cavitation, in which formation of cavities (bubbles) occurs when the water liquid phase undergoes a phase change due to a sudden reduction of pressure below a certain critical value (Phan et al., 2021). The reduction in pressure relating to a fluid flow and propagating ultrasonic waves through the liquid is referred to hydrodynamic (HC) and acoustic cavitation (AC), respectively (Phan et al., 2021; Ulatowski and Sobiezuk, 2020). HC is less costly and energy efficient MNB generation technique and is easier to scale and operate (Jia et al., 2023). HC can be achieved by different systems such as venturi, spiral liquid flow, depressurizing, and ejector-type HC as annotated in Figure 3 (Phan et al., 2021). Venturi type system based on HC has been extensively used due to the ease of operation and control. With respect to AC, ultrasonication can generate MNB by inducing cavitation when the ultrasound intensity is sufficiently high (Zhang et al., 2023). Another common technique to generate MNB is membrane method, where a gas is pressed through the membrane pores into a flowing aqueous phase. Nonetheless, the generation of MNB is influenced by certain factors, including pressure and temperature, type and concentration of dissolved gas, surfactants, and electrolyte (Ulatowski and Sobiezuk, 2020). However, MNBs have extraordinary physical and chemical properties and physiological activities, such as large specific surface areas, high gas–liquid transfer efficiency, small volume per unit mass, longer persistence in aqueous solution, and production of free radicals when bursting (Phan et al., 2021; Jia et al., 2023). The generation of reactive oxygen species from MNB allows them to be effective as disinfectant and sanitizer for cleaning FFVs. For example, Nghia et al. (2021) proved that nano bubbles (NBs) significantly reduced *Vibrio parahaemolyticus* (AHPND strain) populations and improved dissolved oxygen levels above 20 mg L^{-1}, which could be beneficial for aquaculture farming.

2.4 | Other activated water systems

In this section, recent AWS such as plasma bubble activated water (PBAW) and hydrogen rich water (HRW) that are at infancy in terms of application in the agri-food industry will be briefly discussed. The potential for

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PBAW and HRW in FFVs application were discussed. The research needs to elucidate their role as antimicrobials were highlighted.

2.4.1 | Plasma bubble activated water

According to Guo et al. (2021), one of the shortcomings of PAW is that the transfer of RONS at gas–liquid interface is very low due to their slow transport into the aqueous medium; the authors further reported that only a fraction of the active species in gaseous plasma can penetrate the gas–water interface. Therefore, to address this drawback of PAW and improvement of the efficiency in plasma activation, MNBs are well known for highly efficient mass transfer of gases into water, due to their high surface-to-volume ratio, longevity in water, high internal pressure, and agitation induced when bursting (Atkinson et al., 2019; Wu et al., 2020). MNBs generate enormous surface area for effective saturation of the active species generated from cold plasma into water. MNB integrated with cold plasma technology may significantly improve the efficiency of water activation.

Recently, various researchers have explored the application of PBAW for inactivation against foodborne pathogens (Baek et al., 2020; Han et al., 2023), algal inactivation and cell damage (Rao, Chu, et al., 2022), and enhancement of essential oil extracts (Sharanyakanth et al., 2021). Research by Rao, Chu et al. (2022) stated that air-PBAW and O_2-PBAW were equally effective in the immediate and long-term reduction of cell numbers (65%–100% Milli*Q*) and increasing cell damage and inactivation (100% in Milli*Q*) of *Chlorella vulgaris*-laden. Moreover, PBAW (185 V, 90 min treatment time, and 0.5 mm bubble size) increased essential oils yield and extraction efficiency from 2.4% to 3.2% and 55.9% to 74.4%, respectively (Sharanyakanth et al., 2021). Overall, these studies have shown that PBAW has the potential to be used for PW of FFVs for microbiological safety and quality management. Therefore, forthcoming investigations need to be carried out to explain the antimicrobial mechanism of PBAW and application for preservation of FFVs.

2.4.2 | Hydrogen rich water

Molecular hydrogen (H_2) is becoming recognized as a molecule with potential application for the treatment of postharvest FFVs, including flowers (Hancock et al., 2022). Delivery mode of H_2 can be in gaseous or in H_2-enriched solutions, such as HRW (Hui et al., 2017). Another variety of HRW is hydrogen nano-bubble water. One of the disadvantages with HRW is that the H_2 will rapidly decompose and return to the atmosphere, thereby depleting the desired/effective concentration in the solution. This drawback implies that HRW should be applied immediately after production. Furthermore, the combination of HRW with MNB can mitigate the rapid decomposition of H_2, as MNB can effectively be impregnated with active gaseous species and these bubbles remain relatively stable longer in solutions compare to HRW alone. Applications of HRW have shown positive results in maintaining postharvest quality of various FFVs (Hui et al., 2017). Therefore, the need for up-scale design and broader fresh commodity application is warranted to optimize effective H_2 dosage, treatment duration, and delivery approaches.

For instance, Hu et al. (2014) reported that 80% HRW had the most significant effect in decreasing the rot incidence and preserving the firmness of “Huayou” kiwifruit. The researchers further stated that 80% HRW reduced pectin solubilization and the activities of cell wall-degrading enzymes, along with respiration rate (RR) peak. According to Zhao, Meng et al. (2021) treatment of kiwifruit (cv. Xuxiang) with 0.051 mmol L^{-1} of HRW resulted in (i) delayed decrease in bio- and phytochemical properties (such as TA, chlorophyll and ascorbic acid content, total phenolics, and total flavonoids); (ii) reduced the total colony count and WL; (iii) inhibited the increase in total soluble solids (TSS), malondialdehyde content, and electrolyte leakage, and (iv) maintained the green color and firmness, compared to the control during 8 days at $4 \pm 1°C$ storage. In a recent study, Dong, Shi, et al. (2022) showed that 15 min dipping in 0.22 mM HRW delayed softening and firmness loss and extended shelf-life in okras stored at $25 \pm 1°C$ and ≈90% RH for up to 15 days. In summary, as shown in Table 1, it is evident that HRW can be applied to a wide range of FFVs for postharvest quality maintenance. However, the biochemical action of HRW needs further research since it is still not known if the treatment induces any negative effects. In addition, microbial inactivation of HRW needs further exploration.

3 | CHEMICAL PATHWAYS OF ACTIVATED WATER SYSTEMS

3.1 | Electrolyzed water

The main reaction pathways at the electrodes during electrolysis when NaCl dissociates into Na^+, Cl^-, H^+, OH^- were previously outlined (Wang et al., 2022; Zhang, Cao et al., 2021; Zhang, Zhao, et al., 2021). For production of AEW (anode) and ALEW (cathode) the following typical reaction occurs:

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TABLE 1 Postharvest application of hydrogen rich water treatments in fresh fruits and vegetables (FFVs).

FFVs	Salient results	References
"Huayou" kiwifruit	Delayed ripening and senescence	Hu et al. (2014)
Hypsizygus marmoreus	Better storage mediated by antioxidants	Chen, Zhang, et al. (2017)
Tomato	Altered defense responses, increased PPO activity and NO	Lu et al. (2017)
"Huaizhi" litchi	Reduced pericarp browning, lower oxidative stress indicators	Yun et al. (2021)
"Jiafen No. 2" tomato	Reduced nitrite accumulation, with relevant enzymes affected	Zhang et al. (2019)
"Xuxiang" kiwifruit	Reduced loss of antioxidants such as flavonoids and delayed chlorophyll loss. Reduced oxidative stress markers	Zhao et al. (2021)
Rosa sterilis	Maintained overall quality, mediated by ROS and energy metabolism	Dong, Zhu et al. (2022)
Okras	Delayed fruit softening, better cell wall maintenance	Dong, Shi et al. (2022)
"Guilin" Chinese water chestnut	Less tissue yellowing, reduced oxidative stress, and influenced the phenylpropanoid pathway	Li, Hu, et al. (2022)
"Baxijiao" banana	Delayed ripening, through ethylene metabolism mediation	Yun et al. (2022)

NO, nitrous oxide; PPO, polyphenol oxidase; ROS, reactive oxygen species.

Anode:

$$2H_2O \rightarrow 4H^+ + O_2^{\uparrow} + 4e^-$$

$$2NaCl \rightarrow Cl_2^{\uparrow} + 2e^- + 2Na^+$$

$$Cl_2 + H_2O \rightarrow HCl + HOCl$$

Cathode:

$$2H_2O + 2e^- \rightarrow H_2^{\uparrow} + 2OH^-$$

$$2NaCl + 2OH^- \rightarrow 2NaOH + Cl^-$$

Moreover, the main electrode reactions for producing SAEW or NEW are shown below (Sun et al., 2022):

Anode:

$$2Cl^- \rightarrow Cl_2^{\uparrow} + 2e^-$$

$$Cl_2 + H_2O \rightarrow HCl + HClO$$

Cathode:

$$2H^+ + 2e^- \rightarrow H_2^{\uparrow}$$

3.2 | Plasma activated water

Gas source and the type of liquid used to generate plasma have a direct effect on the type and concentrations of reactive species (Lukes et al., 2014). The reactive species are formed in the liquid or at the liquid–gas interface. There is existing literature detailing the chemical pathways involved in generation of reactive species by PAW (Zhou et al., 2019; Kaushik et al., 2019; Machala et al., 2018; Mohades et al., 2020). Other researchers also reported some predicted reactions that generate RONS during PAW generation as follows (Corella Puertas et al., 2020; Zhao et al., 2020).

ROS:

$$H_2O + e^- \rightarrow OH + H \bullet + e^-$$

$$H_2O + e^- \rightarrow OH + H^+ + 2e^-$$

$$O_2 + O\bullet \rightarrow O_3$$

$$OH \bullet + OH\bullet \rightarrow H_2O_2$$

$$O_2 + e^- \rightarrow O^+ + O \bullet + 2e^-$$

RNS:

$$NO_2^- + H^+ \rightarrow HNO_2$$

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$$NO_2\bullet + OH \rightarrow HNO_3$$

$$3NO_2^- + 3H^+ \rightarrow 2NO + NO_3^- + H_3O^+$$

$$2NO_2 + H_2O \rightarrow NO_2^- + NO_3^- + 2H^+$$

$$NO_2^- + H_2O_2 + H^+ \rightarrow ONOOH + H_2O$$

Reaction pathways for argon were reported by Bolouki et al. (2021) and Ghimire et al. (2021):

$$Ar + e \rightarrow Ar^+ + e + e$$

$$Ar + e \rightarrow Ar^* + e$$

$$Ar^* + H_2O \rightarrow Ar + OH\bullet + H$$

3.3 | Micro–nano bubbles

There are few studies that elucidated the reactive pathways and mechanisms of MNB-derived reactive oxygen species formation of different gas sources except ozone (Marcelino et al., 2023). Nonetheless, rapid collapse of MNB is important in harnessing this phenomenon. The collapse of MNB releases high amount of surface energy, leading to excitation state of electrons, and resulting to the formation of ROS from the decomposition of water molecules (Phan et al., 2021). Small MNBs below 1 μm have a high Laplace pressure, which refers to the pressure difference between the interior and exterior of MNB. The high Laplace pressure facilitates energy shockwaves of ROS. Another possible mechanism of MNB-derived ROS is by adiabatic compression during collapse of bubbles. However, extreme internal pressure, temperature, and a rapid collapse are required to support adiabatic compression during MNB collapse to produce ROS. One of the most important ROS generated by oxygen and air MNB is hydroxyl radicals (Rafeeq & Ovissipour, 2021). However, it is still unknown whether MNB-derived hydroxyl radicals can be produced without applying mechanical and ultrasonic agitation or by lowering pH of the solution (Takahashi et al., 2021; Yasui et al., 2018). Moreover, current findings have not reported the generation of other ROS such as superoxide radicals, peroxide, singlet oxygen, and peroxyl radicals from MNB produced with oxygen and air (Marcelino et al., 2023).

4 | IMPACTS OF ACTIVATED WATER SYSTEMS ON FRUITS AND VEGETABLES QUALITY ATTRIBUTES

Physical and biochemical quality attributes of FFVs such as surface color, firmness, weight, TSS, titratable acidity (TA), and pH of FFVs are critical postharvest quality indicators that influence consumer's acceptance and purchase decision. Studies on the effect of EW, PAW, and MNB treatments on physical and biochemical quality attributes and development of bioactive compounds of FFVs are summarized in Tables 2–4, respectively. This subsection provides an extensive report on the impact of AWS on the quality of fresh produce.

4.1 | Surface color

FFV color significantly affects how consumers perceive the product (Belay et al., 2021). As a result, any unfavorable color alteration in FFVs during processing/storage would hinder their consumption. Various AWS have been shown to have varying impacts on the color of FFVs (Tables 2 and 3). Hayta and Aday (2015) showed that EW treatment using 25, 50, and 100 mg L^{-1} of ACC on "0900Ziraat" sweet cherry in passive atmosphere packaging stored for 25 days at 4°C resulted in higher a^* values, whereas EW with ACC above 200 mg L^{-1} resulted in lower a^* values; the lower a^* values were attributed to the strong oxidizing activity and high ACC negatively destabilizing the anthocyanins. In the same study, the L^* values of EW-treated samples increase with the increment of EW ACC. Similarly, SAEW treatment negatively affected the lenticels of "Granny Smith" apple fruit and led to a bright color and appearance change in comparison with the control after 4 weeks of storage at 24°C (Nyamende et al., 2021). Additionally, 1 min treatment with NEW conferred high L^* values on minimally processed fresh cut lettuce after 7 days of storage at 4°C (Rico et al., 2008). These findings corroborated those reported on "Fuyan" longans (Chen et al., 2020), fresh cut "Florida" and "Ionathan" apples (Plesoianu et al., 2022), and "Crimson Blaze" nectarine (Belay et al., 2021). The authors reported that this could be due to the bleaching effect on the surface tissues because of oxidizing capacity of EW; high ACC of EW could have produced more damage to the tissues and increasing the chances of nonenzymatic browning. These findings indicated the negative corrosive drawback of EW due to high ACC concentrations as previously reported (Hopkins et al., 2021). Contrarily, PAW has

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TABLE 2 Recent studies on the effects of electrolyzed water treatments on quality and physiological postharvest parameters of fresh fruits and vegetables (FFVs).

FFVs	Treatments and storage conditions	Effects on quality parameters	Salient results	References
Fresh cut lettuce	1 min treatment with NEW (ACC = 60 and 120 mg L^{-1}), 7 days storage at 4°C	↑ *L**	Blanching on skin surface	Rico et al. (2008)
Fresh cut iceberg lettuce	90 and 180 s dipping in EW (ACC = 100 mg L^{-1}, pH = 7.2), 9 storage days at 5°C	ND	Delayed browning	Kumar et al. (2011)
"Deglet Nour" date palm	2 min dipping in NEW (100 mg L^{-1} ACC, pH 11.28 ± 0.1, ORP ≈ −800 mV) and ALEW (100 mg L^{-1} ACC, pH ≈ 7.2, ORP ≈ 814 mV) followed by 1 min dipping in tap water and stored in BPP film (0.7 mm perforation), 30 days storage at 20°C	↓ WL; ↑ F	Quality attributes of dates were maintained after 30 days storage at 20°C	Jemni et al. (2014)
"0900Ziraat" sweet cherry	3 min treatment with EW (ACC = 25, 50, and 100 mg L^{-1}), packaged in MAP (21% O_2, 0.03% CO_2, and 79% N_2), 25 days storage at 4°C 80%–85% RH	↑ *L**; ↑ *a**; ↑ $C_{21}H_{21}C_1O_{11}$; ↑ $C_{27}H_{31}C_1O_{15}$; ↑ $C_{27}H_{31}O_{14}$; ↓ pH; ↓ TSS; ↓ RR; ↓ F	Increased anthocyanins, maintained firmness, delayed decay	Hayta and Aday (2015)
Fresh tea shoots	AEW (ACC = 100 mg L^{-1}), sealed in PPE bags, 5 days of storage at 5°C	↑ RR	Effective treatment in reducing microflora load	Kyaw et al. (2015)
"Okubao" peach	20 min dipping in AEW, 8 days storage at 25°C	↓ BI; ↓ PPO; ↓ RR; ↓ C_2H_4; ↓ H_2O_2; ↓ MDA; ↑ SOD; ↑ POD; ↓ CAT; ↑ O_2^-	Delayed browning, maintained fruit firmness, higher levels of phenolic compounds	Zhi et al. (2017)
"Camellia" and "Brightwell" blueberries	5 min dipping in AEW (48 mg L^{-1} ACC, pH = 2.8), 15 days of 4°C storage	↑ F; ↓ WSP; ↑ NSP	Delayed softening of both cultivars, deactivated CWDEs, PG, cellulase, and β-galactosidase	Chen, Hung et al. (2017)
"Brightwell" blueberries	5 min washing with AEW (pH = 2.8, ACC = 48 mg L^{-1}, ORP = 1125 mV at 25°C), 15 days storage at 4°C 90% RH	↑ F; ↑ TPC; ↑ SOD; ↑ CAT; ↑ APX; ↓ CMP	Regulated ROS metabolism, increased ROS scavenging capacity, and maintained structural integrity thereby enhancing storability	Chen et al. (2019)
"Fuyan" longan fruit	10 min dipping with AEW (pH = 2.5, ACC ≈ 0, 40, 80, and 120 mg L^{-1}), 6 days storage at 25°C with 90% RH	↑ *L**; ↑ *a**; ↑ *b**; ↓ BI; ↓ RR	Delayed pericarp browning	Chen et al. (2020)
"Jiancui" jujube	5 min soaking in SAEW (pH = 5.95, ORP ≈ 922 mV, ACC ≈ 29.8 mg L^{-1}), packed in PE bags, 60 days storage at 1°C	↑ F; ↑ *L**; ↑ *b**	Reduced fruit rot and maintained an acceptable quality	Li et al. (2020)
"Satsuma" orange	3 min treatment in EW (pH ≈ 2.6, ORP = 1125 mV, and ACC = 0.062 g L^{-1}), 60 days of 2 ± 1°C storage	↓WL; ↓ CI; ↑ TSS; ↑ TA; ↓ TSS/TA; ↓CMP; MDA; ↑SOD; ↑POD; ↑CAT	Improved quality of the fruit	Shi et al. (2020)
"Jingan No. 9" sweet potato slices	EW (pH = 2 ± 3; ACC = 55.98 ± 2.27 mg L^{-1}), 8 days storage at 4°C	↓ BI; ↓ PPO	Delayed browning	Liu et al. (2021)

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TABLE 2 (Continued)

FFVs	Treatments and storage conditions	Effects on quality parameters	Salient results	References
"Malvina" strawberry	2 kJ m^{-2} ultraviolet irradiation + AEW, 21 days storage at 8°C	↓ TSS; ↑ WL; ↑ F; ↓ WL	Decreased anthocyanin and maintained firmness	Nour et al. (2021)
"Granny smith" apple	5-, 10-, and 15-min dipping in SAEW (pH ≈ 11, ORP > −800 mV, ACC = 400 and 500 mg L^{-1}), 21 days at 5°C and 2 days at 24°C	ND	Damaged lenticels and led to a bright skin color at higher concentration	Nyamende et al. (2021)
"Crimson Blaze" nectarine	10 min dipping in ALEW (ACC = 200 mg L^{-1}, pH = 6.7, ORP ≥ −800 mV), 31 days storage at −0.5°C, 95% RH	↑ *L**; ↓ *a**; ↓ WL; ↑ F; ↑ TSS; ↓ TA	Suppressed the decrease of color qualities of peel, reduced browning incidence and surface decay	Belay et al. (2021)
Fresh cut egg plant	AEW (pH = 6.25, ORP = 861 mV, ACC = 31 mg L^{-1}), 8 days at 4°C	↑ TPC	Extended storability and shelf life	Li, Yue, et al. (2020)
"Tommy Atkins" mango slices	15 min treatment with NEW (pH = 8.33–8.49, ACC = 75, 150, 225, and 300 mg L^{-1}), 12 days storage at 3 ± 2°C, 85% ± 5% RH	↑ *L**; ↑ *b**; ↑ F; ↑ VC	Improved quality than other treatments	Lopes et al. (2021)
Fresh cut "Florida" and "Ionathan" apples	5 min dipping in AEW (pH = 3.54), stored in plastic containers under normal atmospheric conditions during 14 days at 8°C	↑ *L**	Delayed browning	Plesoianu et al. (2022)
"Fuyan" longan fruit	10 min dipping in AEW (pH = 2.5, ACC = 80 mg L^{-1}), 5 days of 25°C storage	↑ F; ↓ CWDE; ↓ WSP; ↓ CSP	Delayed pulp softening and retained higher pulp CWP, delayed degradation of cellulose and hemicellulose	Sun et al. (2022)
"Xiangmi" carambola fruit	10 min soaking in SAEW (pH = 6.0, ORP = 1340 MV, and ACC = 80 mg L^{-1}), sealed in PE bag, stored for 24 days at 15°C 85% RH	↑ TSS; ↓ TA; ↑ VC; ↓ RR; ↓ CMP; ↑ *b**; ↑ *L**; ↓ *a**; ↑ *h*°; ↑ FL; ↑ PP	Achieved high fruit quality and nutritional values	Zhang et al. (2023)
Fresh cut apple	3 min dipping in SAEW (ACC = 10, 20, 30, and 40 mg L^{-1})	↑ VC; ↑ Δ*E*; ↑ TSC	Effectively controlled number of colonies of microbes, slowed quality deterioration, and extended shelf-life	Gao et al. (2023)
Fresh cut jackfruit	AEW (pH = 4.2–4.5, ACC = 35–38 mg L^{-1}), 8 days storage (storage temperature not reported)	↓ BI; ↑ F; ↑ TA; ↑ TSC; ↑ AA; ↑ TP	maintained the quality of fresh cut jackfruit during storage	Yu et al. (2023)
"Lingwu long" jujube	2.5 min soaking in AEW (ORP ≈ 1177 mV, pH = 2.2, and ACC = 60 mg L^{-1}), 40 days storage at 1°C and 85%–90% RH	↓WL; ↑TSS; ↓TA; ↑F; ↑*L**; ↑*a**; ↑*b**; ↑AA; ↑SOD; ↑CAT	Alleviated quality deterioration and postharvest senescence	Li et al. (2023)

Note: ↑ Higher or increase in value (after day 0 of storage); ↓ Lower or decline or reduction in value (after day 0 of storage). Δ*E*, color change; *a**, redness.

Abbreviations: AA, ascorbic acid; ACC, available chlorine concentration; AEW, acidic electrolyzed water; ALEW, alkaline electrolyzed water; APX, ascorbate peroxidase and catalase; *b**, greenness; BI, browning index; BPP, biobased polypropylene; $C_{21}H2_1ClO_{11}$, cyanidin 3-glucoside; $C_{27}H_{31}ClO_{15}$, cyanidin-3-rutinoside; $C_{27}H_{31}O_{14}$, pelargonidin 3-rutinoside; C_2H_4, ethylene; CAT, catalase; CI, chilling injury; CMP, cell membrane permeability; CSP, covalent-soluble pectin; CWDE, cell wall degrading enzymes; CWP, cell wall polysaccharides; EW, electrolyzed water; F, firmness; FL, flavonoids; *h*°, Hue angle; H_2O_2, hydrogen peroxide); *L*, lightness; MAP, modified atmosphere packaging; MDA, malondialdehyde; ND, not determined; NEW, neutral electrolyzed water; NSP, Na_2CO_3-soluble pectin; O_2^-, ion oxide; ORP, oxidation-reduction potential; PE, polyethylene; POD, peroxidase; PP, polyphenols; PPE, polypropylene; PPO, polyphenol oxidase; RH, relative humidity; ROS, reactive oxygen species; RR, respiration rate; SAEW, slightly acidic electrolyzed water; SOD, superoxide dismutase; TA, titratable acidity; TPC, total phenolic content; TSC, total sugar content; TSS, total soluble solids; VC, vitamin C; WL, weight loss; and WSP, water-soluble pectin.

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TABLE 3 Summary of studies on the effects of plasma activated water treatments on quality and physiological postharvest parameters of fresh fruits and vegetables (FFVs).

FFVs	Plasma discharge	Preparation parameters	Exposure time and storage conditions	Effects on quality parameters	Salient results	References
"Toyonoka" strawberries	Air and O_2 plasma jet	10-kHz, sinusoidal, high-voltage source, 18-kV_{pp} voltage, 98% Ar and 2% O_2, 5 L min^{-1} flow rate, 20 min activation above 10 mm water (500 mL)	5, 10, and 15 min soaking in PAW, 4 days storage in an environmental incubator at 20 ± 2°C temperature and 70% ± 5% RH	↑F; ↑pH; L^{*ns}; a^{*ns}; b^{*ns}	Delayed softening by reducing microbial load	Ma et al. (2015)
Button mushrooms	Ar and O_2 plasma jet	10-kHz, sinusoidal, high-voltage source, 18-kV_{pp} voltage, 98% Ar and 2% O_2, 5 L min^{-1} flow rate, 20 min activation above 10 mm of water (500 mL)	5, 10, and 15 min in 500 mL of PAW, 7 days storage at ≈20°C and ≈70%	↑F; ↓WL; ↑L^*; ↓b^*; ↑MDA; ↑SOD; ↑VC; ↓RR	Reduced browning and softening by inactivating mesophilic bacteria and fungi	Xu et al. (2016)
"Dongkui" bayberry grapes	Air plasma jet in dielectric barrier discharge design	Air with 260 L h^{-1} gas flow rate, 20 kHz voltage, 25 min activation time at 34.8°C; ORP ≈ 512 mV, $\sigma \approx 12.3/\approx 125.0\ \mu S\ cm^{-1}$ and ≈3.6 pH units	0.5, 2, and 5 min soaking in 1600 mL PAW, 8 days storage at ≈3°C, ≈85% RH	↑F; ↑CIRG ↑TSS; ↓TVC	Controlled decay and maintained quality	Ma et al. (2016)
Grapes	Air plasma jet	Current and voltage were 1.1–1.3 mA and 8.2 kV, respectively, flow rate = 1.2 L min^{-1}, 30- and 60-min activation time	30 min soaking, 8°C for 3 days	L^{*ns}; a^{*ns}; b^{*ns}; TPC^{ns}	Microbial inactivation without affecting grape quality	Guo et al. (2017)
Grapes	Air plasma jet	25 kV_{pp} peak voltage, $f = 20$ kHz, 5 L min^{-1}, 2 cm below the liquid surface, excited in 400 mL DI, 1, 5-, 10-, 20-, and 30-min activation time	10 min treatment, 1 h air-drying at 20°C	L^{*ns}; a^{*ns}; b^{*ns}; ΔE^{ns}; F^{ns}; TSC^{ns}; VC^{ns}; SOD^{ns}	Removed phoxim pesticides without affecting quality	Zheng et al. (2019)
Fresh cut kiwi	Atmospheric-pressure cold air microplasma array	$V_{pp} = 10$ kV, $f = 8$ kHz, air flow rate = 1.0, 40 mL DW activated for 30 min	1-mL PAW spraying, 8 days storage at 4°C	b^{*ns}, F^{ns}; ↓H_2O_2; ↓O_2^-; ↑SOD; ↑POD; ↑CAT	Enhanced antioxidant enzymes activities without affecting quality	Zhao et al. (2019)

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TABLE 3 (Continued)

FFVs	Plasma discharge	Preparation parameters	Exposure time and storage conditions	Effects on quality parameters	Salient results	References
"Huangguan" fresh cut pears	Air microplasma array with dielectric barrier discharge	V_{pp} = 10 kV, f = 9.0 kHz, air flow rate = 1.0 standard L min^{-1}	5 min soaking, 12 days at 4 ± 1°C	TA^{ns}; TPC^{ns}; AA^{ns}. TSS^{ns}; ↓WL; ↑F; $DPPH^{ns}$; $ABTS^{ns}$	Maintained antioxidant properties	Chen et al. (2019)
Mung bean sprouts	Air plasma jet	5 mm distance between plasma source and water, discharge power was set at 750 W, gas flow rate of 30 L min^{-1}, 30 s activation time	0-, 20-, and 30-min treatment, 6 days storage at 4°C	$DPPH^{ns}$; $ABTS^{ns}$; TPC^{ns}; TFC^{ns}; F^{ns}; pH^{ns}	Inactivated bacteria, yeast, and fungi without affecting nutritional and sensory quality attributes	Xiang et al. (2019)
FC "Fuji" apple	Dielectric barrier discharge	Air, flow rate of 1.0 standard liter per minute, V_{pp} = 6–10 kV at a frequency of 7.0 kHz, 10 min activation time	5 min treatment, packed in PE cling film (10-μm thickness, permeability characteristics: O_2 = 10,030 cm^3 m^{-2} 24 h^{-1} bar^{-1}; CO_2 = 36,300 cm^3 m^{-2} 24 h^{-1} bar^{-1}), 12 days storage at 4 ± 1°C and 90% RH	F^{ns}; ↓BI; WL^{ns}; TSS^{ns}; TA^{ns}; $DPPH^{ns}$; $ABTS^{ns}$	Inhibited microbial growth and reduced browning	Liu et al. (2020)
Rocket leaves	Corona	Air, 5 mm distance from liquid surface, V_{pp} = 9 kV, f = 5 kHz, 4 min activation time	2, 5, 10, and 20 min in the ratio product:liquid of 1:20 (w:v)	pH^{ns}; ↓$L*$; ↓$a*$; ↓$b*$; ↓BI; ↑TPC' ↑TFC	Decontaminated rocket leaves with limited changes in quality parameters	Laurita et al. (2021)
Tomato fruit	Plasma jet	Ar/O_2 ratio of 98/2, 1-, 3-, 5-, and 10-min activation time, f = 50 kHz, AC power source at 220 V with a DC output voltage of 2–7 kV operating at 600 W	15 min treatment, drying at room temperature of 25°C for 2 h	$L*^{ns}$; $a*^{ns}$; $b*^{ns}$; ΔE^{ns}; pH^{ns}; TSS^{ns}; TA^{ns}; AA^{ns}; LP^{ns}; F^{ns}	Effectively degraded pesticides residues with no effect on quality attributes	Ali et al. (2021)
"Ning No. 7," "Ning No.9," and "Meng No.1" goji berries	Atmospheric plasma jet	30, 60, and 90 s processing time, 400, 600, and 800 W power	40 days storage at 0°C and 90% RH	↑RR; ↓MDA; ↓WL; ↑$L*$, ↑$a*$; ↑$b*$; ↑FL; ↑VC; $C_{40}H_{56}$	Higher quality attributes, nutritive properties, and better storability	Cong et al. (2022)

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TABLE 3 (Continued)

FFVs	Plasma discharge	Preparation parameters	Exposure time and storage conditions	Effects on quality parameters	Salient results	References
Rocket-Salad leaves	Air, corona	5 mm from the surface of 450 mL of DW, 9 kV, 5 kHz	2-, 5-, 10-, and 20-min dipping, kept for 2 weeks at −20°C	↑AA; ↑$C_{17}H_2ON_4O_6$; ↑C_6H_5NO; ↓POD	Led to higher quality preservation	Abouelenein et al. (2023)
"Liaohe 1" walnut kernels	Air plasma jet	1 L DW treated with 19 kV, 22.5 L min^{-1} and ionized with a 20 kHz pulsed power supply	15 min, packaged in PE bags, stored for 12 days at 4°C	↓TVC; ↑SPC; ↑RSC; ↓BI; ↓POD; ↓PPO	Inhibited microbes and maintained quality	Xiao et al. (2023)

Note: ↑ Higher or increase in value (after day 0 of storage); ↓ lower or decline or reduction in value (after day 0 of storage). Δ*E*, color change; **L*, lightness; *a**, redness; *b**, greenness; *σ*, conductivity; *h°*, Hue angle.
Abbreviations: AA, ascorbic acid; ABTS, 2,2′-azino-bis(3 ethylbenzothiazoline-6-sulfonic acid); BI, browning index; $C_{17}H_{20}N_4O_6$, riboflavin; $C_{17}H_{20}N_4O_6$, riboflavin (vitamin B2); C_2H_4, ethylene; $C_{40}H_{56}$, *β*-carotene; C_6H_5NO, nicotinic acid; CAT, catalase; CIRG, coloration and color index of red grapes; DPPH, 2,2-diphenyl-1-picryl-hydrazyl-hydrate; DW; distilled water; F, firmness; FC, fresh cut; FL, flavonoids; FRAP, ferric reducing antioxidant power; H_2O_2, hydrogen peroxide; HOC_6H_4COOH, salicylic acid; LP, lycopene; MAP, modified atmosphere packaging; MDA, malondialdehyde; ^{ns}; no significant effect; PE, polyethylene; PG, polygalacturonase; POD, peroxidase; PPE, polypropylene; PPO, polyphenol oxidase; RH, relative humidity; ROS, reactive oxygen species; RR, respiration rate; RSC, reducing sugar content; SPC, soluble protein content; TA, titratable acidity; TFC, total flavonoid content; TPC, total phenolic content; TSC, total sugar content; TSS, total soluble solids; TVC, total viable count; VC, vitamin C; Vpp, voltage peak-to-peak; WL, weight loss.

minimal impact on surface color of FFVs (Table 3). Xiang et al. (2020) found no significant differences between control and PAW treated grape berries on *L**, *a**, and *b** values. Furthermore, the researchers assessed the grapes color changes (Δ*E*) before and after PAW treatments; the study revealed that Δ*E* values of grapes were <1 and not affected by PAW treatments combined with mild heating at 25–55°C for 30 min. Other researchers reported similar findings for fresh grapes (Guo et al., 2017; Zheng et al., 2019) and fresh cut kiwi fruit (Zhao et al., 2019). However, it is hypothesized that inappropriate doses of ORP and RONS in PAW could cause oxidative stress to fresh produce. For example, the color index of red "Dongkui" bayberry grapes immersed in PAW was significantly higher than the sterilized deionized control samples stored at 3 ± 1°C and 85% ± 5% RH for 8 days (Ma et al., 2016); this was due to the bayberries defense response, by enhancing the antioxidant capacity through producing much more antioxidants. Moreover, there is increasing evidence showing that the levels of anthocyanins in Chinese bayberries can be elevated to control the ROS level by postharvest treatments with high oxygen atmosphere, which could cause oxidative stress through production of ROS, such as superoxide, hydrogen peroxide, and the hydroxyl radical (Yang et al., 2009). Therefore, exposure to appropriate doses of ROS and RNS in plasma activated water and free ACC for EW are beneficial to maintain the quality of FFVs.

The dipping of fresh cut "Florida" and "Ionathan" apples in acidic EW before packaging in plastic containers under normal atmospheric conditions minimized browning during 14 days at 8°C (Plesoianu et al., 2022). Application of plasma activated water combined with EW for 90 and 180 s delayed surface browning incidence on fresh cut iceberg lettuce stored for 9 days at 5°C (Kumar et al., 2011). Similarly, EW treatment of "Jingan No. 9" sweet potato slices for 1 h led to a lower surface browning degree than untreated samples stored at 4°C for 8 days (Liu, Yu, et al., 2021). Treatment with SAEW for 20 min significantly reduced tissue browning compared to control group of "Okubao" peach stored at 25°C for 8 days (Zhi et al., 2017). Plasma activated water for 5-, 10-, and 15-min exposure successfully inhibited surface browning and overall color change in button mushroom stored at 20 ± 2°C for 7 days (Xu et al., 2016). Similar findings were reported for fresh shiitake mushrooms (Karim et al., 2021), rocket leaves (Laurita et al., 2021), and "Liaohe 1" walnut kernels (Xiao et al., 2023) pretreated with plasma activated water. Therefore, due to changes in consumer preferences to fresh cut FFVs because of their ready-to-eat convenience, freshness, and taste, EW and PAW can be utilized to maintain the aesthetic and nutritional value of fresh cut FFVs. These results demonstrate that EW and PAW are effective techniques to mitigate surface browning,

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TABLE 4 Summary of studies on the effects of micro-nano bubbles on quality and physiological postharvest parameters of fresh fruits and vegetables (FFVs).

FFVs	Gas source	MNBs characteristics	Exposure time and storage conditions	Effects on quality attributes	Salient results	References
"Cos" FC lettuce	O_3	Water temperature was 25–30°C	5 min washing, 10 days storage at 4°C	↓TPC; ↓PPO; ↓QC;	Improved quality	Pongprasert et al. (2016)
"Hom Thong" banana	1-MCP	25–30°C, 1-MCP gas feed rate was 200 mL min^{-1}, and the water pH 7.0–8.0	8 days storage at 25°C	↓C_2H_4; ↓RR; ↑TC; ↑ $h°$; ↑F	Delayed ripening	Pongprasert and Srilaong (2014)
Shredded red cabbage	O_3	0.5 mg L^{-1} O_3, 25–30°C water temperature	5 min washing, packed in top sealed plastic trays, 9 days storage at 4°C	↓TPC; ↓PPO	Improved quality	Pongprasert et al. (2018)
"Rongrien" rambutan fruit	CO_2	27–30°C water temperature	5 min washing, 12 days storage at 13°C	↑L^*; ↓QC; PPO^{ns}; ↓TPC; ↓PPO	Improved shelf-life quality	Pongprasert and Srilaong (2018)
"Hom Thong" banana	HOC_6H_4COOH	NR	15- and 30-min treatment, 4 days storage	↑L^*; ↑b^*; ↑F; ↑TA; ↑DPPH; ↑FRAP;	Maintained peel color and bioactive compounds	Anuchai et al. (2018)
"Donatello" melons	1-MCP	16–20°C and the pH was 7.3	10-, 20-, and 30-min treatment, 9 days storage at 20°C	↓C_2H_4; ↓RR; ↑F; ↑ $h°$; ↑TC	Delayed ripening	Le Nguyen et al. (2019)
"Cavendish" banana fruit	C_2H_4	30–110 μm size, 28–30°C and pH 7.0–8.0, and C_2H_4 gas feed rate at 500 mL min^{-1}, 10 min generation	10- and 20-min dipping, 10 days storage at 25°C	↑C_2H_4; ↓RR; ↑$h°$; ↓TC; ↑TSS; ↓F	Accelerated ripening	Pongprasert et al. (2020)
Celery, pakchoi and cowpea	O_3	0.059 mg L^{-1} DO, 0.272 min^{-1} mass transfer coefficient	2, 10, and 18 min	AA^{ns}	Caused negligible damage to the nutrients in vegetables	Li et al. (2023)

Note: ↑Higher (after day 0 of storage); ↓lower (after day 0 of storage). b^*, greenness; $h°$, Hue angle.

Abbrevaitions: 1-MCP, 1-methylcyclopropene; AA, ascorbic acid; C_2H_4, ethylene; DPPH, 2,2-diphenyl-1-picryl-hydrazyl-hydrate; F, firmness; FC, fresh cut; FRAP, ferric reducing antioxidant power; HOC_6H_4COOH, salicylic acid L, lightness; ^{ns}, no significant effect; PPO, polyphenol oxidase; QC, quinone content; RR, respiration rate; TA, titratable acidity; TC, chlorophyl; TFC, total flavonoid content; TPC, total phenolic content; and TSS, total soluble solids.

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particularly of fresh cut FFVs. Nevertheless, the underlying mechanism of EW and PAW reactive species to inhibit polyphenol oxidase (PPO) and peroxidase (POD) browning enzymes is not well elucidated; however, researchers showed that HOCl, OH, and H_2O_2 oxidizing substances generated in EW could be the reason for PPO and POD activity inhibition (Li et al., 2017; Wu, Nie, et al., 2018). Previous research also reported that AEW could destroy the conformation of PPO by decreasing its α-helix (Sun et al., 2018). Nonetheless, only a few studies investigated the effect of MNB on surface color of FFVs (Table 4). Pongprasert et al. (2020) results indicated that the peel color of "Cavendish" banana dipped in C_2H_4–MBs was more yellow (≈90$h°$ value) than the control fruit samples (≈115$h°$ value) after 6 days of storage; this could be due to C_2H_4 degrading chlorophyll, which paralleled with decreasing $h°$ values. Other researchers found that 1-MCP MNB maintained high chlorophyll content and $h°$ values of "Hom Thong" banana fruit (Pongprasert & Srilaong, 2014) and "Donatello" melons (Le Nguyen et al., 2019). These results demonstrate the diverse applications of MNB as a nonthermal technology either to hasten or to delay color change and ripening of FFVs. Consequently, physicochemical properties and efficiency of MNB are influenced by the gas type for generating the bubbles (Kobayashi & Ushida, 2023). Moreover, longer stagnation and higher mass transfer efficiency of gases such as 1-MCP or C_2H_4 improve the effectiveness of MNB.

4.2 | Texture and weight loss of fruits and vegetables

4.2.1 | Textural profile of fruits and vegetables

Textural changes such as softening, hardening, brittleness, mealiness, and wooliness during postharvest handling and storage of FFVs severely limit their quality, storability, and marketing potential. The effects of AWS on the firmness of FFVs vary in different studies due to the physicochemical properties of the AWS. According to literature, some researchers found that EW do not interact positively with the cell wall-degrading enzymes during postharvest storage, subsequently not delaying softening and altering textural parameters of FFVs (Chiabrando et al., 2017; Liu, Wang, et al., 2021; Zhao et al., 2019). Likewise, PAW combined with mild heat treatment had no impact on firmness of grapes (Xiang et al., 2020). The researchers found no significant differences ($p > .05$) in firmness of grapes soaked in PAW and sterile distilled water after mild heating at 25–55°C. Similarly, there was no significant changes in the firmness of strawberries (Ma et al., 2015), Chinese bayberries (Ma et al., 2016), and grapes (Zheng et al., 2019). This suggests that PAW could be ineffective in delaying firmness of specific fruits, such as berries. However, PAW should be tested on other FFVs commodities to validate these findings. Comparably, some authors found that AWS can inhibit FFVs firmness loss. For instance, PAW (for 10 and 20 min, 10- and 20-PAW, respectively) generated with 98% argon (Ar) or 2% oxygen (O_2) gas was used to treat "Toyonoka" strawberries (Ma et al., 2015); the authors demonstrated that 20-PAW better maintained higher firmness than control after 4 days of ≈ 20°C and ≈70% RH storage.

Similarly, EW treatment led to a higher firmness for "0900Ziraat" sweet cherry for 30 days storage (Hayta & Aday, 2015). "Fuyan" longan fruit firmness was also maintained by EW when stored for 5 days (Sun, Chen, et al., 2022). Similarly, ultraviolet irradiation in synergy with acidic EW maintained "Malvina" strawberry fruit firmness after 7- and 14-days storage at 8°C (Nour et al., 2021). Furthermore, the application of O_3- and 1-MCP-MNBs water delayed the loss of firmness for "Florida 683" fresh parsley (Shi et al., 2023) and "Hom Thong" banana fruit (Pongprasert & Srilaong, 2014). Similar observations were also reported by Le Nguyen et al. (2019) for "Donatello" melons dipped in 1-MCP-microbubbles for 20 and 30 min; the treatments maintained higher firmness for "Donatello" melons compared to the untreated control samples for 9 days shelf-life storage at 20°C.

Recent reports suggest that flesh and pulp softening of FFVs during storage could be attributed to the destruction of cell wall materials, cell wall polysaccharides, and accelerated activities of relevant cell wall degrading enzymes via expression of genes, mainly characterized by declining in pectin, cellulose, and hemicellulose and increasing in activities and gene expression of polygalacturonase, pectinesterase, xyloglucan endotransglycosylase, and cellulase (Chen et al., 2021; Li et al., 2019; Lin et al., 2019, 2020; Shi et al., 2019). Thus, the possible mechanism by which these AWS could be maintaining firmness of FFVs includes: (i) by reducing the relative expression levels of enzymes and genes associated with cell wall polysaccharides-disassembling, (ii) by reducing the activities of cell wall polysaccharides-disassembling enzymes, (iii) by maintaining higher contents of covalent soluble pectin, ionic soluble pectin, cellulose, and hemicellulose, but a reduced content of water-soluble pectin, and (iv) by retaining higher contents of cell wall materials and higher pulp firmness (Sun, Chen, et al., 2022; Sun, Jiang, et al., 2022).

4.2.2 | Weight loss

Another quality attribute that limits the long-term storage and marketability of FFVs is weight loss (WL), particularly when/if above 5% (Gallotta et al., 2018). EW has been reported to exert positive effects maintaining WL at <5% on FFVs (Belay et al., 2021; Hayta & Aday, 2015; Jemni et al., 2014). For "Deglet Nour" date palm immersed in acidic and ALEW treatments for 2 min, a WL of ≈2.5% and 2.1%, respectively, at the end of storage (30 days at 20°C) was reported by Jemni et al. (2014). Belay et al. (2021) reported a higher percentage WL in "Crimson Blaze" nectarine dipped in chlorinated water (10.9%), when compared with ALEW (5.3%) and control (7.3%) samples after 31 days of −0.5°C storage. Hayta and Aday (2015) documented the highest weight loss in "0900Ziraat" cherries immersed in EW with 400 mg L^{-1} ACC at the end of 30 days storage at 4°C. Although the above reports showed that EW leads to <5% WL, a high ACC was associated with the cause. High ACC in EW could trigger cell wall and tissue damage, leading to less internal turgor and loss of epidermis cohesiveness (Belay et al., 2021). Therefore, immersing FFVs in tap water led to lower percentage WL for "Deglet Nour" (Jemni et al., 2014) and "0900Ziraat" cherries (Hayta & Aday, 2015) compared with EW.

Similarly, studies on PAW have demonstrated diverse impact on FFVs WL during postharvest storage. For instance, Xu et al. (2016) reported about 10%–15% WL for button mushroom treated with Ar/O_2-PAW and stored for 7 days in an environmental chamber at 20 ± 2°C, 70% ± 5% RH; however, PAW could not maintain WL below 5% limit for longer storability. In contrast, Zhao et al. (2019) showed WL of 1.4% for fresh cut "Huangguan" pears pretreated with 8 kV air-PAW and stored at 4°C for 12 days; this efficiency was due to the low pH of PAW influenced by the gas (air) source, which generates RNS that are more stable than ROS. Furthermore, the differences in WL between the two studies could be attributed to the commodity types, being mushroom with a high transpiration rate compared to pears. Shi et al. (2023) recently investigated the impact of O_3-MNB on weight loss of fresh parsley and confirmed that O_3-MNB treated samples were 64.1% lower in WL in comparison to the control on day 5 of storage at 20 ± 1°C. Overall, amongst the AWS, the EW treatment has been demonstrated as the most effective AWS to keep FFVs WL below 5% compared with PAW and MNB based on commodities reported. The mitigation of WL by EW can be caused by the strengthening of FFVs cell wall tissues by HOCl and OCl^- species (Hao et al., 2015). Furthermore, the combination of EW with modified atmosphere packaging (MAP) has been demonstrated to further minimize WL of fresh produce. For example, a 3 min EW washing step combined with MAP significantly delayed WL for white button mushroom stored at 4°C for 12 days (Aday, 2016). These findings are in agreement with those of Li et al. (2023) who reported that acidic EW combined with MAP reduced WL of "Lingwu long" jujube stored for 40 days at 1 ± 0.5°C and 85%–90% RH. The reduction in WL in EW treated samples under MAP could be attributed to the increased in-package vapor pressure and low produce transpiration rate (Amorós et al., 2008).

4.3 | Total soluble solids, titratable acidity, and pH

The common parameters used to assess the taste of FFVs are TSS, TA, and pH. Youssef and Hussien (2020) found no significant difference in TSS, TA, and pH of acidic and ALEW treated "Valencia" oranges compared with the control samples. Similar observations were reported on "Crimson Blaze" nectarine (Belay et al., 2021), "Satsuma" orange (Shi et al., 2020), "Malvina" strawberries (Nour et al., 2021), and "Duke" blueberries (Chiabrando et al., 2017) treated with EW. With respect to vegetables, no significant changes in pH values were reported between EW treated and untreated red cabbages (Chen et al., 2018). These findings imply that EW has no deleterious effects on taste of FFVs. However, it is possible that high ACC may lead to high TSS. This was evident when Hayta and Aday (2015) reported a higher TSS of "0900Ziraat" cherries dipped in EW with 300–400 mg L^{-1} ACC compared with lower chlorine concentration EW containing 25–200 mg L^{-1}.

In contrast, and based on the current research, PAW has demonstrated to not alter the TSS, TA, and pH contents of FFVs during postharvest storage. Xiang et al. (2020) observed no significant differences in TSS, TA, and pH of "Summer Black" grapes pretreated with 90 s PAW combined with mild heat compared to control. Similarly, Xu et al. (2016) reported no distinct differences between the pH values of control, water, and PAW-treated button mushroom samples during a 1-week storage period at ≈20°C and ≈70% RH. In addition, no significant changes in the TSS, TA, and pH of were reported for PAW-treated "Dongkui" Chinese bayberry (Ma et al., 2016), fresh cut "Huangguan" pears (Chen, Liu, et al., 2019), and grapes (Zheng et al., 2019).

At the time of compiling this review, only two studies had been conducted on the application of MNB treatment on fresh produce. MNB infused with ozone resulted in lower TSS content of fresh parsley (Shi et al., 2023). The decrease in TSS content of parsley is attributed by the conversion of sugar or high levels of respiration (Hu et al., 2021). In the other available report, ethylene (C_2H_4)-infused MNB treatment was shown to accelerate the accumulation of TSS content in treated "Cavendish" banana fruit (Pongprasert et al., 2020). The increase in TSS was due to the C_2H_4 transfer efficiency aided by MNB, which initiates irreversible series of sweetness through conversion of starch into sugar. Based on reviewed

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literature, studies have conclusively demonstrated that both EW and PAW have minimal negative impact on TSS, TA, and pH of FFVs. However, the limited data on the implication of MNB treatment infused with diverse gases on the sensory quality attributes of FFVs calls for further research to better understand the impact of MNB treatment and mechanism of action on FFVs TSS, TA, and pH during postharvest handling and storage.

4.4 | Respiration rate and ethylene production

RR and C_2H_4 production are some of the most important physiological change indicators correlated with quality deterioration in FFVs. The effectiveness of various AWS in reducing RR and C_2H_4 production of FFVs has been reported in several studies. Chen et al. (2020) reported that EW treatment maintained lower RR in longans. Similar observation of decline in RR and C_2H_4 production was noted for the application of SAEW treatment on “Okubao” peaches during postharvest storage at 25°C by Zhi et al. (2017). Hayta and Aday (2015) recorded lower CO_2 production (7%–8%) for 25, 50, and 100 mg L^{-1} EW groups and higher CO_2 concentration (9%–10%) for control and “0900Ziraat” cherry samples treated with higher EW concentration (200, 300, and 400 mg L^{-1}) during 30 days of storage at 4°C. These reports indicate that the ACC of EW is crucial, and optimum concentration should be utilized to minimize RR for FFVs. Furthermore, the effect of EW varies amongst different fruit and vegetable types, and this should be carefully investigated. The effectiveness of EW to inhibit C_2H_4 production of FFVs could be associated with the interference of the C_2H_4 biosynthesis pathway and ROS metabolism by the chlorine active species (Wei et al., 2019). Additional research elucidating this underlying mechanism is required.

Several studies have demonstrated the impact of PAW on the physiological response of FFVs. For example, soaking button mushroom in PAW for 15 min reduced RR compared with soaking the samples in water after 7 days of storage at 20 ± 2°C and 70% ± 5% RH (Xu et al., 2016). In contrast, Cong et al. (2022) reported that soaking “Ning No. 7,” “Ning No. 9,” and “Meng No. 1” goji berries in PAW resulted in accelerated RR during long term storage of 40 days at 0°C and 90% RH. The differences reported in the influence of PAW on these investigated products demonstrate the need for more studies and broader application on other commodities to understand and validate the above findings.

In the case studies involving the application of MNB, 1-MCP was infused into MNB water treatment for “Hom Thong” banana (Pongprasert & Srilaong, 2014) and “Donatello” melons (Le Nguyen et al., 2019). Both studies reported that 1-MCP-MNB treatment remarkably retarded RR and C_2H_4 production rate in “Hom Thong” banana and “Donatello” melons, respectively, during storage. This could be due to the higher solubility of 1-MCP in water, which improves its saturation to block receptors responsible for C_2H_4 production in the fresh produce tissue. The potential for MNB in the postharvest management of FFVs remains underexplored, and additional research is required.

4.5 | Bioactive compounds and antioxidants

FFVs are rich in biologically active compounds and antioxidants that are beneficial to human health (Zhang & Jiang, 2019). Several studies revealed that AWS such as EW and PAW do not cause changes in bioactive compounds and antioxidants of FFVs (Ali et al., 2021; Chen et al., 2019; Guo et al., 2017; Puligundla et al., 2018; Xiang, Liu, et al., 2019, 2020). However, other studies reported the benefits of AWS to increase FFVs bioactive compounds. Treatment with SAEW led to a higher total phenolic content and flavonoids on “Okubao” peach (Zhi et al., 2017), “Brightwell” blueberries (Chen et al., 2019), and “Jiancui” jujube (Li, Zhi et al., 2020). In addition, Li et al. (2021) observed a slightly higher TPC during the storage of eggplants treated with acidic EW compared to those treated with SAEW. In the same study, the researchers found that high TPC correlated with the ability of eggplants to scavenge 2,2-diphenyl-1-picrylhydrazyl (DPPH). These results were similar to those reported on rocket leaves subjected to PAW generated by air corona discharge for 5–20 min, which attained higher TPC and total flavonoids (Abouelenein et al., 2023; Laurita et al., 2021). Likewise, Anuchai et al. (2018) reported higher TPC, antioxidant capacity, total flavonoid in “Hom Thong” banana immersed in fine-bubble, and salicylic acid treatment than in untreated control group. In the same investigation, the authors found the amount of DPPH radical scavenging activity to be significantly higher after 15 min treatment using fine-bubble technique compared to other treatments. These findings resonated with Phornvillay et al. (2022) results, who found higher total phenolics, DPPH radical scavenging ability, and total flavonoid on Roselle microgreens immersed in 5% hydrogen peroxide (H_2O_2) + MBs and 5% H_2O_{2n} + UV-C + MBs samples rinsed with distilled water.

Chen et al. (2018) reported a significant decline in TPC including anthocyanin of red cabbages treated with EW. Liu, Yu, et al. (2021) also found that the TPC of “Jingan No. 9” sweet potato slices treated with EW declined within 6 days of storage at 4°C. This finding could be attributed

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to the oxidative property of the EW, which could cause the degradation of polyphenols. Furthermore, the oxidative EW can penetrate cell matrices resulting in dissolution and oxidation of cyanidin and pelargonidin. Castaneda-Ovando et al. (2009) reported that anthocyanins with an *o*-dihydroxyl substitution, such as cyanidin, delphinidin, and petunidin, are the most susceptible to oxidation. Perinban et al. (2022) recent findings revealed that chlorophyll content of kale and spinach was significantly reduced after being treated with PAW generated with a longer activation time.

The observed demerits of EW and PAW on bioactive compounds of FFVs could be related to differences in pH, ACC, ORP, plasma source, activation and treatment time, plasma configurations. Therefore, appropriate pH, ACC, and treatment time should be taken into consideration before washing FFVs with EW. In addition, apart from plasma sources applied, the treatment time, and gases used, factors such as the distance between the liquids and plasma plume or the nature of electrodes might influence the accuracy of results reported above, which necessitate further research as PAW is a new novel technology.

5 | IMPACT OF ACTIVATED WATER SYSTEMS ON SPOILAGE AND MICROBIAL SAFETY OF FRUITS AND VEGETABLES

5.1 | Electrolyzed water

The impact of EW for inactivating microorganisms on FFVs has been extensively reviewed (Lu et al., 2022; Rebezov et al., 2022; Villarreal-Barajas et al., 2022). Spoilage and contamination of FFVs due to fungi, bacteria, and virus infections can cause severe illnesses in humans. To ensure the safety of FFVs for human consumption and prolong the shelf-life of FFVs, EW has been widely proven to be one of the most advanced treatments in inactivating microbial pathogens. The sanitizing effect of various EW types against certain microorganisms is shown in Table 5. NEW is effective in inhibiting FFVs disease incidences induced by various fungi, bacteria, and viruses on “Ramses” tomato fruits (Vasquez-López et al., 2016), “Nemo-Netta” tomatoes (Sibomana et al., 2017), and spinach leaves (Ogunniyi et al., 2020) during storage. These studies demonstrated that EW could result in a significant reduction of rot incidence in FFVs.

With respect to the effects of AWS on viruses, there are limited studies on this area (Fang et al., 2016). For example, Huang et al. (2019) observed a reduction in MS2 bacteriophage viral load of approximately 1 $\log_{10}$ on strawberries washed with NEW, which was more than with tap water washing. Similarly, NEW was found to be effective at inactivating murine norovirus strain 1, MS2 bacteriophage, and hepatitis A on blueberries (Leblanc et al., 2021).

Various studies in which for the application of acidic EW was tested showed the inactivation of various microorganisms during the postharvest handling of mung bean sprouts (Liu & Yu, 2017), broccoli sprouts (Puligundla et al., 2018), and longan fruits (Chen, Xie, et al., 2020). According to Chen, Xie, et al. (2020), the acidic EW treatment enhanced the fruit disease resistance through promoting the activities of some disease-resistant enzymes, boosted H_2O_2 content, increased the activities of antioxidant enzymes, and maintained high levels of nonenzymatic antioxidant systems. Liu and Yu (2017) associated the effectiveness of acidic EW with higher ACC and lower pH.

Akther et al. (2023) applied a SAEW treatment to fresh cut cauliflower, which led to yeasts and molds log reduction of 3.59 ± 0.09 log CFU g^{-1} compared to 6.24 ± 0.25 log CFU g^{-1} (control). Similarly, a SAEW, fumaric acid (FA), and antioxidant solution treatments showed that total bacterial count was reduced for yellow and red fresh cut bell pepper (Saravanakumar et al., 2021). In another study, a SAEW combined with FA inhibited the growth of *E. coli* O157:H7 and *Listeria monocytogenes* on fresh fruits, including apple, mandarin, and tomato (Chen et al., 2019). Cap et al. (2020) reported that SAEW significantly reduced *Salmonella* populations in lettuce. Moreover, SAEW inactivated *L. monocytogenes* Scott A and *S. aureus* biofilm cells within 5-min treatment (Yan et al., 2022). In general, SAEW treatments have shown to be effective in decontaminating FFVs against yeasts, molds, and bacteria over a short exposure time and are reported to be a more stable sanitizer than acidic EW. Additionally, the abundant active species under 2.2–6.5 pH range is HOCl, which is a powerful oxidizing agent responsible for microbial inactivation (Block & Rowan, 2020).

So far, it is evident that the application of EW has been mainly focused to control fungi and bacterial growth on FFVs. However, EW has proved to be effective in killing enteric viruses linked to most foodborne outbreaks such as human noroviruses and hepatitis A virus (Bozkurt et al., 2021; Fang et al., 2016; Li et al., 2015). Enteric viruses have been detected in strawberries, raspberries, blueberries, cherries, and mixed berries, as well as in leafy greens (Brassard et al., 2012; Li et al., 2015; Parada-Fabian et al., 2016). Generally, EW delays spoilage in FFVs by inactivating fungi, bacteria, and viruses. However, from the above studies, the germicidal effectiveness of EW could be influenced by various factors, such as type of infection (natural or inoculated), concentration of inoculated microorganism, inoculation time and inoculation method (immersion or spray atomization), diameter of the lesion on the commodity surface, fruit or vegetable tissue,

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TABLE 5 Effect of electrolyzed water treatments on microbial inactivation in fresh fruit and vegetables (FFVs).

FFVs	Target microorganism (s)	EW treatment parameters: Type	pH	ACC (mg L^{-1})	ORP (mV)	Exposure (min)	Storage conditions	Microorganism reduction	References
Tomato	*Galactomyces geotrichum*	NEW	7.0	10	850	3, 5, and 10	22°C, 8 days	40%–50%	Vásquez-López et al. (2016)
				30				10%–50%	
				60				60%–70%	
Mung bean sprouts	Yeast and molds	AEW	3.87	7.81	NA	10	NA	0.24 log CFU g^{-1}	Liu and Yu (2017)
			3.27	27.48				1.06 log CFU g^{-1}	
			2.88	44.32				1.42 log CFU g^{-1}	
			2.76	69.14				1.92 log CFU g^{-1}	
Tomato	Fungi	NEW	6.5	200	800	5	16–28°C, 28 days	2.3 log CFU g^{-1}	Sibomana et al. (2017)
Pineapple	*Fusarium* sp.	AEW	NA	100, 200, 300	NA	10	28°C, 7 days	68.75% at day 3	Whangchai et al. (2017)
Broccoli sprouts	Yeast and molds	AEW	3.66	230	NA	Dipped every 2 s for 60 s	NA	1 log CFU g^{-1}	Puligundla et al. (2018)
Apples, mandarins, and cherry tomatoes	*Escherichia coli* O157:H7 and *Listeria monocytogenes*	SAEW + FA	5.42	30	818	3	NA	2.31–4.08 log CFU $fruit^{-1}$	Chen, Tango et al. (2019)
Longan	*Phomopsis longanae* and *Lasiodiplodia theobromae*	AEW	2.5	80	1490	10	25°C, 6 days	22%	Chen et al. (2020)
Eggplant	Yeast and molds	SAEW	6.25	31	861	5	4°C, 8 days	6.5 log CFU g^{-1}	Li, Yue et al. (2020)
		AEW	2.34	51	1176	5		6 log CFU g^{-1}	
	Aerobic bacteria	SAEW	6.25	31	861	5		7 log CFU g^{-1}	
		AEW	2.34	51	1176	5		6.5 log CFU g^{-1}	
Tumeric	*E. coli*	AEW	2.39	400	250	10	NA	1.84 log CFU g^{-1}	Keatsirirote et al. (2020)
Fresh cut mango	*Salmonella spp.*	NEW	8.1–8.5	75–300	−800		3°C, 12 days	100%	Lopes et al. (2021)
Fresh cut yellow and red bell pepper	*Salmonella enterica* Typhimurium	SAEW + fumaric acid + calcium oxide	≈2.5	NA	NA	2	4 and 15°C, 15 days	4.9- and 4.2-fold	Saravanakumar et al. (2021)

(Continues)

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TABLE 5 (Continued)

FFVs	Target microorganism (s)	EW treatment parameters: Type	pH	ACC (mg L^{-1})	ORP (mV)	Exposure (min)	Storage conditions	Microorganism reduction	References
Blueberries	Hepatitis A	NEW	NA	200	NA	1, 3, 5, 10, and 20	NA	1–2 log 10 PFU	Leblanc et al. (2021)
	Murine norovirus strain							1–2 log 10 PFU	
	Bovine rotavirus							<4 log 10 PFU	
Cabbage	Human norovirus	SAEW	≈5.5	26.6–50.8	≈975	NA	NA	5.0–5.3 log genomic copies	Kang et al. (2021)
Tomato	*Fusarium oxysporum*			10				20%–50%	
				30				40%–60%	
				60				60%–70%	
Tomato	*Alternaria sp.*			10				30%–40%	
				30				20%–40%	
				60				50%–60%	
"Granny smith" apple	*Botrytis cinerea*	SALEW	≈11	200–500	>−800	5, 10, and 15	5 and 24°C, 21 days	<50% lesion area	Nyamende et al. (2021)
Dried figs	Mesophilic aerophilic bacteria	NEW	7.65	71.4	855	1	25°C, 6 months	0.73 log CFU g^{-1}	Yamaner (2022)
FC pennywort	yeast and molds	ALEW	11	NA	NA	2	NA	2.43 log CFU g^{-1}	Rosli et al. (2022)
FC cauliflower	Yeast and molds	SAEW	5.5–5.6	≈40	800–900	10	NA	≈3.6 log CFU g^{-1}	Akther et al. (2023)
	Aerobic bacteria							≈4.0 log CFU g^{-1}	

Note: microorganism reduction refers to % or log reduction of treated microorganism in comparison with the control group (untreated microorganism) after a specific exposure time or reduction in lesion area of inoculated fruits.

Abbreviations: AEW, acidic electrolyzed water; ALEW, alkaline electrolyzed water; ACC, available chlorine concentration; NEW, neutral electrolyzed water; NA, not available; ORP, oxidation-reduction potential; SAEW, slightly acidic electrolyzed water; SALEW, slightly alkaline electrolyzed water.

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treatment method (immersion or spray atomization), pH, ACC, ORP, treatment time, and storage conditions (packaging, temperature, and relative humidity) (Villarreal-Barajas et al., 2022). Moreover, efficacy of EW is reduced when it interacts with organic matter. Thus, rewashing with EW would be a good practice to ensure microbial safety of FFVs during processing. According to literature, acidic and SAEW are strong sanitizers compared with the other EW types and have been shown to achieve sanitization of FFVs in a short period of time compared with neutral, slightly alkaline, and alkaline EW. Therefore, for future application in preserving FFVs, SAEW can be recommended since based on experimental findings, it is less harmful, not corrosive, and rapidly sanitizes FFVs.

5.2 | Plasma activated water

Research that explored the microbial inactivation of PAW treatment against various microorganisms was mostly conducted in vitro with little in vivo investigations dedicated to sanitizing FFVs as shown in Table 6. Nonetheless, the fungicidal effect of argon/oxygen PAW was investigated by immersing button mushroom in PAW, and the OH, $^1O_2$, and $\bullet O_2^-$ ROS generated resulted in a 0.5 log reduction for total aerobic fungi during 20°C for 7 days storage (Xu et al., 2016). Similarly, Ma et al. (2016) documented that OH and NO ROS generated from air PAW reduced total aerobic fungi to 1.1 log for Chinese bayberry stored at 3°C for 8 days. In another study, PAW generated with micro-plasma array device resulted in 1.04 and 0.77 log reduction for yeasts and molds, respectively, on fresh cut pears surface during storage for 12 days at 4°C. These results were consistent with those reported by Xiang, Kang et al. (2019) and Liu et al. (2020). After treatment with air-PAW and O_2-PAW for 30 min, nitrates, nitrites, and hydrogen peroxide that were produced reduced the populations of *Colletotrichum gloeosporioides* spores by 96% and 55%, respectively (Wu et al., 2018). The above investigations revealed that PAW can inactivate fungal pathogens on whole and fresh cut FFVs without, as reported by the authors, causing any changes in organoleptic properties and antioxidant capacities and maintaining the overall quality.

Furthermore, as outlined in Table 6, PAW could effectively inactivate several bacterial strains including aerobic bacteria, thereby promoting the safety of FFVs. PAW prepared with plasma jet produced OH, $^1O_2$, H_2O_2, and O_3 reactive species, which led to 0.38 and 0.53 log reduction of *Saccharomyces cerevisiae* after 30 and 60 min, respectively, on fresh grapes (Guo et al., 2017). Moreover, Joshi et al. (2018) observed population reduction of *Enterobacter aerogenes* B 199 A on grapes, tomatoes, limes, and spiny gourds treated with PAW for 3 min at 50 rpm. In addition, PAW with O_2 or air led to lower log reductions for iceberg lettuce and red leaf lettuce with no significant changes in leaf color parameters (Khan & Kim, 2019). PAW also exhibits antibiofilm activity and can disrupt formed biofilms (Chen et al., 2016; Ercan et al., 2014; Handorf et al., 2020; Smet et al., 2019). Furthermore, PAW reactive species (H_2O_2, NO_2^-, and NO_3^-) efficiently inactivated bacteriophages T4, Φ174, and MS2 (Guo et al., 2017). In addition, H_2O_2 generated from PAW could completely inactivate Newcastle virus disease following a 30 min exposure (Su et al., 2018).

According to Xu et al. (2020), the long-lived RONS are reported to play key roles in PAW-mediated inactivation of microorganisms; these RONS interact with the microbial cell wall and membrane to induce inactivation. For FFVs industrial application purpose, critical factors such as type of feeding gas, activation time, nature of electrodes, and the distance between the liquid surface that will subsequently affect the generation of RONS should be considered (Liu et al., 2017; Thirumdas et al., 2018). For example, PAW generated with air (O_2 and N_2) and water will lead to the production of numerous primary active species (OH, O, N, O_2^-, and $\bullet NO$) and ultimately contribute to the generation of secondary active species (such as NO_3^-, $\bullet NO$, and H_2O_2), which impact on the PAW germicidal efficacy (Thirumdas et al., 2018).

Energy consumption (input voltage, power, and frequency requirements) or energy efficiency is also a critical factor for effective microbial inactivation in the design of PAW devices. Pemen et al. (2017) observed a 0.8 log reduction of *Staphylococcus epidermidis* after 20 mi treatment with 90 W of PAW, meanwhile 120 and 150 W achieved 2.8–4.0 log reduction after 10 min treatment. Qi et al. (2018) results showed that reduction rate of *Shewanella putrefaciens* (2.0 log) positively correlated with the voltage (6–12 kV) of applied PAW. The authors showed that the solution became more acidic with higher concentration of ROS. This emphasizes the need for optimization of PAW systems that are energy efficient but efficacious with short contact time.

5.3 | Micro–nano bubbles

Few research studies exist regarding the efficacy of MNB to inactivate microorganisms as summarized in Table 7. This is because the application of MNB is an emerging technology in the field of food science, crop production, and postharvest quality management of FFVs (Liu et al., 2019; Li, Wang, et al., 2022). An in vitro study by Saijai et al. (2019) recorded a reduction in *E. coli* after treatment with 0.1 mg O_3 L^{-1} MNB generated for 60 min. Similarly, MNB

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TABLE 6 Effect of plasma activated water on microbial inactivation in fresh fruits and vegetables (FFVs).

FFVs	Target microorganism	PAW properties		Exposure (min)	Storage conditions	Impact on microorganism (s)	References
		PAW discharger	Preparation parameters				
Strawberries	*Staphylococcus aureus*	Plasma jet	18 kV, 10 kHz, 2 cm distance, 98% Ar þ 2% O_2 (5 L min^{-1}), 80 mL of SDW, 10 or 20 min	5, 10, and 15	20°C, 4 days	1.6–2.3 log CFU g^{-1} at day 0; 1.7–3.4 log CFU g^{-1} at day 4	Ma et al. (2015)
Chinese bayberry	Total aerobic bacteria and fungi	Plasma jet	20 kHz, 3 cm distance, air (260 L h^{-1}), 1600 mL of SDW, 25 min	0.5, 2, or 5	3°C, 8 days	Day 0: 0.8 log for bacteria, 0.4 log for fungi; day 8: about 1.1 log for bacteria and fungi	Ma et al. (2016)
Button mushrooms	Total aerobic bacteria and fungi	Plasma jet	18 kV, 10 kHz, 1 cm distance, 98% Ar þ 2% O_2 (5 L min^{-1}), 500 mL SDW	5, 10, and 15	20°C, 7 days	1.5 log for bacteria and 0.5 log for fungi at day 7	Xu et al. (2016)
Grapes	*Saccharomyces cerevisiae*	Plasma jet	8.2 kV, 1.1–1.3 mA, 1.5-mm distance, air at 1.2 L min^{-1}, 20 mL SDW, 30 or 60 min	30/60	NA	PAW 30 min: 0.38 log; PAW 60 min: 0.53 log	Guo et al. (2017)
FC endive lettuce	Total viable count	PLexc2 plasma source	NA	–	2°C, 7 days	Day 0: 0.64–1.6 log CFU g^{-1}; day 7: 0.27–0.95 log CFU g^{-1}	Fröhling et al. (2018)
Grape tomatoes, limes, and spiny gourds	*Enterobacter aerogenes* B 199 A	NA	295 V, 22.5 kHz, 8.1 cm distance, air (1.990 bar), 200 mL of SDW, 5 min	3	NA	1.98 log for grape tomatoes, 1.77 log for limes, 1.03 log for spiny gourds	Joshi et al. (2018)
FC pears	Total aerobic bacteria, yeasts, and molds	Microplasma array device	6, 8, or 10 kV; 9.0 kHz, air at 1.0 SLM, DW	5	4°C, 12 days	12th day: 0.11–0.65 log for total aerobic bacteria, 0.84–1.04 log for yeasts, and 0.31–0.77 log for molds	Chen et al. (2019)
Mung bean sprouts	Total aerobic bacteria, yeasts, and molds	Plasma jet	5 kV, 40 kHz, compressed air (0.18 MPa, 30 L min^{-1}), 0.5 mm distance, 200 mL of SDW	30	NA	2.32 log for total aerobic bacteria and 2.84 log for yeasts and molds	Xiang et al. (2019)

(Continues)

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TABLE 6 (Continued)

FFVs	Target microorganism	PAW properties: PAW discharger	PAW properties: Preparation parameters	Exposure (min)	Storage conditions	Impact on microorganism (s)	References
FC iceberg and red leaf lettuce	*S. typhimurium*	Microplasma discharge	O_2 or air	1 and 30	NA	3.0 log for iceberg lettuce; 2.6 log for red leaf lettuce	Khan and Kim (2019)
FC iceberg lettuce	*P. fluorescens* and *Listeria innocua*	Submerged DBD plasma	20 kV, 7.45 W, 25.8 kHz, air, 700 mL of SDW	0–10	5 min	*P. fluorescens*: reduced below detection limit *L. innocua*: ≈2.4 log after 5 min treatment	Patange et al. (2019)
FC spinach leaves	Total aerobic bacteria	Surface barrier discharge	36 W, 11 kV, 12 kHz, 44.8-mm distance, air, DW, 20 min	2	at 4°C for 8 days	≈1 log	Vaka et al. (2019)
FC kiwifruit	*S. aureus*	Microplasma jet	10 kV, 8 kHz, air at 1.0 SLM, 40 mL of DW, 30 min	NA	4°C for 8 days	1.8 log CFU g^{-1} on the 8th day	Zhao et al. (2019)
FC apple	Total aerobic bacteria, molds, yeasts, and coliforms	Microplasma array device	8 kV, 7.0 kHz, air at 1.0 SLM, DW, 10 min	5	4°C for 12 days	1.05 log for aerobic bacteria, 0.64 log for molds, 1.04 log for yeasts, and 0.86 log for coliforms	Liu et al. (2020)
FC lettuce	Total plate count	PLexc^2 plasma source	DW for lab-scale experiment, tap water for upscaled experiment	NA	NA	Up to 5 log	Schnabel et al. (2020)
Sliced potatoes and white radishes	GFP-*Pectobacterium carotovorum* 10057	Microplasma jet	1 cm distance, N_2, sterile PBS, 5 min	NA	NA	NPB exerted strong antibacterial effect on GFP-*P. carotovorum*	Seo et al. (2020)
Grapes	*S. cerevisiae*	Plasma jet	5 kV, 750 W, 40 kHz, compressed air (0.18 MPa, 30 L min^{-1}), 300 mL SDW, 90 s	30	25°C	0.39 log	Xiang et al. (2020)

Note: DBD, dielectric barrier discharge; DW, distilled water; FC, fresh cut; NA, not available; PAW, plasma activated water; SDW, sterile distilled water.

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TABLE 7 Effect of micro–nano bubbles on microbial inactivation in fresh fruits and vegetables (FFVs).

Sample	Target microorganism	Treatment parameters: Gas concentration	Treatment parameters: Diameter	Exposure (min)	Storage conditions	Impact on microbes/ Log reduction	References
In vitro	*Bacillus subtilis* spores	140 mg L^{-1} O_3	49.7 μm	NA	NA	5.2 log reduction	Zhang et al. (2013)
FC Pineapple	*Escherichia coli* O157:H7	0.14, 0.12, 0.06, and 0.03 mg O_3 L^{-1}	NA	10 min	28°C, 2 days	<1 log CFU g^{-1}	Chuajedton et al. (2016)
Chinese cabbage	Total bacterial count	O_3	110 nm	120 s	NA	3.7 log CFU g^{-1} by ozone MNBs	Ushida et al. (2017)
In vitro	*E. coli*	0.1 mg O_3 L^{-1}	NA	NA	NA	3.3 log10 CFU mL^{-1} after 60 min of generation	Saijai et al. (2019)
In vitro	*E. coli* O157:H7 and *Listeria monocytogenes*	Air, CO_2, and N_2	NA	NA	NA	CO_2-MNB ≈ 2.7 logs for both pathogens	Singh et al. (2021)
In vitro	*E. coli* O157:H7, *Vibrio parahaemolyticus*, and *L. innocua Biofilms*	40 mg L^{-1} O_2		10 min	NA	Completely removed *V. parahaemolyticus* biofilm; 1–3 log CFU cm^{-2} reduction of *E. coli* and *L. innocua*	Shiroodi et al. (2021)
Spinach leaves	*L. innocua* and *E. coli* O157:H7	O_2 combined with ultrasonication	NA	10 and 15 min		6 log CFU mL^{-1} reduction after 15 min and 7 log CFU mL^{-1} reduction after 10 min of *L. innocua* and *E. coli*	Rafeeq and Ovissipour (2021)
		O_2 gas combined with ultrasound				2 and 4 log CFU cm^{-2} of *L. innocua* and *E. coli*, respectively	
Roselle microgreens seeds	*E. coli*	H_2O_2 + UV-C + MNB	NA	15 min	NA	*E. coli* reduced to non-detectible levels	Phornvillay et al. (2022)

Abbreviations: FC, fresh cut; H_2O_2, hydrogen peroxide; MNB, micro–nano bubbles; NA, not available; UV-C, ultraviolet-C.

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(40 mg L^{-1} O_2) for 10 min completely removed *V. parahaemolyticus* biofilm and resulted in 1–3 log CFU cm^{-2} reduction of *E. coli* and *L. innocua* (Shiroodi et al., 2021). In another in vitro study, CO_2-MNB resulted in 2.6–2.7 logs reduction for *E. coli* O157:H7 and *L. monocytogenes*. Soaking with MNB + H_2O_2 + UV-C for 15 min successfully eliminated *E. coli* to non-detectible levels on Roselle microgreens seeds (Phornvillay et al., 2022).

The curative capability of gaseous MNB was also tested in various studies. For example, fresh cut pineapples inoculated with 10^8 CFU mL^{-1} of *E. coli* O157:H7 and washed with varying O_3 concentrations of MNB (0.14–0.03 mg O_3 L^{-1}) for 5–30 min. The washing step for 10 min significantly reduced *E. coli* O157:H7 after 2 days of storage at 28 ± 1°C (Chuajedton et al., 2016). A synergistic study combining pure O_2-nanobubble solution followed by ultrasonication for 5–20 min against an initial count of 6–7 log CFU mL^{-1} *E. coli* O157:H7 and *L. innocua* on spinach leaves was performed; the treatment resulted in >6 log CFU mL^{-1} reduction of *L. innocua* after 15 min and 7 log CFU mL^{-1} reduction for *E. coli* after 10 min. Nanobubbles in combination with ultrasonication also improved bacterial removal from the surface of spinach leaves, eliminating >2 and 4 log CFU cm^{-2} of *L. innocua* and *E. coli*, respectively (Rafeeq & Ovissipour, 2021). Le Nguyen et al. (2019) demonstrated that dipping “Donatello” melons ozone-infused microbubbles for 5 min and hot water microbubbles for 2 or 5 min were the most effective treatments in killing mesophilic aerobes. These findings agreed with those reported by Ushida et al. (2017) results who found a significant reduction in viable bacterial count to 3.7 log CFU g^{-1} from an initial microbial load of 6.1 log CFU g^{-1} on Chinese cabbages after washing with ultrafine ozone-rich bubble (O_3-MNB). It is important to note that, amongst the three AWS, MNB application in FFVs is immature and rarely explored whilst it presents better advantages compared with EW and PAW in terms of operation costs and ease of application (Kim et al., 2017). In addition, there are no reports detailing MNB inactivating microorganisms while compromising FFVs quality (Le Nguyen et al., 2019).

5.4 | Mechanism of microbial inactivation by activated water systems

A schematic diagram showing the microbial inactivation mechanisms for the AWS is summarized in Figure 3. Cell membranes are the first target for microbial inactivation by AWS; this includes reactive species such as HOCl, Cl^-, Cl_2 OCl^- from EW and RONS from PAW and MNB. These particles and reactive species play an essential role in the antimicrobial efficacy (Akbulut & Eldeniz, 2019). Through passive diffusion, reactive species attacks the cytoderm, intracellular including the components and outer membranee (Figure 3). In addition, HOCl produces Cl^- and ROS (O^- and OH^-) causing substantial disturbance to intracellular components, disruption of normal cellular functions, and microbial ultrastructures in various degrees (Yan et al., 2021).

Similarly, the antimicrobial mechanism of PAW has also been explained owing to the oxidative stress on the cell membranes of microbial cells. After PAW treatment, structural changes were observed in the microbial cells, such as cell shrinkage and holes on the surface of cytoderm (Shen et al., 2016; Xiang et al., 2018), and the deformation of external viral shape Su et al. (2018). Moreover, AWS disrupts the microbial cell membrane integrity and membrane potential, leading to lipid peroxidation, leakage of intracellular components including proteins and nucleic acids, alteration in the DNA structure and chemical bonds and an increase in intracellular RONS levels (Zhang et al., 2016, 2020).

On the other hand, the antimicrobial mechanisms of MNB have not yet been fully investigated; however, a few studies are available. Transmission electron microscopy and excitation-emission matrix spectra analysis revealed that *B. subtilis* spore coats were damaged after exposure to O_2-MNB enhanced visible light photocatalytic water (Fan et al., 2021). Therefore, antimicrobial mechanism of MNB is proposed to be like the action of EW and PAW. In general, the recent studies of antimicrobial mechanism of AWS have mainly focused on changes in cellular structures, metabolism, and physiological functions of treated samples. Nevertheless, the impact of AWS on microbial gene expression and protein synthesis is not yet fully understood. Thus, future studies need to explore the antimicrobial efficacy of AWS at proteomic, metagenomic, and transcriptomic levels for the improvement of microbiological safety of FFVs.

6 | SAFETY, REGULATION ISSUES, AND LIMITATIONS FOR ADOPTION

Generally, these AWSs are considered safe and environmentally friendly technologies for the preservation of FFVs due to no residual waste generated and no negative impact on human health and the environment (Chakka et al., 2021). Amongst the three major AWS discussed in this work, EW treatment systems have been the most researched and upscaled commercially. Ampiaw et al. (2021) recently provided a list of EW generators that are commercially available. Other industry use of EW includes clinical application (Yan et al., 2021), as cleaning-in-place for dairy farms by Dairy Practices Council (Iram et al.,

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2021); and fresh/fresh-cut produce industry (Nyamende et al., 2023). For instance, one of the primary reactive agents generated in EW is HOCl, in 2017, the United States, Food and Drug Administration authorized the use of HOCl for cleaning food contact surfaces (Yan et al., 2021). Japan approved the use of EW as a food additive (Huang et al., 2008), and the United States Department of Agriculture accepted the application of EW in organic products to facilitate a sustainable solution for food system hygiene (Zhang, Cao et al., 2021). Similarly, after series of stipulated guidelines published in 2020 by the Chinese Standardization Administration, EW was approved for washing hands (Ampiaw et al., 2021). Overall, the EW has been approved by an increasing number of food and agricultural regulators globally, and its safety is being recognized by consumers (Wang et al., 2022). Besides the successful commercialization and governmental approvals, there are still barriers to the adoption of EW systems in packhouses and operation line. Most of these barriers are linked to the need for further research and development of a cost-effective EW. This include: (i) concerns over the long-term stability and effectiveness of bulk EW either produced on-site or transported to site; (ii) the impact of source water properties (such as pH, mineral and organic matter content, and temperature) on the efficacy of generated EW; (iii) investigation focused on the corrosion rate and/or anticorrosion of machinery connection joints due to regular cleaning or cleaning-in-place strategies using EW; and (iv) there is still a need for concerted effort by regulatory agencies and researchers to clarify the safety of EW to the general public as an alternative chlorine-based disinfectant. This will foster the broader adoption of the EW generator technologies.

In contrast to EW technology, relatively research publications based on the application of PAW for preservation of FFVs have grown only in the last decade (Wang et al., 2022). However, these studies were conducted at laboratory scale and under controlled environmental settings. Commercially available PAW systems have been used for the treatment of water (e.g., https://www.ingersollrand.com/en-au/ionsolutions/livestock, https://vitalfluid.com/plasma-activated-water/), cleaning of agricultural (controlled) environment (https://www.ingersollrand.com/en-au/ion-solutions/cea), and as plant growth stimulant (https://www.advancedplasmasolutions.com/plasma-applications/agriculture/). Other PAW systems are available for medical sterilization, wound healing, and surgery (Siddique et al. et al., 2019). Recently, Toyokawa et al. (2017, 2018) developed a roller conveyer plasma device, which generates plasma via an atmospheric pressure DBD. This roller conveyer plasma device was successfully applied for the disinfection of fungus-contaminated citrus (Sakudo & Yagyu, 2021). Based on the available literature, the PAW technology is still in its infancy; however, a broader adoption of this emerging device could be achieved if the following barriers and challenges are addressed. First, public safety is a critical factor for the industry adoption of PAW. Therefore, research focused on toxicity assessment is crucial to establishing regulatory standards. This should include assessing potential health risks of RONS generated from PAW in FFVs. Based on data available on ozone, the United States Food and Drug Administration did establish specific safety standards governing the amount of ozone in plasma (Hernández-Torres et al., 2021). Second, due to the complexity of PAW chemistry (discharged plasma, source water, water constituents, etc.), plasma processing systems and optimization for large scale applications remain a challenge and require further interdisciplinary investigations. Third, numerous studies have confirmed the decontamination efficacy of PAW. However, investigations on (i) the development antimicrobial resistance pathways in food pathogens should be considered, (ii) the decontamination effectiveness of PAW as a function food types (e.g., surfaces) and initial microbial load is crucial for standardizing applications, and (ii) the disinfection/inactivation rate (lethality and recovery rate) of microorganisms after plasma activated water treatment. This will provide additional data on the risk assessment of PAW and encourage commercial adoption.

Generation of MNB has been dominantly produced using ozone as a working gas to sterilize FFVs (Chuajedton et al., 2016; Fan, 2021). However, ozone has a lower half-life in aqueous phase than in gas phase. Moreover, at 20°C, dissolved ozone in water decomposes rapidly within 20 min (Batakliev et al., 2014). Furthermore, it is known that excess levels free radicals and oxidants can cause oxidative stress; a harmful process that can negatively affect cellular structures, including that of humans. Like the EW systems, the MNB generator technology has been commercially successful for diverse bioremediation of water bodies (lakes, dams, and ponds) and wastewater-related treatments (Khan et al., 2020; Singh et al., 2021). For FFV applications, MNB has shown promising results in maintaining quality and safety. However, there are still several drawbacks, which need to be resolved from the generator design and development to the fresh produce industry. This includes the instability of MNB due to the rapid change in the dissolved gas concentration, which could be impacted by lack of appropriate storage and infrastructure (Park et al., 2020). In addition, several factors, such as storage/holding temperatures, pH, source water quality, and operating systems, require further optimization to establish relevant standard or desired concentration of RONS and activated particles derived from MNB. This implies that the use of AWS with lower levels of reactive species

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should be encouraged to curb potential food safety hazards (Esua et al., 2021). Similarly, the complexity of maintaining the optimum gas and/or water flow rate, ensuring consistent process time, regulating the pumping device, and optimizing the mechanical parts (e.g., variable-pitch spiral cavitation). Therefore, more investigation is required for the process optimization and the design of low-cost MNB generators.

7 | CONCLUSIONS AND FUTURE PERSPECTIVES

Recently, the application of AWS on a variety of FFVs for quality preservation and germicidal activity has been extensively studied. The data collected thus far indicates that AWS can assure postharvest quality of FFVs through inhibition of surface browning, weight and texture loss, and alleviation of high RR and C_2H_4 production. Reviewed studies also revealed that AWS can promote the development of bioactive compounds and the ability to scavenge DPPH. However, the impact of MNB, HRW, and PBAW in FFVs quality attributes is not sufficiently reported in literature, and further studies are needed. Furthermore, EW and PAW have minimal effects on sensory qualities of FFVs. Contrarily, MNB offers a broad spectrum of application to either accelerate or delay ripening of FFVs. Nevertheless, the detailed mechanism of AWS to inhibit surface browning and develop bioactive compounds must be elucidated in forthcoming studies. From several researchers, EW was associated with deleterious effects on FFVs such as bleaching and nonenzymatic surface browning when high doses of chlorine species are used. Moreover, PAW should be used immediately after production because the reactive species are short-lived in water due to the slow transfer of RONS between the gas–liquid interface. Synergistic application MNB with either PAW or EW can improve the effectiveness of AWS. This is due to the unique properties of MNB, such as high stability, large specific-surface area, high gas dissolution rate, and generation of free radicals.

Reviewed studies showed that AWSs are strong sanitizers and can be used as alternatives to synthetic chemicals. In addition, antimicrobial mechanisms of EW and PAW are well studied. In contrast, that of MNB is poorly understood. Antimicrobial effectiveness of MNB is dominantly affected by the applied gas, pH, and ORP of water. Meanwhile, germicidal activity of PAW is affected by physicochemical properties, plasma sources, activation time, distance between plasma-plume and liquid surface, voltage, and frequency. On the other hand, EW effectiveness is also influenced by physicochemical properties, including temperature, storage, water hardness, electrolyte type, electrode material, and setting. Therefore, for scale up application, it is important to consider processing factors and storage conditions that limit AWS efficacy. Furthermore, it is worth noting that AWS will yield different sanitizing results depending on the application methods, physiology of FFVs, and type of microorganism. On these grounds, AWSs are promising nonthermal technologies to develop considerable application value in FFVs industry.

AUTHOR CONTRIBUTIONS

Harold K. Malahlela: Conceptualization; investigation; data curation; writing—original draft. **Zinash A. Belay and Gunnar O. Sigge**: Conceptualization; supervision; resources; writing—review and editing. **Rebogile R. Mphahlele**: Conceptualization; writing—review and editing; supervision; resources. **Oluwafemi J. Caleb**: Conceptualization; supervision; validation; project administration; funding acquisition; writing—review and editing.

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CONFLICTS OF INTEREST STATEMENT

The authors disclose no conflicts of interest.

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