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Enhancement and Stability of Reactive Oxygen and Nitrogen Species in Water Treatment Processes Using Cold Plasma

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Abstract

Cold plasma technology has significant potential for application in water treatment due to its capacity to generate highly reactive oxygen and nitrogen species (RONS). This study compared the performance of dielectric barrier discharge (DBD) and corona discharge (CD) plasma reactors, both operated using ambient air, to evaluate the influence of reactor geometry on RONS generation under identical operating conditions. Comparative analysis showed that the CD method consistently produced higher concentrations of RONS, including H_2O_2, NO_2^-, NO_3^-, and O_3^-, than the DBD system. Based on this superior performance, the CD method was selected for a detailed investigation into the effects of treatment time and water volume, and, crucially, the temporal stability of RONS. The long-term analysis revealed that hydrogen peroxide (H_2O_2) and nitrate (NO_3^-) are relatively stable in plasma-activated water (PAW) over a week of storage, while ozone (O_3) and nitrite (NO_2^-) were unstable, with O_3 rapidly decomposing and NO_2^- converting into the stable NO_3^-. This PAW, rich in stable RONS, demonstrated strong microbicidal activity, achieving over 90% inactivation against single and mixed bacterial cultures (including *E. coli*, *P. aeruginosa*, and *S. aureus*). These findings not only identify the CD configuration as the more efficient plasma generation method but also provide critical insights into RONS transformation pathways and the storage potential of PAW, highlighting its viability as a sustainable approach for water quality enhancement.

Keywords

dielectric barrier discharge, corona discharge, plasma reactor, reactive oxygen and nitrogen species, plasma-activated water

1 Introduction

Water scarcity continues to intensify worldwide due to the rapid depletion and contamination of freshwater resources. Industrial expansion, population growth, and the emergence of persistent organic pollutants have exposed the limitations of conventional water treatment technologies, emphasizing the need for sustainable and scalable alternatives [1]. Cold plasma, a non-thermal ionized gas containing electrons, ions, and neutral species, has emerged as a promising tool for water purification owing to its ability to operate under ambient conditions and generate a diverse mixture of reactive oxygen and nitrogen species (RONS) in aqueous systems [2]. During plasma–liquid interaction, species such as hydrogen peroxide (H_2O_2), ozone (O_3), nitrite (NO_2^-), and nitrate (NO_3^-) are produced, offering strong oxidative capability for microbial inactivation, pollutant degradation, and advanced oxidation processes [3]. Dielectric barrier discharge (DBD) [4] and corona discharge (CD) [5] are two widely used atmospheric-pressure plasma configurations, yet direct comparisons of their RONS-generation behaviour under identical operating conditions remain scarce. Previous study [6], focused primarily on reactor innovation and performance enhancement, introducing a novel multi-compartment dielectric barrier discharge (MCDBD) design aimed at scaling up the treatment process to activate larger volumes of water efficiently. Research advancements, including microbubble-enhanced plasma systems and pulsed-DBD configurations, have shown improved mass transfer, higher inactivation efficiencies, and strong dependence on water matrix composition, highlighting the complex chemistry governing plasma-activated water (PAW) [7, 8]. Various international standards are available for the measurement of reactive species in aqueous systems, ensuring accuracy and reliability in quantifying plasma-generated species [9–11]. Among these, understanding the formation pathways [12, 13] of H_2O_2 is particularly important, as it often acts as a precursor that

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influences the generation and stability of other reactive oxygen and nitrogen species crucial for disinfection [14, 15]. Ozone, another major species produced during plasma–liquid shapes the overall composition of reactive nitrogen species in plasma-activated water [16, 17]. A comprehensive understanding of these species, along with accurate measurement techniques, is therefore essential for optimizing the performance and application of plasma-activated water. The novelty of this study lies in its direct comparison of CD and DBD plasma systems, both operated under the same air atmosphere, voltage, and treatment time. The corona discharge produces unrestricted micro discharges that interact directly with the water surface, while the dielectric barrier in the DBD setup restricts current flow and disperses the discharge, altering how reactive species are transferred into the liquid. By tracking the behaviour of H_2O_2, O_3, NO_2^-, and NO_3^- over time, the work uncovers how these reactive oxygen and nitrogen species are connected through a chain of oxidation and reduction reactions. The rise or depletion of one species influences the next, creating a dynamic chemical balance within plasma-activated water. This mechanistic insight into how discharge geometry shapes both RONS formation and persistence offers a clearer path to designing efficient plasma systems for water treatment. The current paper emphasizes comparative study and temporal analysis. Two distinct reactor configurations: DBD and CD are considered under consistent operating conditions to determine which is superior at generating RONS. This research goes beyond mere generation to thoroughly investigate the long-term stability (lifetime) of these reactive species within the plasma-activated water. Providing essential data for practical application and storage, which was not the core objective of the previous study, which was design-focused [6].

2 Methodology

2.1 Dielectric barrier discharge plasma setup

The DBD system employed a pin-to-plate configuration to generate non-thermal plasma at atmospheric pressure. A quartz plate (1 mm thickness) was used as the dielectric barrier owing to its excellent thermal stability and insulation properties. The plate was fixed at the base of a cylindrical container containing the treatment water. The bottom electrode, made of stainless steel (SS 304), was attached beneath the quartz plate, whereas the top electrode, also made of SS 304 in a pin-type geometry, was positioned 3 mm above the water surface. Plasma was initiated using a high-voltage AC power supply delivering 3 kV peak-to-peak at 20 kHz with a discharge current of 30 mA. The working gas was ambient air, and no external gas flow was introduced. A plasma–liquid interaction occurred in the air gap between the top electrode and the water surface. To evaluate the influence of treatment parameters, experiments were conducted for a water volume of 200 mL for 15 min of treatment time. All the experiments were performed at room temperature and atmospheric pressure. A schematic of the DBD setup is shown in Fig. 1(a).

2.2 Corona discharge plasma setup

The CD plasma system utilized a pin-to-pin electrode configuration designed to enhance the direct plasma–liquid interaction. Both electrodes were fabricated from stainless steel (SS 304). One electrode was immersed in the water sample, while the other was positioned 3 mm above the water surface, aligned vertically to maintain the same electrode tip-to-water-surface gap as in the DBD system.

The same high-voltage AC power supply (3 kV peak-to-peak, 20 kHz, 30 mA) was used to generate the corona discharge. Ambient air served as the discharge medium with no additional gas input, ensuring parity with the

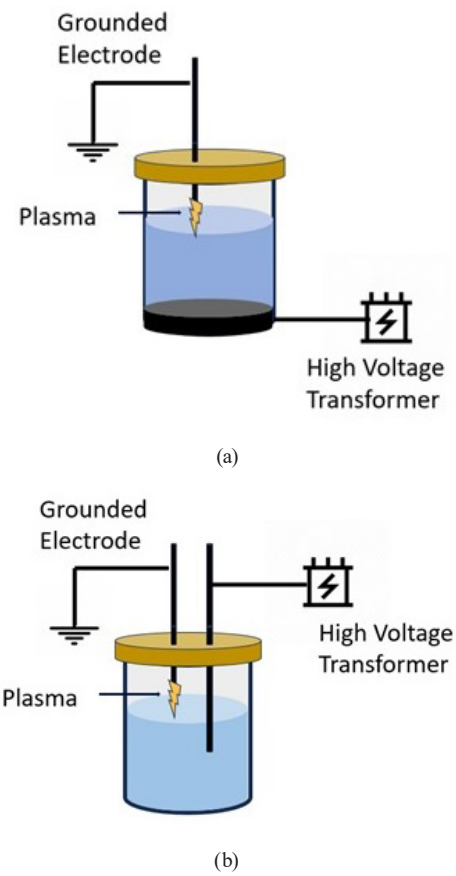

Fig. 1 Scheme of different methods for PAW generation: (a) dielectric barrier discharge method, (b) corona discharge method

DBD experiments. The immersed electrode acted as a discharge target, promoting efficient species transfer into the water. A water volume of 200 mL was treated for 15 min. All discharges were generated at room temperature and at atmospheric pressure.

Table 1 shows the parameters used during the experiments. The CD configuration allowed for a direct comparison with the DBD setup by eliminating the dielectric barrier and altering the electrode–water interface geometry. A schematic representation of the CD system is shown in Fig. 1(b). After comparison of the two methods based on results, the CD method was applied for the analysis of various reactive species. To understand the time-based evaluation of species, 200, 300 and 400 mL of water (15 mm, 22.5 mm and 30 mm thickness) were treated for different durations (10 min, 20 min, 30 min, 40 min, 50 min, 60 min). Readings were taken immediately after treatment.

To understand the stability of reactive species 200 mL of water was treated for different time duration ranging from 10 to 60 min with steps of 10 min. Stored in different containers and reading were taken for 1 week for every 24 h.

2.3 Measurement of reactive species

RONS generated in the plasma-treated water were quantified using Aquasol water testing kits, which adhere to standard protocols based on the APHA/AWWA/IS guidelines [9–11]. The measurement methods and corresponding chemical reactions for each species are described below.

2.3.1 H_2O_2 measurement

The concentration of hydrogen peroxide in PAW was measured using the AQUASOL AEHP - Hydrogen Peroxide Test Kit, which is based on a color-disappearance titrimetric method. A 10 mL sample was transferred into the test vial, followed by the addition of 20 drops of reagent HP-1 and thorough mixing. Then, two spoonfuls of reagent HP-2 were added to initiate the color reaction. Reagent HP-3 was added dropwise until the solution turned completely colorless, indicating the endpoint.

The hydrogen peroxide concentration was calculated directly using the manufacturer-provided calibration chart based on the number of HP-3 drops used. This validated method is widely applied in water-treatment and disinfectant monitoring and is suitable for oxidant-rich matrices such as plasma-activated water.

Table 1 Operating parameters for different plasma generators

Parameter	Value
Electrode material	Stainless steel (SS 304)
Electrode gap	3 mm
Input voltage	3 kV (peak-to-peak)
Current	30 mA
Working gas	Ambient air (no external flow)
Water volumes treated	200 mL
Water thickness	10 mm
Treatment durations	15 min
Operating conditions	Atmospheric pressure, room temperature

2.3.2 Nitrite and nitrate measurement

Nitrite measurement

Nitrite concentration was measured using the AQUASOL AE207 – nitrite test kit which operates on the standard colorimetric diazotization–coupling reaction (Griess method). In this procedure, nitrite (NO_2^-) present in the sample reacts with sulfanilic acid under acidic conditions to form a diazonium salt. This intermediate subsequently couples with N-(1-naphthyl)ethylenediamine dihydrochloride (NED), producing a characteristic pink-to-red azo dye. The intensity of the developed color is directly proportional to the nitrite concentration. After adding the kit reagents, the sample color is compared visually with the standardized color chart provided by the manufacturer, allowing semi-quantitative estimation of nitrite levels (mg/L).

Nitrate measurement

Nitrate concentration was measured using the AQUASOL AE308 – nitrate test kit, in which nitrate is reduced to nitrite using the kit's reducing reagent, followed by titrimetric color-based quantification using the same color comparison principle.

2.3.3 O_3 measurement

Ozone concentration was measured using the AQUASOL AEOZ3H – Ozone Test Kit. In this titrimetric iodometric method, ozone oxidizes iodide ions in a phosphate-buffered solution, producing iodine that forms a pink-colored complex with N,N-diethyl-p-phenylenediamine (DPD). The pink color is titrated with sodium thiosulfate until complete disappearance, with the amount of thiosulfate consumed directly proportional to the ozone concentration.

All analytical procedures were performed in accordance with standard protocols (e.g., Method 4500-Cl F) described in "Standard Methods for the Examination of Water and Wastewater" [11] published by APHA. All measurements were performed in triplicate, and the average

values were used for analysis. Proper calibration and blank correction were performed according to the kit instructions. All measurements were conducted immediately after plasma activation to avoid the decay of the species.

2.3.4 Microbial inactivation testing

For the microbial inactivation study, *Escherichia coli* (1 mL containing 1×10^8 CFU) was added to 200 mL of tap water and plasma-activated water (PAW) generated using the corona discharge method. After 5 min of exposure, CFU counts were determined to evaluate the bactericidal efficiency of PAW.

For the mixed-culture inactivation study, a suspension containing *E. coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus* (1 mL with 1×10^8 CFU) was added to 200 mL of tap water and PAW. After 10 min of exposure the CFU counts were measured to assess the inactivation efficiency.

3 Results and discussion

Table 2 shows a comparative analysis of the water quality parameters, revealing significant variations between untreated water and water subjected to DBD and CD plasma treatments. The pH of water was slightly increased after plasma treatment. Both discharge systems generated hydrogen peroxide, nitrite, nitrate, and ozone, with the corona discharge consistently producing higher concentrations than the dielectric barrier discharge. 200 mL of water was treated with corona discharge and dielectric barrier discharge method for 15 min (thickness 15 mm).

The results indicate that both plasma treatment methods effectively modified the physicochemical properties of water; however, CD consistently produced higher levels of reactive oxygen and nitrogen species than DBD. Initially, the pH increases slightly but is subsequently reduced. The greater decrease in pH after CD treatment suggests a higher dissolution of acidic oxides, primarily nitric and nitrous acids, formed through plasma-induced reactions.

Table 2 Water quality parameters before and after DBD and CD treatments

Parameter	Value	Before treatment	After DBD treatment	After CD treatment
H_2O_2	mg/L	0	15	20
NO_2^-	mg/L	0	7	15
NO_3^-	mg/L	0	7	20
O_3	mg/L	0	1.5	3
pH	–	6.5	7.0	7.0
EC*	µS/cm	680	726	928

*Electrical conductivity

The higher concentrations of nitrite and nitrate observed in CD-treated water arise from the stronger local electric fields generated at the corona electrode tip, which produce a larger population of energetic electrons at the air–water interface. These electrons efficiently dissociate N_2 and O_2, thereby enhancing the formation of reactive nitrogen species that subsequently dissolve and convert into nitrite and nitrate in the liquid phase. In contrast, the dielectric barrier in the DBD configuration restricts current flow and distributes the plasma over a wider region, which reduces both the peak electron density and the mean electron energy. As a result, electron-impact reactions leading to reactive nitrogen species (RNS) formation occur less intensively in DBD, whereas the direct, barrier-free corona discharge sustains a more localized, dense electron environment that favours higher RNS production. Elevated hydrogen peroxide and ozone concentrations in CD-treated water confirmed its higher oxidative potential, likely linked to a greater electron density and higher generation rates of hydroxyl and atomic oxygen radicals. Overall, the comparative analysis demonstrated that CD treatment is more effective than DBD in generating oxidative and nitrogenous reactive species, which may enhance its applicability in advanced water treatment processes. Based on the analysis the CD method was used for further time based and stability analysis of RONS.

3.1 Hydrogen peroxide

In the gas phase, hydroxyl radicals ($^\bullet$OH) are primarily generated through oxygen-atom interactions and electron-impact dissociation of water vapor. In the liquid phase, the dominant route for H_2O_2 formation is the recombination of dissolved $^\bullet$OH radicals [12, 13].

$$H_2O + {}^\bullet O \rightarrow {}^\bullet OH + {}^\bullet OH \quad (1)$$

$$H_2O + e^- \rightarrow {}^\bullet H + {}^\bullet OH + e^- \quad (2)$$

$$^\bullet OH + {}^\bullet OH \rightarrow H_2O_2 \quad (3)$$

Water was treated for 10 to 60 min with step of 10 min for volume of 200, 300 and 400 mL. The results (Fig. 2) show that the H_2O_2 concentration increased consistently over time for 200 mL of water. In contrast, for 300 mL and 400 mL of water, the concentration initially increased but then decreased, which can be attributed to the decomposition of H_2O_2 into H_2O over time. The decomposition pathway involves reactions with hydroxyl radicals (Eqs. (4) and (5)), producing hydroperoxyl radicals ($^\bullet HO_2$)

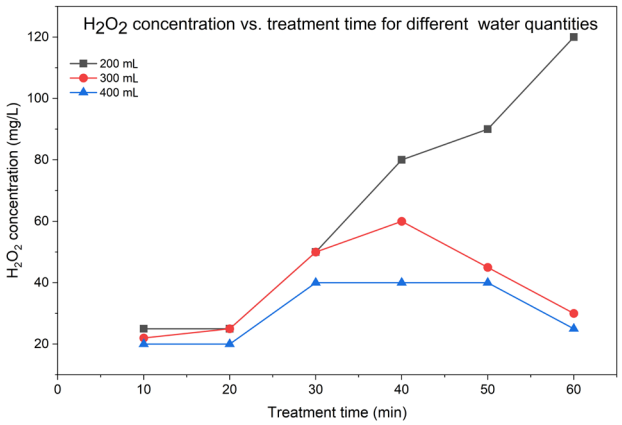

Fig. 2 Effect of treatment time on H_2O_2 concentration at different water volumes

and ultimately oxygen and water.

$$H_2O_2 + {}^{\bullet}OH \rightarrow {}^{\bullet}HO_2 + H_2O \quad (4)$$

$$^{\bullet}OH + {}^{\bullet}HO_2 \rightarrow O_2 + H_2O \quad (5)$$

The highly reactive hydroxyl radical (•OH) readily decomposes hydrogen peroxide into the more stable hydroperoxyl radical ($^{\bullet}HO_2$), which then reacts with another •OH radical to produce oxygen and water. This explains the decreasing trend in H_2O_2 concentration for larger water volumes, where the decomposition rate exceeded the generation rate [14, 15]. But with a smaller water volume, the same discharge power produces a higher density of plasma-generated radicals (•OH). Their rapid recombination forms H_2O_2 faster than it can decompose, leading to net accumulation.

To further investigate H_2O_2 stability in PAW, measurements were taken daily for up to one week. Fig. 3 shows that the H_2O_2 concentration decreased slowly during the first four days, after which it stabilised and remained

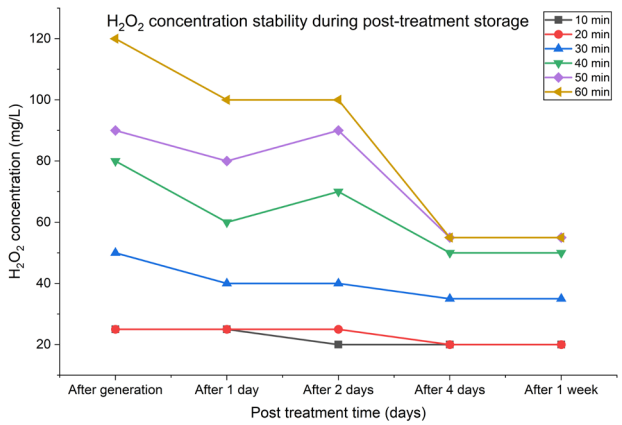

Fig. 3 Long-term stability of H_2O_2 in plasma-activated water over one week for 200 mL at different treatment times

constant for a longer period. This indicates that H_2O_2 in PAW is relatively stable, allowing it to be stored for later use in applications that require oxidative potential.

3.2 Ozone

Another important oxygen-based reactive species in plasma-activated water is ozone. Its concentration in water is relatively low because of the complexity of ozone dissolution and its rapid reaction with atomic oxygen (O) to form more stable molecular oxygen (O_2) [18]. Nevertheless, trace amounts of ozone were detected shortly after plasma treatment. Fig. 4 illustrates the variation in the ozone concentration over time for different water volumes.

Ozone formation begins with the dissociation of molecular oxygen into atomic oxygen via electron impact (Eq. (6)). Atomic oxygen then reacts with molecular oxygen in the presence of a third body (M) to form ozone (Eq. (7)) [19].

$$O_2 + e^- \rightarrow {}^{\bullet}2O + e^- \quad (6)$$

$$^{\bullet}O + O_2 + O_2 \rightarrow O_3 + O_2 \quad (7)$$

However, ozone is unstable in aqueous environment. It decomposes when atomic oxygen interacts with ozone, producing molecular oxygen (Eq. (8)) [20].

$$^{\bullet}O + O_3 + M \rightarrow 2O_2 + M \quad (8)$$

As shown in Fig. 4, ozone generation is unstable owing to its high reactivity with atomic oxygen, leading to a rapid decline in concentration after plasma treatment. Fig. 5 further demonstrates the ozone stability over time, where the species becomes undetectable after a few days. This instability is attributed to its transformation into molecular oxygen, which is thermodynamically more stable under aqueous conditions.

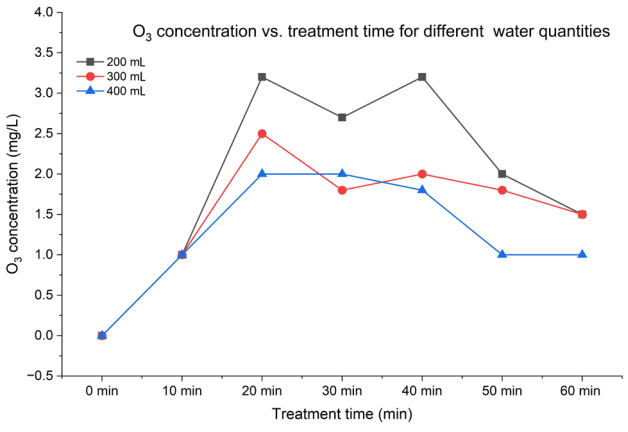

Fig. 4 Effect of treatment time on O_3 concentration at different water volumes

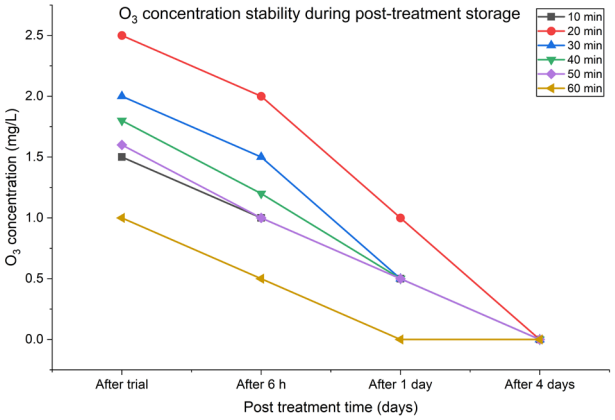

Fig. 5 Long-term stability of O_3 in plasma-activated water over one week for 200 mL at different treatment times

3.3 Nitrite

The formation of nitric oxide (•NO) plays a crucial role in generating RNS in PAW [21, 22]. Nitrite (NO_2^-) is a relatively stable species present in PAW. The interaction of nitric oxide with atomic oxygen (O) leads to the formation of nitrogen dioxide (•NO_2), as shown in reaction (Eq. (9)), which is an important pathway for nitrite production:

$$^{\bullet}NO + {}^{\bullet}O + M \rightarrow {}^{\bullet}NO_2 + M \quad (9)$$

Additionally, nitric oxide reacts with ozone, formed during plasma treatment, to yield nitrogen dioxide and molecular oxygen, which are more stable products than ozone (Eq. (10)) [23, 24]:

$$^{\bullet}NO + O_3 \rightarrow {}^{\bullet}NO_2 + O_2 \quad (10)$$

Another significant route for nitrite formation is the reaction of nitric oxide with the hydroperoxyl radical (•HO_2), generated during the decomposition of hydrogen peroxide, producing nitrogen dioxide and hydroxyl radicals reaction (Eq. (11)) [25].

$$^{\bullet}NO + {}^{\bullet}HO_2 \rightarrow {}^{\bullet}NO_2 + {}^{\bullet}OH \quad (11)$$

Furthermore, when electronically excited nitric oxide (•NO*) transfers its energy to molecular oxygen, it produces nitrogen dioxide and atomic oxygen reaction (Eq. (12)) [26].

$$^{\bullet}NO^* + O_2 \rightarrow {}^{\bullet}NO_2 + {}^{\bullet}O \quad (12)$$

Hydration of •NO_2 Takes place once it enters into water (Eq. (13)) [27].

$$^{\bullet}NO_2 + H_2O \rightarrow HNO_2 + {}^{\bullet}OH \quad (13)$$

Nitrous acid is weak acid as it forms immediately converts it into nitrite in liquid phase (Eq. (14)).

$$HNO_2 \leftrightarrow H^+ + NO_2^- \quad (14)$$

Fig. 6 shows nitrite concentration with reference to treatment time. The trend shows that it increases along with the treatment time, but is affected due to oxidation of nitrite to nitrate in the presence of hydrogen peroxide (Eq. (15)).

$$NO_2^- + H_2O_2 + H^+ \rightarrow NO_3^- + H_2O + H^+ \quad (15)$$

To better understand the conversion of nitrite to nitrate, the evolution of pH with treatment time was also monitored (Fig. 7). The results show a gradual decrease in pH as the treatment time increases, indicating progressive acidification of the plasma-activated water due to the dissolution of nitrogen oxides and the formation of nitrous and nitric acids. Under these mildly acidic conditions, reaction Eq. (15) becomes more favourable, promoting the oxidation of nitrite to nitrate in the presence of hydrogen peroxide. This behaviour explains the simultaneous

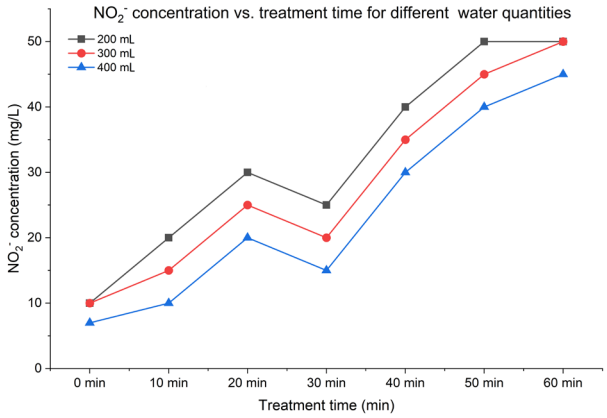

Fig. 6 Effect of treatment time on Nitrite concentration at different water volumes

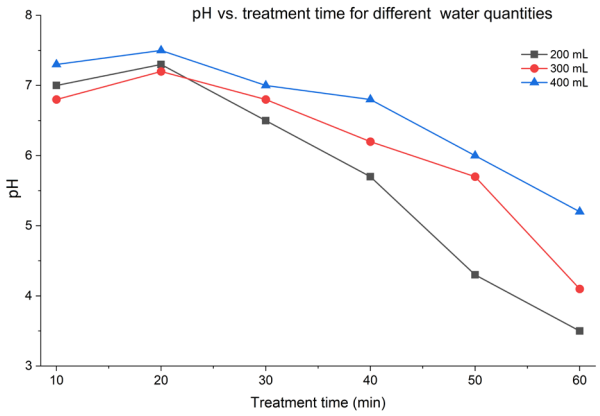

Fig. 7 Effect of treatment time on pH evaluation at different water volumes

decrease in nitrite and increase in nitrate observed at longer treatment times, confirming the mechanistic role of Eq. (15) in the nitrogen species transformation pathway.

3.4 Nitrate

When nitrite is oxidised to nitrate in the presence of hydrogen peroxide, as shown in reaction Eq. (13), nitrite acts as an intermediate species. Therefore, the concentration of nitrate in PAW is directly influenced by the amount of nitrite present in the water [18, 28, 29].

Fig. 8 shows the variation in nitrate concentration with different treatment times. The trend closely follows the crease in nitrite concentration observed in the previous figure, indicating that nitrate formation is linked to the availability of nitrite.

Fig. 9 presents the stability of nitrate in PAW over a post-treatment period of up to one week. The results reveal that nitrate remains stable during storage. A slight increase in nitrate concentration is observed in the initial days, which can be attributed to the continued oxidation of nitrite into nitrate in the presence of hydrogen peroxide (Eq. (15)). Over time, the nitrite concentration becomes negligible as it is completely converted to nitrate. Consequently, hydrogen peroxide concentration also stabilises after this conversion is complete [16, 17].

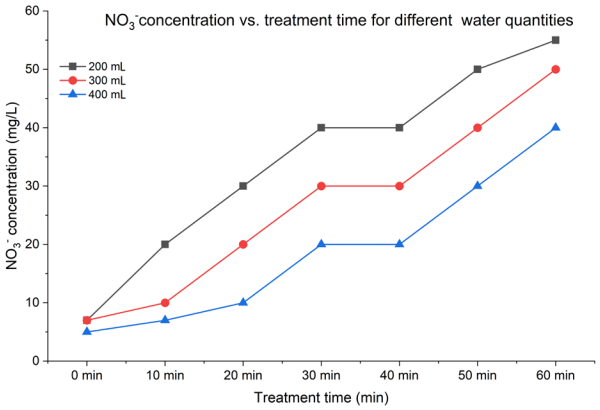

Fig. 8 Effect of treatment time on nitrate concentration at different water volumes

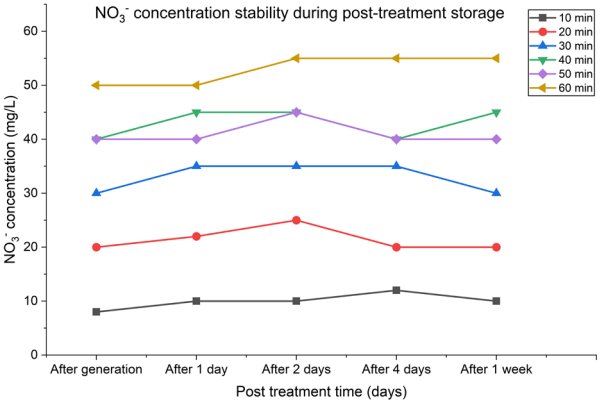

Fig. 9 Long-term stability of nitrate in plasma-activated water over one week for 200 mL at different treatment times

3.5 Microbial decontamination

The testing procedure was designed to evaluate the inactivation efficacy of PAW against both single and mixed bacterial cultures by following standard protocols based on the APHA/AWWA/IS guidelines [9–11]. Results are compared from the CD and DBD treatments. PAW was generated using both the CD and DBD plasma reactors. The plasma activated water produced by treating 200 mL of tap water. Single-culture (*Escherichia coli*) and mixed-culture (*E. coli* and *S. aureus*) inactivation test are performed. The test method is the most common and robust way to quantify disinfection efficacy. Quantitative surface carrier test procedure is followed as below.

- Inoculation (Control): Prepared a high-concentration bacterial suspension (e.g., 108 CFU/mL) of the *E. coli*, *S. aureus*).
- Target surface preparation: Selected a standardized, non-porous surface material stainless steel and glass that represents the target application surface.
- PAW treatment: Applied the 1 mL of PAW to the targeted dried surface by wiping with a PAW saturated cloth.
- Treatment time: Controlled the contact time 5 min and temperature.
- Efficacy calculation: The results are reported as log reduction (LR), which is the standard industry measure for disinfectant performance: LR = log10 (CFU Control) − log10 (CFU Treated)

Figs. 10 and 11 show the comparative inactivation effects of PAW generated by corona and dielectric barrier discharges (DBD) against single and mixed bacterial cultures.

The results demonstrated a significant reduction in bacterial colony-forming units (CFU) in both corona discharge

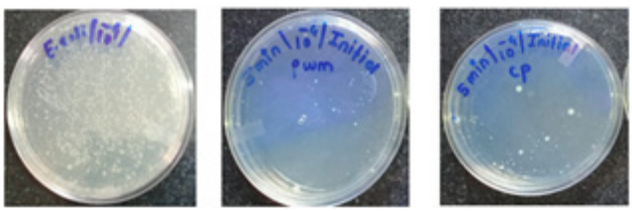

Fig. 10 Microbiocidal inactivation testing - bacteria *E. coli* treatment time 5 min. (a) Tap water, (b) plasma activated water (corona discharge), (c) plasma activated water (dielectric barrier discharge)

Fig. 11 Microbiocidal inactivation testing - bacteria mix culture of *E. coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus*, treatment time

and DBD-treated PAW compared to tap water. In both single and mixed culture experiments, more than 90% bacterial inactivation was achieved with the PAW. This strong bactericidal activity can be attributed to the synergistic effects of reactive oxygen species and RNS in PAW, which damage bacterial cell membranes, disrupt intracellular components, and ultimately lead to cell death.

These findings confirm that the high oxidative potential of PAW renders it an effective antimicrobial agent, highlighting its potential application in water and wastewater treatment processes.

4 Conclusion

Plasma-activated water was generated using two plasma generators: corona discharge and dielectric barrier discharge. Among these, the corona discharge method is relatively simple and generates reactive species more effectively. The generation of hydrogen peroxide is primarily driven by the formation of hydroxyl radicals and increases over time. However, its concentration is influenced by the reduction of nitrite to nitrate. H_2O_2 also exhibits good stability, remaining effective for a longer duration. Ozone is an unstable reactive species owing to its high reactivity with atomic oxygen , forming molecular oxygen , which is more stable. Consequently, ozone was not traceable after the post-treatment period. Nitrite is an intermediate species in nitrate formation. During treatment, its concentration increases over time but becomes undetectable after post-treatment because it is converted into nitrate. In contrast, nitrate remained stable in the PAW for an extended period. Since PAW contains hydrogen peroxide and ozone, it exhibits strong disinfectant properties, making it effective for the deactivation of various microbes. Considering the properties of PAW and the stability of reactive species, it can be widely used in applications such as water purification, medical disinfection and agriculture. However, further studies are required to explore its large-scale implementation and environmental safety issues.

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