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Effect of Plasma Activated Water (PAW) on Fruits and Vegetables

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Abstract In recent time, the consumption of fruits and vegetables has raised, the variety of pathogens of fresh fruits and vegetables has enhanced, and it's believed that pathogens are capable to resisting the stress conditions that are major causes of fresh produce related food-borne ill health. In order to ensure microbial safety and reduce nutrient loss, non-thermal plasma technology has received increasing attention in food preservation applications. Non-thermal plasma has high reactivity and has potential applications in food safety, nutritional quality and environmental safety. Plasma activated water (PAW) abundant source of reactive oxygen species (ROS) and reactive nitrogen species, which can inactive the microorganisms. In addition to its bactericidal activity, it can also be used to degrade pesticide residues and antibiotic residues in water and packaging materials. Non-thermal plasma is applied to water to generate plasma-activated water, potentially applied in fruits and vegetables in recent years. PAW has been successfully applied as washing agent or disinfect agent in fruits and vegetables. In addition, it can inactivate food-borne pathogens on fruit and vegetable contact surfaces and on fruits and vegetables without adverse effect on the environment and human health. Reported findings indicates that plasma activated water has the least affect the sensory parameters and quality of fruits and vegetables. Therefore, it can be potentially applied in fruits and vegetables industry as substitute of traditional washing agent i.e. chlorinated water, quaternary ammonium salts etc. Furthermore, High bactericidal ability and easy to produce plasma activated water function can be used in every food field, such as meat, dairy products, fruits and vegetables and grains. However, the chemistry of PAW is taken into account to be extraordinarily complicated, and controlling the reaction is one in all the challenges for future analysis. Furthermore, it also requires from regulatory agencies to generally recognize as a safe (GRAS) status.

Keywords: *Fruits, Non thermal plasma (NTP), Plasma activated water (PAW), reactive oxygen species, reactive nitrogen specie, vegetables*

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1. Introduction

Fruits and vegetables are known for their health benefits. However, the modern food supply chain is inherently very complex, so most foods require a certain unit operations of processing to maintain their freshness. Such processing may change the functional composition of fruits and vegetables [1]. Recently, the consumption of fresh fruits and vegetables in human diets worldwide has rapidly increased, and consumers continue to eat more fruits due in part to the reported health benefits. However, minimal processing of fruits and vegetables including washing, peeling and cutting can cause mechanical damage to the tissue and even cause adverse consequences such as high microbial load, browning of the cut surface, texture destruction and off- odor development during storage. The minimally treated surface will facilitate the growth of certain pathogenic bacteria and spoilage microorganisms [2]. Microbial contaminations of fresh produce as well as foods are the main concerned in food safety. Due to contamination, it will result in various food born infections as well as illness. The US Centers for Disease Control and Prevention (CDC) reports that 48 million people suffer from food-borne illnesses, of which 128,000 are hospitalized each year and approximately 3,000 die. According to the World Health Organization (WHO) report, 600 million people worldwide experienced food borne illness in 2010 and 420,000 deaths [3].

Pathogenic bacteria, such as Listeria monocytogenes, *Escherichia coli O157:H7, Salmonella spp.*, and *Shigella spp.* may contaminate fresh-cut fruits and vegetables. Therefore, it is necessary to effectively inactivate food borne pathogens on fresh products before reaching the final consumer, which is essential for safe food in any food industry [4]. To ensure microbiological safety, various convectional thermal processing have been utilized such as pasteurization, sterilizations, canning etc. However, this technique has been negative impact on food quality and nutritional view. Because of this, food industry is looking for an alternative for thermal processing. Hence, research has been focused on novel non thermal technology for food preservation. This non thermal technology preserved food with minimum nutritional loss of food [5].

Non-thermal techniques can be defined as preserved food with eliminating or minimized negative thermal effects on nutritional and quality of food and are efficient at ambient or sub lethal temperature. So far, the most concerned non-thermal technologies are high pressure processing, irradiation, pulsed electric field, ozonations, cold plasma, etc. Among them, cold plasma technology has been widely used in food surface decontaminations. In addition to solids, liquids and gases, plasma is taken into account the fourth state of matter. By addition of enough amount of energy to material, eventually generate electrons and ionic gases, which is called "plasma". It consists of positive and negative ions, free radicals, excited and neutral atoms, electrons, ultraviolet photons, and ground and excited molecules. According to the thermodynamic temperature equilibrium of composition, the plasma is divided into thermal plasma (hot) and non-thermal (cold) plasma [6,7]. If a gas is heated to a high enough temperature (usually around 20,000 K) for achieve ionization of the gas, this type of plasma will be called as "thermal plasma." In thermal plasma, all the chemical species compositions such as electrons and ions are in thermodynamic temperature equilibrium. In non-thermal plasma, it is obtained by releasing electricity in gases and also called non equilibrium plasma or cold plasma. The cooling of ions and uncharged molecules is more effective than electrons to transfer energy, and the gas remains at low temperature [6].

The temperature of the cold plasma is below 60°C, depending on the type of plasma jet used. This cold plasma technology is mainly used to inactivate microorganisms and enzyme, enhance seed germinations and improve cooking quality of rice. However, some research reports said that due to etching and degradations of bioactive compounds after surface treatment, some negative effects may occur, such as loss of colour, surface topography changes. To overcome this cold plasma problem, an alternative method for disinfections of food is needed. Therefore, one of the potential uses of cold plasma includes generating plasma activated water to replace chemical disinfectants. This plasma activated water is also called plasma acid, plasma activated liquids, plasma treated water containing reactive oxygen and nitrogen species, which can be used for foods sterilization. Plasma activated water is very easy to use and replace traditional disinfection solutions, used for disinfections of foods [7,8].

Plasma activated water is produced using water, air and electricity. Ambient air enters the plasma phase together with electrical energy to produce plasma activated air. The plasma activated air comes into contact with water. Reactive nitrogen and oxygen (RNOS) are dissolved in water to produce plasma activated water. The plasma activation process takes place in the absence of any other chemical substances and results in the product with obvious broad-spectrum bactericidal activity. It is also worth noting that the activity of PAW is temporary, and PAW will return to pure water after a period of time, further confirming the potential of this method as a green method for inactivating pathogens [9,10].

PAW has many advantages as a disinfectant in fruits and vegetables. Compared with traditional chemical disinfectants, PAW is a more environmentally friendly disinfectant [11], that is, chlorine-related products have the risk of forming carcinogenic by-products, which has caused more and more environmental and public health problems. When the plasma interacts with water, various reactive substances and some free electrons are generated. The reactive substances present in PAW, such as active oxygen and nitrogen substances are mainly responsible for the antibacterial efficiency of PAW [9]. This review focuses on the impact of plasma activated water on quality of fruits and vegetables in terms of microbial inactivation, quality parameters as well as sensory parameters.

2. Producing Systems of Plasma Activated Water

The reactive species present in PAW are mainly responsible for the inactivation of microorganisms, and their concentration and type are affected by the gas and liquid used to generate the plasma, the chemical environment, the excitation voltage and the generation method. Three types of cold plasma discharge generations are mainly used. 1) Direct discharge 2) Indirect discharge 3) Multi-phase discharge. Plasma jet, sliding arc discharge, dielectric barrier discharge (DBD) and surface micro discharge (SMD) are the most common plasma sources used to produce PAW. This is because these types of plasma can effectively transfer RONS from gaseous plasma to liquid phase [12].

2.1. DBD (Dielectric Barrier Discharge) and Plasma Jet System

Basically, cold atmospheric plasma is generated by two methods, particularly direct discharge and indirect discharge. In indirect discharge, the active plasma species are transported by the gas flow from the main discharge arc. In the case of direct discharge, the product is one of the electrodes, which is the active part of the discharge. On the basis of these principle methods, plasma jet and dielectric barrier discharge have been developed and widely used in plasma food. In these two devices, a violet plasma is generated between associate electrode i.e. anode and cathode. Either anode or cathode is covered by a layer of dielectric materials. Generally, quartz is used as dielectric materials.

2.1.1. Plasma Jet Device

In these devices, the anode is connected to high voltage and the cathode is grounded. In some plasma jet devices, the hollow quartz tube is surrounded by a metal cathode (i.e., copper) as a dielectric material. In addition, gases like argon or helium are carried to maintain the formation of cold atmospheric plasma generation. Due to the continuous flow of the carrier gas, a cold atmospheric plasma jet is formed. Therefore, sample is processed by this plasma jet (Figure 1).

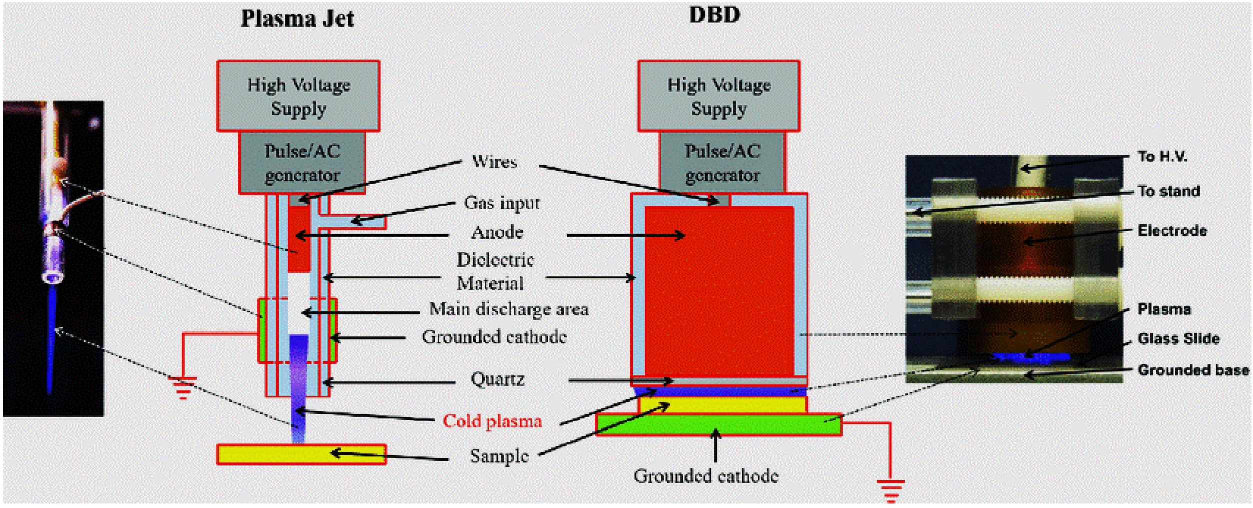

Figure 1. Plasma Jet and DBD Setup (Adopted from [13])

2.2.2. Dielectric Barrier Discharge

In DBD, the configuration is the same as that of plasma jet equipment. However, this device can directly generate plasma in the air. In some cases, carrier gases (such as oxygen and nitrogen) have been used to produce specific chemical components in the plasma. DBD devices tend to produce short and wide plasmas. The main difference between plasma jet and DBD is that the sample are part of the discharge in case of DBD. If the sample is not close enough to the second electrode, the cold atmospheric plasma in the DBD will not be generated [13].

3. Physicochemical Properties of Plasma Activated Water

When the plasma interacts with the liquid, various complex chemical reactions occur in the interface area between the two media, which leads to the production of reactive substance and the physical and chemical properties of the treated solution (including its pH, oxidation-reduction potential (ORP)) and conductivity.

3.1. pH

pH is a measure of the concentration of hydrogen ions in a solution. pH value is mainly caused by the formation of nitric and nitrous acids as well as ONOOH, generated from the NO, NO_2, and NO_x formed in the plasma phase. In addition, the generation of acidic hydronium ions (H_3O^+) by the reaction of the water molecules with H_2O_2 generated in air or liquid might also contribute to the decrease in the pH value. Therefore, acidic pH is play a critical role in the inactivation of microorganisms by PAW [14].

3.2. ORP

ORP reflects the oxidation or reduction ability of a solution, and it is related to the concentration of the oxidant and its strength or activity. The ORP values of PAW displayed a significant increase, mainly depending on the plasma activation time. Of all the ROS generated in PAW, H_2O_2 is believed to be mainly responsible for ORP because it can act as an oxidizing agent (E^0 = 1.77 V) or as a reducing agent (E^0= −0.7 V). Higher the ORP value, stronger is the oxidizing capability, and higher is the antimicrobial property [9].

3.3. Electrical Conductivity

Electrical conductivity, a measure of the ability of an aqueous solution to conduct electricity, depends on the types of ions, their concentrations, and the solution temperature. The presences of extraneous ions in water greatly affect the conductivity. The formation of ROS and RNS during plasma activation of water will contribute to an increase in the conductivity of PAW. The electrical conductivity of PAW increased dramatically with the activation time. As the pH drops, the electrical conductivity of the solution increases which is due to the higher mobility of H^+ relative to OH^- ions.

3.4. Reactive Species

During plasma discharge, various species are generated in the gas, such as nitric oxide radical (·NO), hydroxyl radical ($\cdot OH^-$), superoxide anion radical ($\cdot O_2^-$), atomic oxygen (O), singlet oxygen ($^1O_2$), nitrogen ions (N_2^+), and excited nitrogen molecules (N_2^+). When these reactive species come into contact the liquids, numerous long-lived reaction products are formed, e.g., hydrogen peroxide (H_2O_2), nitrate (NO_2^-), nitrite (NO_3^-), ozone (O_3), peroxynitrite anion ($ONOO^-$), and peroxynitrous acid ($ONOOH^-$). The type and concentration of the reactive species present in the PALs are significantly affected by the plasma device, the working gas, and the liquids used [15].

4. Applications of Plasma Activated Water in Food Industries

Food is contaminated and spoiled by pathogenic organisms during the process of growth, storage, transportation and sales, leading to major health problems and losses of economic. Recently, PAW has shown excellent antibacterial and anti-bio film activities and potentially applied for removing food borne microorganisms or disinfects food borne pathogen in various food industries (Figure 3). In agriculture, PAW has been used to germinate seeds and promote plant growth. The presence of H_2O_2 in PAW can increase catalase, leading to the synthesis of new proteins, thereby helping to enhance seed germination [16]. Reference [17] reported that rye seed germination increased by 50% when treated with PAW for 5 minutes compared with the control sample. In addition, the germination amount of PAW-treated soybean seeds also increased [18].

PAW also successfully applied for the degradations of pesticides, as a thawing agent and curing agent in meat and meat products [12,19]. The Institute for Plasma Research has developed a novel device and method that can use non-thermal plasma to produce plasma activated water. They reported that potatoes treated with PAW shows higher germinations compared to potatoes washed with tap water (Figure 2). In FCIPT (Facilitation Centre for Industrial Plasma Technologies) journal organization reported that tomatoes and potatoes washed with PAW will make them look and maintain their freshness for nearly 40 days at room temperature [20].

Figure 2. Potato washed with PAW and with tap water

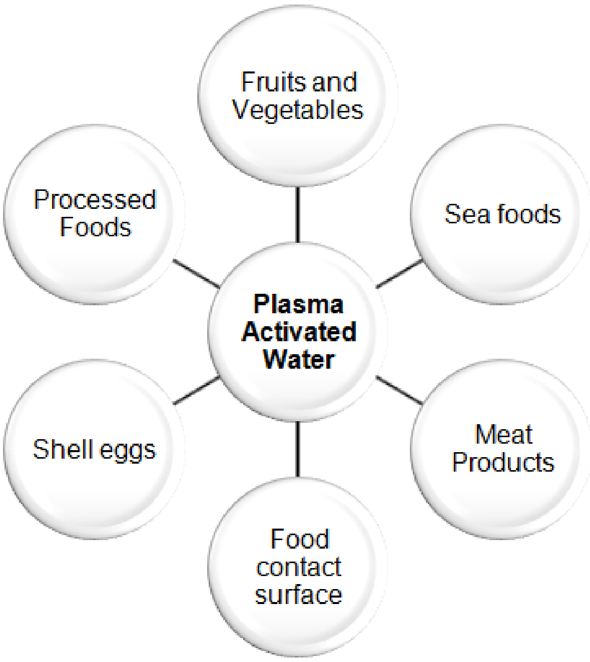

Figure 3. Schematic representations of applications of PAW in various food industries

As far as the fruit and vegetable industry is concerned, the biggest challenge is its high sensitivity to post-harvest spoilage, which leads to huge losses. Washing is one of the important post-harvest operations to prevent fruit from decay and obtain reasonable prices from the market. However, this may leads in residual chlorine on the surface of fruits and vegetables, which may cause serious health issues. In this case, PAW is used as a substitute for chlorinated water because of bactericide activity of species generated during PAW generations. PAW not only helps to reduce microorganisms, but also does not cause changes in firmness of fruits and vegetables.

5. Effect of PAW on Microbial Inactivation of Fruits and Vegetables

PAW has been with success applied to decontamination of fruits like strawberries, bayberry, grapes and vegetables (such as spinach and lettuce). Therefore, the time period of fruits and vegetables is enhanced and therefore the production of waste is reduced. Studies have reported that PAW effectively inactivates aerobic bacteria, yeasts and molds in fruits and vegetables. In addition, PAW is also used to preserve fresh-cut fruits, such as apples, pears and kiwis [2,21,22]. The microbial inactivation depended on the critical parameters such as fruits and vegetables surface texture, treatment or exposure time and power during PAW generations. Therefore, for simultaneously inactivate pathogenic microorganisms, optimizing these key parameters is necessary to maintain the quality of fruits and vegetables [3]. PAW for the inactivation of fruits and vegetables products is outlined in Table 1.

The first study on decontamination of fruits was reported by [4] on strawberry fruits. They found that during processing and storage, PAW activated for 20 minutes can reduce the rate of Staphylococcus aureus bacteria on strawberries (about 3.4 log CFU/g). Later, similar authors reported that compared with the control, Plasma Activated Water treatment was able to reduce the rot of Chinese berries at the end of storage by about 50%, indicating that PAW treatment had no effect on the physical quality of processed foods. In case of bacteria and fungi 1.1 log CFU/g maximum reduction was reported at the end of storage [23]. Moreover, grapes treated with PAW for 60 min were able to reduce *Saccharomyces cerevisiae* count up to 0.53 log CFU/mL [24]. Plasma Activated Acidified Buffer and Plasma Activated Water were also used for decontaminations of *E. aerogenes* on spiny gourds, grape tomatoes and limes [25]. The efficacy of microbial decontamination influenced by the skin surface, the surface of fruits and vegetables, and the composition of texture [24]. Similarly, the smoothest surface showed the highest reduction rate (6.32 log CFU/surface) compared with the roughest surface (2.52 log CFU/surface) after plasma activated acidification buffer treatment [25]. In addition to surface roughness, other surface features, such as surface hydrophobicity and the presence of cuticular waxes, may also influenced inactivation efficiency [3].

Table 1. Microbial inactivation in fruits and vegetables using PAW or PAL

Fruits and Vegetables	Treatment Conditions	Microorganisms	Log reduction	References
Fresh cut iceberg lettuce	Immerse the sample in the Plasma Activated Water for 1, 3 or 5 minutes	*E. coli K12, P. fluorescens, P. marginalis, L. innocua and P. carotovorum*	1.8 to 6.1 log	[26]
Strawberries	Sample were immersed in 5, 10 and 15 min, stored 4 days	*S. aureus*	1.7 to 3.4 log CFU/g at day 4	[4]
Chinese bayberry	Samples were soaked for 0.5, 2, or 5 min in PAW and stored at 3 C for 8 days	Total aerobic bacteria and fungi	On days 8, 1.1 log for bacteria 1.1 log for fungi	[23]
Fresh cut radicchio	Treated sample with PAW for 5, 20, 40 and 60 min	*Listeria monocytogenes*	5 log CFU/g	[27]
Fresh cut celery	Treated sample with PAW for 5, 20, 40 and 60 min	*Listeria monocytogenes*	0.57 CFU/g	[27]
Grapes	Soaked in PAW for 30 min	*S. cerevisiae*	0.38 log for 30 min 0.53 log for 60 min	[24]
Limes, Grape tomatoes and spiny gourds	Washed with PAW for 3 min at 50 rpm	*E. aerogenes B 199 A*	1.03 log for spiny gourds 1.77 log for lime 1.98 for grape tomatoes	[25]
Fresh cut endive lettuces	Washed with or without PAW, stored at 2 C for 7 days	Total viable count	0.27 to 0.95 log CFU/g at days 7	[28]
Limes, Grape tomatoes and spiny gourds	Washed with Plasma activated buffer for 3 min at 50 rpm	*E. aerogenes B 199 A*	1.62 for spiny gourds 1.97 log for lime 2.00 for grape tomatoes	[25]
Fresh cut kiwifruits	Sprayed PAW with 1 mL on sample and stored 8 days at 4 C	*S. aureus*	1.8 log CFU/g at 8 th days	[22]
Fresh cut iceberg lettuce	Washing with PAW for 0 and 10 min	*P. fluorescens and L. innocua*	*L. innocua :* 2.4 log after 5 min *P. fluorescens:* Reduce below detectable limit	[29]
Fresh cut pears	Immersed in Plasma Activated Water for 5 min and stored 12 days at 4 C	Total aerobic bacteria, yeast and molds	Total aerobic bacteria: 0.11 to 0.65 log Molds: 0.31 to 0.77 Yeast: 0.84 to 1.04 log (After 12 days)	[21]
Fresh cut red leaf and iceberg lettuce	Washing with PAW for 1 or 3 min	*S. typhimurium*	Red leaf lettuce: 2.6 log Iceberg lettuce: 3.0 log	[30]
Fresh cut spinach leaves	Rinsed the sample with Plasma Activated Water at 120 rpm for 2 minutes and store at 4 C for 8 days	Total aerobic bacteria	1 log at 8 days	[31]
Fresh cut endive lettuces	Washing with PAW with different treatment	Total aerobic bacteria	Maximum 2 log reduction at pilot scale	[32]
Fresh cut lettuces	Washing with PAW with different treatment	Total Plate Count	Maximum 5 log	[33]
Grapes	Immersed in PAW for 30 min	*S. cerevisiae*	0.39 log	[8]
Fresh cut apple	Immersed apple in PAW for 5 min, stored 12 days at 4 C	Total aerobic bacteria, yeast, molds and coliform	Yeast: 1.04 log Molds: 0.64 Total aerobic bacteria: 1.05 Coliform: maximum 5 log	[2]

Plasma activated water can be used for washing of fresh-cut fruits and vegetables instead of chlorinated water. For instance, fresh-cut celery and chicory treatment with plasma activated water for 60 minutes can efficiently decrease the amount of *Listeria monocytogenes* and *E. coli* [27]. Reference [22] reported that PAW treatment can reduce the populations of *Staphylococcus aureus* in fresh-cut kiwifruit by approximately 1.80 log CFU/g. Reference [21] found that PAW successfully reduced the number of bacteria, molds, and yeasts in fresh-cut pears Similarly, after 12 days of PAW treatment, the maximum reduction of aerobic bacteria (number of aerobic plates), mold, yeast and coliform in fresh-cut apples was 1.05, 0.64, 1.04 and 0.86 log CFU/g, respectively [2]. PAW washing has also been tested on fresh-cut lettuce on a laboratory scale and a pilot scale. Studied have shown that total aerobic count reduced maximum 5 log and approximate 2 log at lab scale and pilot scale, respectively. Additionally, PAW washing treatment not adversely effects on color, texture, surface structure and lettuce tissue cells [33]. At the same time, by washing baby spinach leaves with PAW, the total number of bacteria was reduced by about 1 log CFU/mL [31].

6. Impact of PAW on Quality of Fruits and Vegetables

Reactive oxygen and nitrogen substances present in plasma activated water are the main factors for the change of all the chemical properties of the processed products, such as the nutrients and antioxidants of fruits and vegetables. Table 2 summarizes the detailed chemical properties of fruits and vegetables treated with PAW.

6.1. pH and Acidity

pH and acidity are key factors in most processed foods because they reflect changes in metabolism. Various species present in PAW, such as oxidation reduction potential, reactive oxygen species, reactive nitrogen species and food ingredients, including nutrients present in processed foods, will cause pH changes [34]. Several previous studies have reported that in fruits and vegetables, PAW treatment does not significantly change the pH. For instance, Reference [2] and [8] reported no difference between fresh-cut pears and grapes respectively. Similarly, reference [35] reported that compared with untreated samples, the acidity of Chinese cabbage shreds treated with plasma activated water was not statistically different.

6.2. Vitamins

Vitamins are essential micronutrients in fruits and vegetables. Generally, majority of vitamins are unstable during processing, therefore it's necessary to look into how plasma activated water affects stability of vitamins. According to Reference [21], there was no considerable difference in the ascorbic acid concentration of PAW-treated fresh-cut pears after 6 days storage period as compared to the control. Similarly, no significant difference observed in levels of ascorbic acid in plasma activated water treated grapes compared to DIW and unprocessed groups reported by [36] and [37]. However, the ascorbic acids concentration in fresh-cut apples treated with plasma activated water decreased after 12 days of storage [2]. Overall, these finding show that PAW does not significantly affect ascorbic acids levels in fruits and vegetables. However, further research is needed to investigate the impact of plasma activated water on other vitamins.

6.3. Protein and enzymes

Protein and enzymes found in fruits and vegetables had both positive and negative effects on quality of fruits and vegetables. Enzymes are major concern in fruits and vegetables. Peroxidase (POD) is an enzyme that causes degradation in processed fruits and vegetables, affecting flavor, texture, appearance, and nutrition. Reference [35] reported that there was a statistically significant reduction in peroxidase action in shredded salted Chinese cabbage after plasma activated water treatment. The antioxidant effect of enzymes is necessary to preserve the quality of fruits and vegetables and to extend their shelf life. Superoxide dismutase (SOD) is an enzyme that protects fruits and vegetables from free radical damage [38]. Reference [36] reported that there was no significant difference in superoxide dismutase activity in PAW-soaked grapes compared with the unprocessed and DIW groups. Additionally, superoxide dismutase activity increased in fresh cut kiwifruits after plasma activated water treatment [22]. Overall, PAW is a promising technology to enhance the activity of antioxidant enzymes and reduce certain undesirable enzymes.

6.4. Sugar Content

Carbohydrates are the most common sugar type found in most foods. PAW not significantly affected reducing sugar content in shredded salted Chinese cabbage compared with control groups [35]. In addition, Reference [36] and Xiang [8] also reported that there was no significant change in the sugar content in grapes treated plasma activated water as compared to commercial fresh detergents and DIW. Although the research on the effect of PAW on sugar content is very limited, this will be one of the areas of interest for food scientists.

Table 2. Impact of Plasma Activated Water on quality of fruits and vegetables

Fruits and Vegetables	Conditions	Protein and enzymes	Lipid/MDASugar	pH & acidity	Ascorbic Acid	Total phenolic	References
Fresh-cut pear	Plasma Activated Water	Not Available	Not Available	+	+	-	[21]
Fresh-cut kiwifruit	Plasma Activated Water	SOD (+), POD(+), CAT (+)	Not Available	Not Available	Not Available	Not Available	[22]
Fresh-cut apple	Plasma Activated Water	Not Available	Not Available	Not Available	–	+	[2]
Grape	Plasma Activated Water+ mild Heat	Not Available	Not Available / (+)	+	+	+	[8]
Grape	Plasma Activated Water	SOD (+)	Not Available / (+)	Not Available	+	Not Available	[36]
Grape	Plasma Activated Water	Not Available	Not Available	Not Available	Not Available	Not Available	[24]
Shredded salted kimchi cabbage	Plasma Activated Water+ mild heat	POD (-)	Not Available / (+)	+	Not Available	Not Available	[35]

Note: (+): stable, Compared with the control (untreated), the treated sample has no significant difference or even improvement; (−): Significant difference compared to control (untreated).

7. Impact of Plasma Activated Water on Sensory Attribute of Fruits and Vegetables

Sensory attributes include color, appearance, aroma and taste, which are used for the evolution of sensory performance. Several authors evaluated sensory performance based on this parameter of PAW-treated fruits and vegetables [4,36,39]. From the perspective of consumers, the acceptance of fruits and vegetables mainly depends on these sensory parameters.

7.1. Color

The presence of pigments and chemical reactions such as enzymatic and non-enzymatic browning of fruits and vegetables are primarily responsible for their colour. From the consumer's point of view, color is a key parameter of fruits and vegetables, and it is the main element of the appearance of fruits and vegetables [40]. Color variations in fruits and vegetables are directly observed in their appearance and have a huge effect on customer acceptance.

The effect of PAW on the colour of fruits and vegetables has been noted, depending on the treatment conditions [4]. According to reference [24], there was no major difference in the colour of grapes treated with plasma activated water compared to control grapes. In addition, anthocyanin content in grapes has not been significantly affected. Reference [41] reported variations in color index in tomato after PAW treatment. At the same time, reference [27] noted that the color of fresh-cut radicchio treated with PAW changed significantly. Several studied reported no significant losses in colour of fresh cut apple [2], fresh cut kiwifruits [22], grapes [8,24,36], chinese berry [23], fresh cut endive lettuce [32], shredded salted kimchi cabbage [35] and strawberries [4]. Overall, PAW treatment did not significantly affected on color changes in fruits and vegetables. However, plasma activated water treatment parameters such as treatment time, reactive substances critical factors affect the color changes in fruits and vegetables.

7.2. Aroma and Taste

Sensory characteristics; the taste and aroma of food will particularly affect consumers' decisions regarding food material preferences. These characteristics guide consumers to food sources, preferences, choices, and food satisfaction [42]. Reference [32] reported that the test and aroma of fresh-cut endive lettuce treated with PAW were not significantly different from the control. This result indicates that PAW treatment has no adverse effect on sensory attributes.

8. Future Outlook and Concluding Remarks

In recent years, the antibacterial activity of PAW on a variety of fruits and vegetables has been extensively studied. The data collected so far indicate that PAW can be used to assure the microbiological safety and quality of fruits and vegetables. However, the practical application of PAW in fruits and vegetables preservation and processing still needs further research. In contrast to plasma treatment, PAW is considered to be cheaper and easier to obtain. Therefore, its application has the potential to be used on a commercial scale. However, comprehensive safety assessment PAW must be carried out before practical applications in different areas of the food industry, and regulatory guidelines should be established. Besides that, the toxicity of reactive species and final reaction products created by chemical decontamination, further study into PAW's applications in food is needed. The surface of fruits and vegetables will also affect the inactivation efficiency of PAW, which will attract more attention in future research. Thus, optimizing processing parameters such as surface characteristics of fruits and vegetables, PAW production, exposure time, etc. will require further research for effective inactivation of microorganisms in fruits and vegetables. In the future, it is necessary to combine other antiseptic technologies (such as ultrasound, mild temperature, etc.) to pay attention to the synergistic effect of microbial safety in fruits and vegetables. Therefore, the impact on quality attributes is minimal. However, the sustainability of this technology is dependent on its ability to expand in the future and to operate continuously with minimal maintenance.

In concluding remarks, PAW is an emerging technology that can disinfect the surfaces of fruits and vegetables with minimal impact on product quality. In addition, the literature cited in this review indicates that that PAW have also been applied for inactivation of microorganisms on fresh cut agriculture produce. Therefore, its wide application in fruits and vegetables has attracted widespread attention. In addition, it has minimum adverse effect on the nutritional as well as sensory attribute of fruits and vegetables as compared to commercial disinfectant agent i.e. chlorinated water. Therefore, PAW potentially leading to positive consumer acceptance as compared with product treated with commercial disinfect agent or washing agent. However, further investigations still needed on established of legislation or regulatory guidance specific to PAW treatment on food can be developed by any of the regulatory bodies around the world. In addition, optimization studies are needed to achieve maximum inactivation efficiency and to better understand the toxicity of reactive species generated when PAW is produced. Overall, plasma activated water appears to be a promising environment friendly and cost-effective disinfectant with the potential to improve the safety and quality of fruits and vegetables.

Contribution of Authors

All the authors contributed equally. They read the final version, and approved it for the publication.

Conflict of Interest

The authors declare that they do not have conflict of interest.

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