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RESEARCH ARTICLE

# Effectiveness of Plasma Activated Water Generated by AC Gliding Arc Discharge for Bacterial Inactivation on Strawberries

***Santosh Dhungana[1*], Rajan Karki[2], Akhilesh Kumar Singh[3], Deepak Prasad Subedi[3], Raju Khanal[1], Hom Bahadur Baniya[4*]***

*[1]Central Department of Physics, Tribhuvan University, Kirtipur, Nepal*
*[2]Department of Microbiology, Xavier International College, Kathmandu, Nepal*
*[3]Department of Physics, School of Science, Kathmandu University, Dhulikhel, Nepal*
*[4]Department of Physics, Amrit Campus, Tribhuvan University, Thamel, Kathmandu, Nepal*
**Email: sanein1@yahoo.com; hom.baniya@ac.tu.edu.np*

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## Highlights

- PAW was generated using an AC gliding arc discharge system
- OES confirmed the presence of reactive species (OH, $NO_x$, $N_2$, $N_2^+$)
- Higher voltage, lowered pH and raised ORP and conductivity, boosting PAW reactivity
- PAW acts an efficient, chemical-free approach for fruit sterilization

## Abstract

*This study investigates the effectiveness of plasma-activated water (PAW), generated using an AC gliding arc discharge (GAD) system, for bacterial inactivation on strawberries. The discharge was produced in air between divergent aluminum electrodes powered by 7–10.1 kV at 50 Hz. Optical emission spectroscopy revealed the presence of reactive species such as OH, NOx, $N_2$, and $N_2^+$, confirming the generation of reactive oxygen and nitrogen species (RONS) crucial for antimicrobial activity. Physical characterization of PAW showed a significant decrease in pH (from 6.8 to 4.06), an increase in oxidation reduction potential (from 300 mV to 420 mV) and conductivity (up to 71.33 µS/cm) with increasing applied voltage, indicating enhanced reactivity. The antibacterial efficacy of PAW was evaluated by washing strawberry samples with plasma-treated and untreated water. After 24 hours of incubation, the bacterial colony count for strawberries washed with plasma-treated distilled water decreased from 1100 to 34 CFU/mL. This result demonstrates that PAW generated by AC gliding arc discharge effectively reduces bacterial contamination on strawberries, offering a safe, chemical-free, and sustainable approach for food sterilization and preservation.*

**Keywords:** *non-thermal plasma, plasma-activated water, reactive oxygen and nitrogen species, antibacterial activity, food sterilization*

## Introduction

A distinguishing characteristic of low-temperature plasma or non-thermal plasma is its non-equilibrium nature, where the bulk

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[*] *Corresponding author*

gas remains at or near ambient temperature despite the presence of energetic electrons. There are various methods of producing non-thermal plasma. Among the different methods, one of the simplest discharge systems which can operate in atmospheric pressure is gliding arc discharge (GAD) system (Doria et al., 2018).

GAD system was first invented by Czernichowski in 1988 for the treatment of gaseous pollutants (Bo et al., 2007). In GAD, sparks start between the shortest gap of two divergent electrodes and glide along the direction of air/gas flow (Dhungana et al., 2020). In this situation the plasma or discharge changes thermal (at minimum gap) to non-thermal state when flows through diverging electrodes (Mitsugi et al., 2014). GAD offers a cost-effective approach for producing non-thermal plasma. Owing to its transitional nature between thermal and non-thermal regimes, it can operate at higher power levels than typical corona discharges (Du et al., 2007). At the initial stage of invention, it was used for chemical applications i.e. for oxidation of different types of gases. The work of Czernichowski in the early 1990s established the gliding arc discharge as a promising plasma source for chemical processing, leading to its widespread recognition (Mutaf-Yardimci et al., 2000).

Recent studies have primarily concentrated on applications involving gas conversion and decontamination processes. In the GAD system, energetic electrons generate excited species, free radicals, ions, and ultraviolet (UV) photons, all of which have been reported to contribute to antimicrobial activity (Slade et al., 2025). Du et al. (2006) and Gong et al. (2020) reported that GAD can be applied to remove Polycyclic Aromatic Hydrocarbons (PAHs) and soot particles from fuel gas. As high oxidizing agents, humid air GAD applied to water surfaces has recently been used for degradation of organic pollutants in water (Doubla et al., 2008; Ghezzara et al., 2013). Similarly, GAD system is used to generate plasma activated water (PAW) and plasma activated liquid (PAL) in various fields viz., in agriculture, medical, food processing, material processing etc.

## Plasma activated water

When water is exposed to plasma either directly or indirectly, it becomes PAW, containing various reactive species. The type of reactive species found in it depends on the gas and liquid used to generate plasma. Reactive oxygen and nitrogen species (RONS) are the main components that attribute some important properties of water like pH, oxidation reduction potential, conductivity, nitrate and nitrite concentrations and these factors distinguish PAW from regular water and enable it to serve as an effective alternative approach for microbial disinfection (Thirumdas et al., 2018; Zhang et al., 2012; Wong et al., 2023). Generation of PAW has become an increasingly important topic in the field of plasma science and technology. Meanwhile, there has been a significant rise in the number of studies focusing on plasma-activated liquids (PAL). PALs are widely used in the biomedical and agricultural fields with applications in the treatment of cancer (Lu et al., 2017), inactivation of bacteria (Yusupov et al., 2013), medical device sterilization (Abuzairi et al., 2018), to increase the germination and growth rate (Judée et al., 2017), food sterilization (Ma et al., 2015), etc.

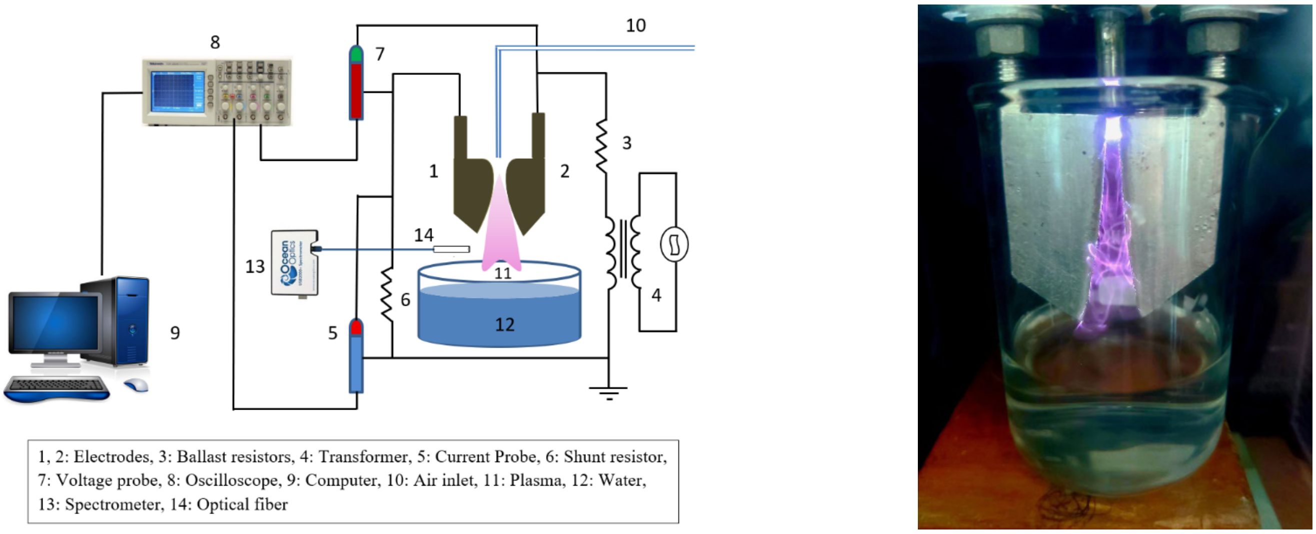
## PAW on food/fruit sterilization

It is always challenging for us to keep the fruit fresh and nutritious for longer periods of storage. Factors including environmental conditions, cultivation practices, soil and seed quality, moisture, temperature, and postharvest handling such as processing and packaging can contribute to bacterial and fungal contamination in fruits (Khalili et al., 2018). The contaminated fruits degrade fast and cause food poisoning to human health due to the presence of common bacteria like *Escherichia coli (E. coli), Salmonella spp., Shigella spp.,* and pathogenic fungi. To get rid of these problems scientists, health workers and microbiologists are searching for new disinfection methods. Sterilization of fruits or food using non-thermal plasma is one of the best methods which does not leave any chemicals and side effects on human health. Application of non-thermal plasma in fruit sterilization has been practiced by two ways: direct method and indirect method. In direct method atmospheric non-thermal plasma directly applied to the fruits or vegetables to minimize or kill the harmful microorganisms. Plasma consists of charged particles, reactive species UV photons, electric fields etc. which can show the antimicrobial effects on food stuff by damaging microbial cell membrane and DNA (Dasan et al., 2017). Research on the use of gas plasmas for microbial inactivation began in the early 1990s, with the objective of developing alternative sterilization methods for heat-sensitive materials. Khalili et al. (2018) reported that the treatment of plasma on almond for 4 minutes can decrease *Salmonella spp., Shigella spp.,* density from 8.17 to 3.59 and 4.09 logs, respectively, in NA media. In their study, Berardinelli et al. (2016) observed a significant reduction in *L. monocytogenes* and *E. coli* populations relative to the control group, though the presence of vegetables in the liquid phase hindered the disinfection efficiency. PAW has ability to reduce the bacterial growth in fruits and vegetables. Ma et al. (2015) observed a 3.5 $\log_{10}$ cfu/mL reduction in bacterial count after treating plasma-activated water produced by discharge over the water surface for 15 minutes, with a total exposure time of 20 minutes. Indirect methods where fruits were washed or submerged in PAW or PAL seem more effective for inactivation purpose on the fruits having grooves and eyes on their surface than indirect methods as PAW can enter the cavity of eyes and grooves of the fruits properly. Also, PAW generated by producing discharge beneath the water has shock wave and electric field besides the RONS, and hence its inactivation efficiency is higher than PAW generated creating discharge above the surface (Zhu et al., 2025; Machala et al., 2017). Lukes et al. reported that microbial inactivation efficiency increases when plasma is generated directly within the water or when the plasma plumes come into contact with the liquid surface (Lukes et al., 2014).

Based on these findings, it is evident that PAW plays a significant role in the microbial decontamination of food products. Therefore, this study aims to characterize the plasma generated by an atmospheric GAD system, investigate the production and physicochemical properties of PAW, and evaluate its antibacterial effectiveness on strawberries.

## Materials and Methods

The schematic layout of the experimental system used for discharge generation is presented in Fig. 1(a). The reactor comprised a pair of diverging aluminum electrodes mounted inside a rectangular polycarbonate enclosure ($15 \times 15 \times 15\ cm^3$). A small outlet on the upper surface of the chamber allowed gas to escape during operation. The minimum distance between the electrodes was maintained at 3 mm, and airflow of 10 L/min was supplied. An alternating voltage ranging from 7 to 10.2 kV at 50 Hz was applied through a ballast resistor (1.7 MΩ) to initiate the discharge. The treatments were done for different applied voltages: 7 kV, 7.8 kV, 8.6 kV, 9.3 kV and 10.1 kV. Other experimental details about the setup were explained in our previous work (Dhungana et al., 2023). Power dissipation in the discharge, electron density ($n_e$), electron excitation temperature ($T_e$) were estimated as our previous work (Chalise et al., 2024). PAW was prepared at the maximum applied voltage, corresponding to the highest power dissipation and electron density, to ensure the generation of a greater amount of reactive species using distilled water (DW). pH, electrical conductivity (EC), oxidation reduction potential (ORP), and temperature were tested by multi-parameter probe (Lutron, 2015).



(a) (b)

**Fig. 1.** (a) Schematic illustration of experimental set up of GAD system (b) photograph of the plasma-water treatment process

### Fruits Sterilization

To study the sterilization effects of PAW on fruits, it was employed for strawberries to find the bacterial colony growth. For this, method as mentioned by Ma et al., 2015 was followed. 5 gm of strawberry sample taken from local market was washed with plasma treated and untreated distilled water for 2 minutes. The strawberry samples were smashed in 50 ml of sterile normal saline (0.85%) with help of sterile mortar and pestle. Serial dilutions were made from this initial dilution as $10^{-1}$ up to $10^{-3}$. Solution of

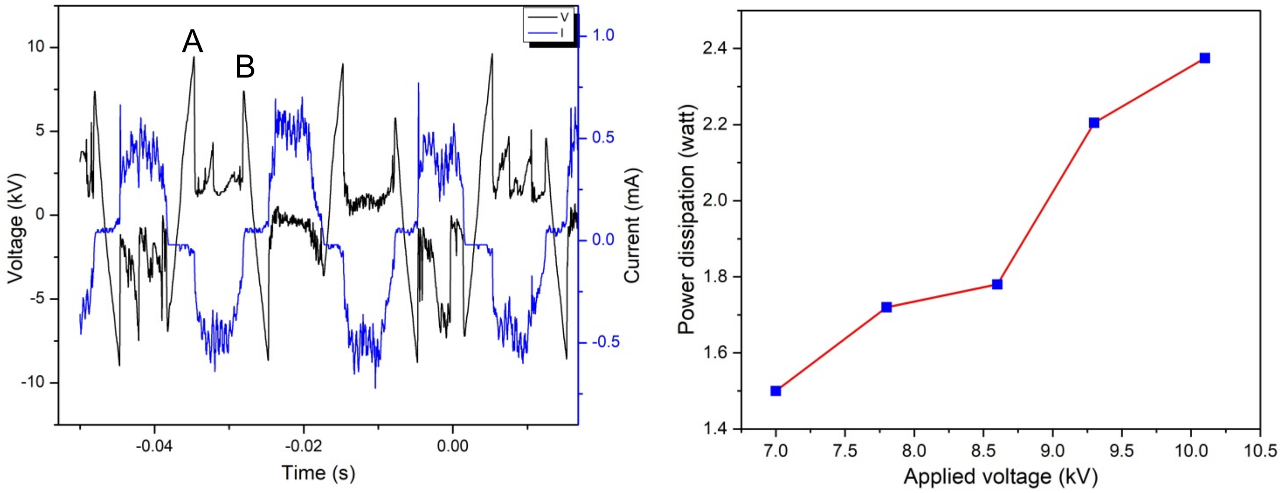
1.0 mL was transferred from each dilution in sterile petri-plate and Plate Count Agar (High Media, India) poured on petri-plates were incubated at 37°C for 24 hours. The serially diluted set was stored at 4°C in refrigerator. Next day, colonies formed in Plate Count Agar were counted and exact number of bacteria colonies was calculated. The experiment was replicated three times for different plates. Total number of bacterial colonies forming unit per ml (CFU/mL) was calculated by using the formula:

$$\mathrm{CFU/mL} = \frac{\text{No.of colonies} \times \text{dilution factor}}{\text{Volume of culture plate}} \qquad (1)$$

## Results and Discussion

### Electrical and optical parameters

Figure 2(a) presents the voltage–current characteristics of the GAD in air. The current waveform exhibits a nearly sinusoidal pattern, whereas the voltage signal deviates from the conventional sinusoidal form, indicating a sawtooth-like profile. In this sawtooth voltage pattern, two distinct breakdown phases can be noticed: the first corresponds to the discharge initiation across the narrowest electrode gap (peak A), and the second represents breakdown occurring along the electrode surface (peak B) (Tu et al., 2009).

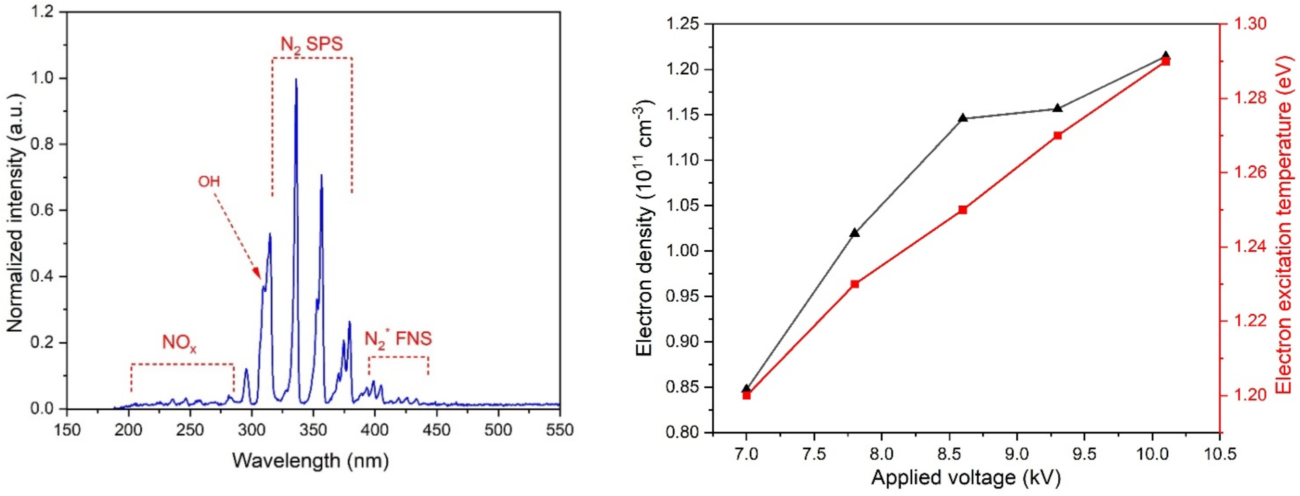


(a) (b)

**Fig. 2.** (a) Current voltage waveform of the discharge, (b) variation of power dissipation with applied voltage.

Figure 2(b) represents variation of power dissipation with applied voltages. It shows that power dissipation directly depends on applied voltages as the applied voltages increase power dissipation increases. This is because as applied voltage increases discharge voltages increase linearly so overall power dissipation increases.

Figure 3(a) demonstrates that emission spectrum confirms the presence of multiple reactive species ($NO_x$, OH, $N_2$, $N_2^+$) typical of an air-based gliding arc discharge or similar atmospheric plasma. The dominant $N_2$ second positive system (SPS) indicates strong excitation of nitrogen, while the presence of OH and $NO_x$ bands show that water vapor and oxygen-containing reactions occur, producing RONS essential for plasma-activated water formation or sterilization effects (Bruggeman et al., 2016).



(a) (b)

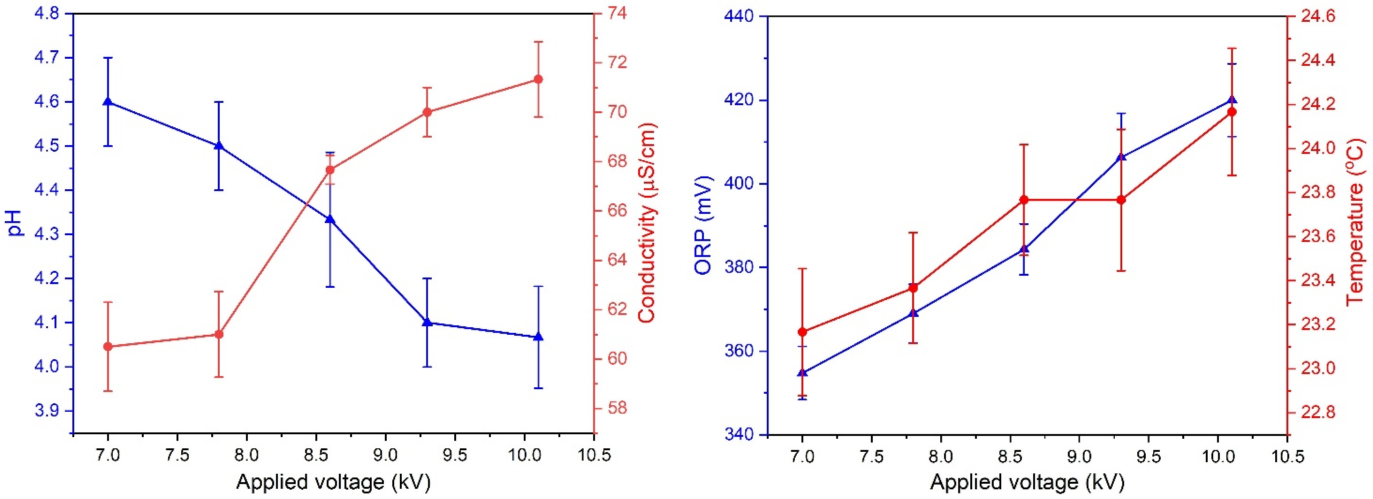
**Fig. 3.** (a) A sample of optical spectra with various reactive species (b) variation of $n_e$ and $T_e$ with applied voltages

$n_e$ and $T_e$ are two important parameters for the characterization of plasma. Figure 3(b) depicts how the $n_e$ and $T_e$ vary with applied voltages. The figure shows that value of $n_e$ rises with increasing applied voltages. At higher applied voltages, energetic electrons more frequently surpass the ionization energy of gas molecules, creating additional free electrons and positive ions. These newly formed electrons can further ionize other gas molecules, resulting in a rapid rise in overall electron density. Further, higher ionization produces more reactive species which are key factors of PAW generations (Miranda et al., 2023). $T_e$ also shows increasing trends with applied voltages although its minimum and maximum value lies within a range of (1.20 to 1.29 eV). As the applied voltage increases, the electric field strength between the electrodes also intensifies. Consequently, electrons are accelerated more effectively between collisions, allowing them to gain greater kinetic energy and excitation efficiency (Hong et al., 2016).

## Physical parameters of PAW

After characterization of plasma and to get optimum effect of plasma to create maximum reactive species, PAW was prepared at maximum applied voltage of 10.1 kV. Figure 4(a) shows how pH and conductivity change with applied voltages. Initially, the untreated DW had pH = 6.8, EC=0 and ORP =300 mV but after 10 minutes of treatment at applied voltage of 7.1 kV all the parameters found to be changed. The value of pH decreases and became minimum (4.06), however EC increases and became maximum (71.33 µS/cm) with rise in applied voltages.

Figure 4(b) represents the variation of ORP and temperature of PAW. Initially, the untreated water has ORP of 300 mV but after 10 minutes of treatment its value became 352 at 7 kV as the applied voltages increases values of ORP increases and gets maximum value of around 420 mV at 10.1 kV. This rise in value of ORP is due to the fact that as the applied voltage rises power dissipation and more energetic electrons are produced. These electrons promote more dissociation and excitation of gas molecules (e.g., $O_2$, $N_2$, $H_2O$), resulting in greater formation of oxidizing species. On the other hand, temperature of PAW increases slightly as we are using non-thermal plasma and air flow maintains the temperature of plume of plasma ambient that strike the water surface.

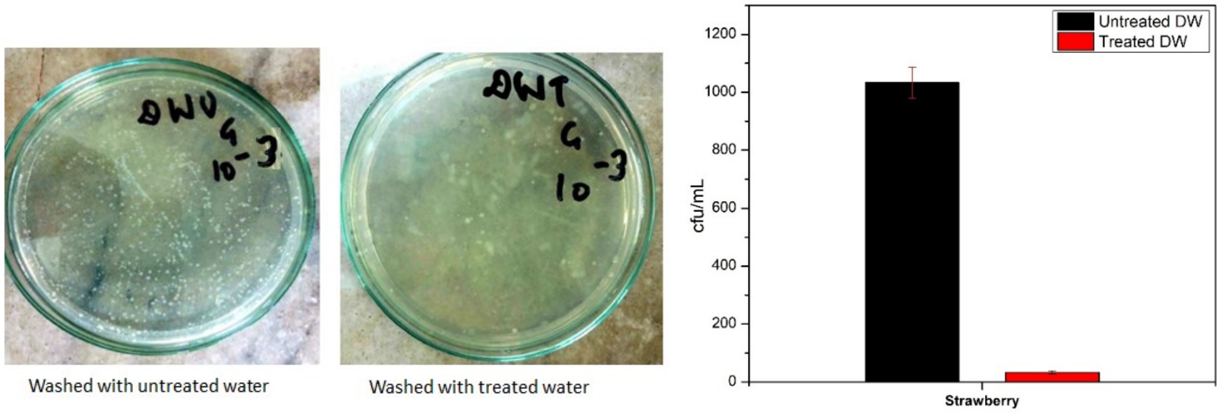


(a) (b)

**Fig 4.** *Variation of (a) pH and conductivity, (b) ORP and temperature with applied voltages*

## Fruits Sterilization

Figure 5(a) depicts the photograph of growth of bacterial colonies in treated and untreated water. The image clearly demonstrates the effectiveness of plasma water over normal water for the sterilization of fruits. Figure 5(b) represents comparison of bacterial growth on strawberry washed with distilled water and plasma treated distilled water after 24 hours. The bacteria colony count for the strawberry washed with distilled water was found to be 1100 cfu/mL but for the strawberry washed with plasma treated distilled water only the count was found to be 34 cfu/mL. There was great reduction in bacteria growth for plasma treated water. Plasma treated water had low pH value, decease the aerobic bacteria, yeast and mold load in strawberry. The low pH and high ORP of plasma-treated water cause protonation of biomolecules, which influences their charge and alters the natural structure and physiology of bacterial cells, ultimately leading to cell death (Mitchell, 1961). Furthermore, plasma-treated water contains various RONS, such as $H_2O_2$, $NO_2^-$, and $NO_3^-$, which induce oxidative and nitrosative stress in bacterial cells, resulting in membrane damage and metabolic inhibition (Judée et al., 2017).



(a) (b)

**Fig. 5.** *(a): Photograph of bacteria growth in strawberry washed with untreated and treated DW, (b) Bacteria growth in strawberry washed with untreated and treated DW*

# Conclusions

PAW generated using an AC gliding arc discharge system exhibited excellent antibacterial properties for strawberry sterilization. When the applied voltage increased from 7 kV to 10.1 kV, a significant decrease in pH (from 6.8 to 4.06) and an increase in oxidation-reduction potential (from 300 mV to 420 mV) and conductivity (from 39.33 to 71.33 µS/cm) were observed, confirming enhanced formation of RONS. Optical emission spectroscopy identified strong emissions corresponding to OH, $NO_x$, $N_2$, and $N_2^+$ species, indicating active plasma chemistry contributing to PAW reactivity. The bacteriological analysis showed a remarkable reduction in microbial load on strawberries: the bacterial colony count decreased from 1100 cfu/mL for distilled water-washed samples to 34 cfu/mL for plasma-treated distilled water. This finding clearly demonstrates that PAW generated by AC gliding arc discharge can effectively inactivate bacteria on fruit surfaces without the need for chemical disinfectants. Overall, this study confirms that gliding arc-based PAW offers a sustainable, non-thermal, and efficient approach for fruit sterilization and food preservation applications.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability

Data will be available upon legal request to the corresponding authors

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