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Effects on Physiochemical Parameters of Water Samples by Non-Thermal Plasma Treatment

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Abstract:
Non-thermal plasma (NTP) is a rapidly advancing multidisciplinary field, gaining recognition for its environmentally friendly and chemical-free attributes. Over the past decade, NTP has drawn considerable interest due to its extensive potential applications, particularly in the realm of water treatment. When applied to water, NTP creates an acidic environment, which significantly modifies several key properties, including pH, electrical conductivity, and turbidity. Additionally, the process generates reactive oxygen and nitrogen species (RONS), which induce notable changes in the chemical composition of the water. These unique characteristics of plasma-treated water present a promising alternative for microbial disinfection. In our research, NTP is generated at atmospheric pressure using a high-voltage power supply operating at 12 kV and 50 Hz. The plasma discharge produced under these conditions is thoroughly examined through electrical and optical diagnostic methods to ensure accurate characterization. Various water samples, including those collected from river, tap, and well, are treated using a non-thermal plasma source. After treatment, the physicochemical parameters of the water samples are systematically analyzed to assess the impact of plasma treatment and to highlight its potential applications in water purification and disinfection.

Keywords: Non-thermal plasma (NTP), Reactive oxygen and nitrogen species (RONS), Physical parameters, Chemical parameters, Water quality

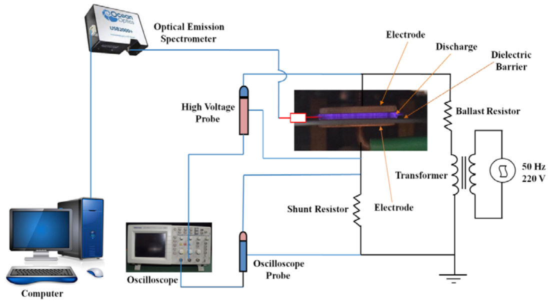
1. Introduction:

Plasma, often termed the fourth state of matter, offers immense potential to tackle critical challenges across various sectors due to its distinctive physical and chemical properties. Its applications span a broad range of fields, including water purification, materials processing, and biomedical advancements. Among the various forms of plasma, NTP has emerged as a transformative innovation in plasma technology [1]. This cutting-edge tool has garnered significant attention in both scientific and industrial domains, particularly for its applications in healthcare and environmental remediation. For example, it is widely used to improve drinking water quality by removing contaminants from surface water, tap water, and groundwater. Furthermore, its biomedical applications have opened new possibilities in medicine, improving patient outcomes and enhancing hospital hygiene [1, 2]. One of the most notable advancements in plasma research is the development of atmospheric pressure plasma with properties resembling traditional low-pressure glow discharges. A key characteristic of this plasma is its ability to produce a high concentration of reactive species under ambient conditions. These reactive species play a vital role in driving chemical reactions, enabling innovative applications in sectors such as healthcare and environmental science. The introduction of cold atmospheric pressure plasma has provided promising solutions to persistent challenges, particularly in biomedicine, where its potential for transformative innovations continues to expand [2, 3]. In recent years, the field of non-equilibrium atmospheric pressure discharges has grown rapidly, demonstrating its versatility and effectiveness in addressing critical biological and medical challenges [4]. A significant concern in healthcare today is the increasing resistance of microorganisms to antibiotics. Plasma-based healthcare technologies offer a compelling solution, delivering rapid and effective methods for maintaining hospital hygiene and combating pathogenic microorganisms [4, 5]. These technologies have the potential to revolutionize sterilization protocols by providing efficient decontamination without the limitations of conventional methods.

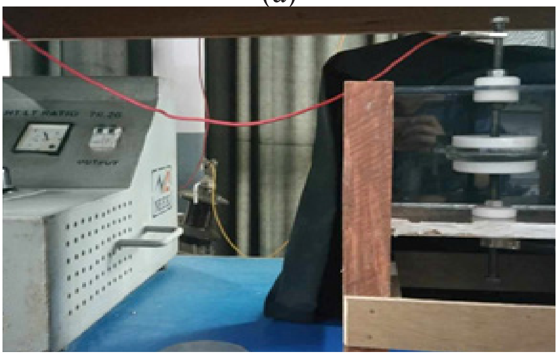
NTP has emerged as a superior alternative, offering low-temperature sterilization that is fast, safe, and minimizes material degradation. These advancements promise to improve the reliability and longevity of medical devices, making them invaluable in modern healthcare [6, 7]. Non-thermal plasma therapy has been proven effective in reducing biological parameters like Escherichia coli and total coliform counts, while also enhancing physical characteristics such as electrical conductivity, turbidity, pH, and total dissolved solids in treated water [8]. This improvement is attributed to the generation of reactive species, such as ozone, during plasma treatment, which effectively neutralizes contaminants. Research into the use of non-thermal plasma for water quality improvement has also focused on its effects on the physical and chemical properties of water, highlighting its potential to address global water security challenges [8, 9]. Moreover, the applications of cold plasma extend beyond water purification and healthcare. In agriculture, plasma treatments are being explored for their ability to enhance crop productivity and protect against pathogens. The multidisciplinary nature of plasma physics and its diverse applications position it as a critical field of study for addressing pressing global challenges. In conclusion, atmospheric pressure cold plasma is a groundbreaking innovation with vast potential to tackle urgent global issues. From enhancing water quality to transforming healthcare and advancing agriculture, this technology offers a wide range of impactful applications. As ongoing research continues to uncover its full potential, cold plasma technology is poised to become a cornerstone of sustainable development in the 21st century [10–12].

2. Experimental Setup

The plasma reactor system consists of a plane parallel dielectric barrier discharge (DBD) configuration, as illustrated in figure 1(a). The reactor was constructed within a cuboidal wooden box (dimensions: 30 cm × 10 cm × 12 cm) with transparent polycarbonate panels on three sides and the top, measuring 26 cm × 12 cm and 13 cm × 12 cm, respectively. This design facilitated visualization of the micro-discharges during operation.



(a)



(b)

Figure 1: (a) The schematic diagram of the reactor system and (b) Image of reactor

Two solid cylindrical copper electrodes (diameter: 7 cm, thickness: 1 cm) were securely mounted on the upper and lower walls of the wooden box using appropriate nuts and bolts. A lathe machine was used to polish the electrode surfaces, ensuring uniform discharge characteristics. The electrodes were further insulated with Teflon to minimize edge effects, localized heating, and power losses, leaving only the discharge area exposed. A quartz plate (diameter: 9 cm) was positioned on the lower electrode, serving as a dielectric barrier. This barrier enhanced discharge uniformity by limiting current flow during operation. The air gap between the electrodes, defining the discharge volume, was adjustable using spacers of varying thickness. The upper electrode was connected to the phase line of a step-up transformer through a 20 MΩ ballast resistor to regulate the discharge current. The lower electrode was grounded via a 10 kΩ shunt resistor, enabling the measurement of discharge current. Voltage across the electrodes was measured using a high-voltage probe (PINTEX HVP-28HF, 1000:1) connected to the upper electrode. A 50 Hz alternating current (AC) power supply from the step-up transformer was applied across the electrodes to generate plasma discharge. Waveforms of applied voltage and discharge current were recorded using a two-channel Tektronix TDS 2002 (60 MHz) digital oscilloscope, which was connected to a laboratory computer for real-time analysis and data storage. The reactive species generated during the plasma discharge were analyzed using an Ocean Optics USB 2000+ spectrometer.

3. Results and Discussion

3.1. Physicochemical Parameters

3.1.1. pH

pH is a key parameter that indicates the acidity or alkalinity of water by measuring the concentration of hydrogen ions (H+) in a solution. According to the World Health Organization (WHO), the optimal pH range for safe drinking water is between 6.5 and 8.5, as significant deviations may affect taste and signal potential contamination [13, 14]. In this study, pH levels were observed in well water, tap water, and river water samples during cold plasma treatment over a period of 0 to 12 minutes. The initial pH values recorded were 8.6 for well water, 8.51 for tap water, and 8.46 for river water.

Figure 2 illustrates a gradual decrease in pH across all water samples. This reduction during plasma treatment is attributed to the formation of reactive oxygen and nitrogen species (RONS), including nitric acid (HNO_3) and nitrous acid (HNO_2), which contribute to increased acidity in water [15]. These findings highlight the potential of cold plasma technology in altering water chemistry and maintaining pH levels within the recommended range for safe consumption. Moreover, they emphasize the applicability of cold plasma treatment in water purification, ensuring compliance with safety standards and enhancing water quality without introducing harmful contaminants.

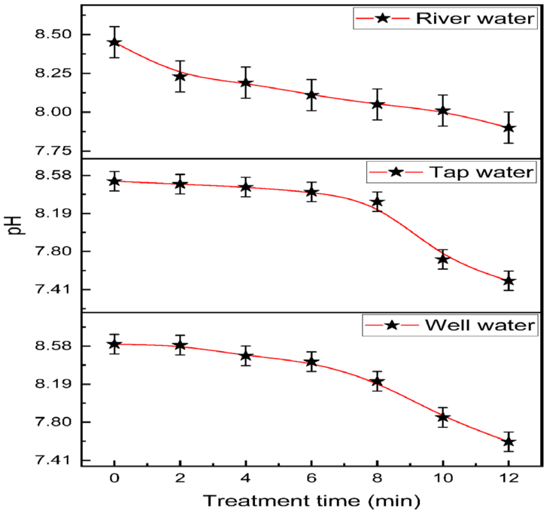


Figure 2: Variation of pH in well, tap, and river water samples with treatment time

3.1.2. Electrical Conductivity

Electrical conductivity (EC) reflects a solution's capacity to conduct electrical current, which depends on the mobility, concentration, and type of ionic species present. It is a crucial parameter for evaluating water purity, as higher conductivity generally signifies a greater presence of dissolved ions, often resulting from salts or other impurities [16].

In this study, the initial electrical conductivity (EC) of well, tap, and river water was measured at 728.8 µS/cm, 294.4 µS/cm, and 295.2 µS/cm, respectively. During cold plasma treatment over a 0 to 12-minute period, the EC of all water samples increased. This rise in conductivity is likely due to the generation of reactive ionic species, including nitrates (NO_3^-), nitrites (NO_2^-), and ammonium (NH_4^+), introduced into the water [17]. These species result from plasma-induced dissociation and ionization of water and dissolved gases, thereby enhancing the solution's ionic strength. The World Health Organization (WHO) sets the permissible EC limit for drinking water at 300 µS/cm. While the EC of tap and river water remained within or close to this range, the well water exceeded this limit even before treatment, likely due to its naturally high mineral content. Cold plasma treatment further increased EC in all water sources, with the most pronounced rise observed in river water, suggesting its higher sensitivity to plasma-generated ionic species.

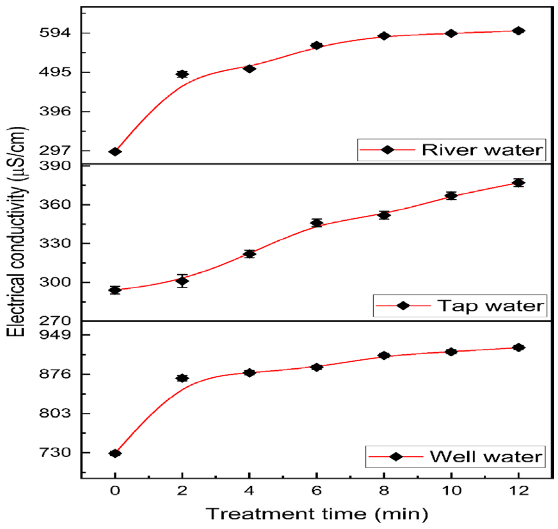


Figure 3: Variation of EC in well, tap, and river water samples with treatment time

3.1.3. Dissolved Oxygen (DO)

Dissolved oxygen (DO) is a key water quality parameter, indicating the concentration of molecular oxygen (O_2) in water [18]. It is vital for aquatic life and reflects the overall health of an ecosystem. DO levels are influenced by factors such as temperature, salinity, atmospheric pressure, and organic pollutants. Figure 4 depicts DO variations in well, tap, and river water samples during non-thermal plasma treatment, demonstrating its effectiveness in modulating oxygen concentrations across different water sources.

In this study, initial DO levels were 2.86 mg/L in well water, 3.5 mg/L in tap water, and 4.72 mg/L in river water. After 12 minutes of plasma treatment, DO increased to 4.81 mg/L in well water, 4.08 mg/L in tap water, and fluctuated between 4.82–3.12 mg/L in river water. The rise in DO for well and tap water is likely due to plasma-generated reactive oxygen species (ROS), such as ozone (O_3) and singlet oxygen (O_2*), which enhance oxygen solubility and drive oxidative reactions [18]. In contrast, the minimal change in river water DO may be attributed to its already high oxygen concentration, making it less responsive to plasma treatment.

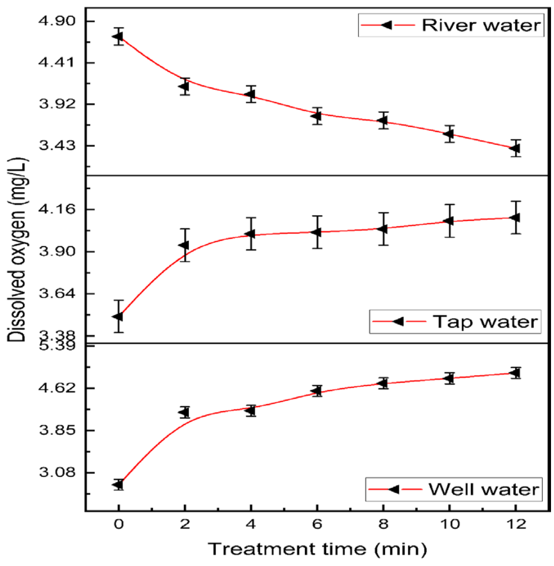


Figure 4: Variation of DO in well, tap, and river water samples with treatment time

3.1.4. Turbidity

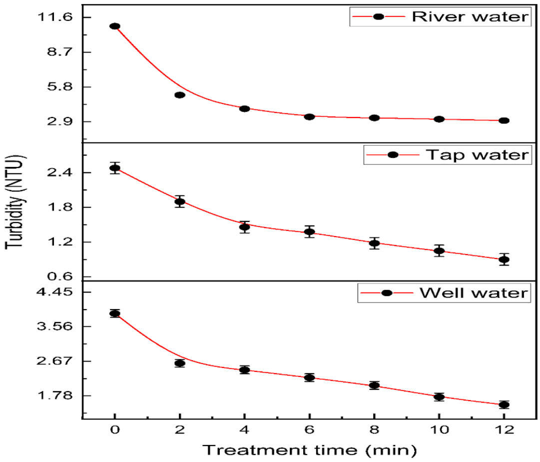


Figure 5: Variation of Turbidity in well, tap, and river water samples with treatment time

Turbidity, caused by suspended particles like sediment, silt, algae, and organic matter, affects water clarity and ecosystem health [19, 20]. Figure 5 illustrates turbidity variations in well, tap, and river water after plasma treatment. Initially, turbidity was 3.88 NTU in well water, 2.49 NTU in tap water, and 10.87 NTU in river water. After 12 minutes of non-thermal plasma treatment, levels dropped to 1.76 NTU, 1.06 NTU, and 3.11 NTU, respectively. This significant reduction demonstrates the effectiveness of cold plasma in enhancing water clarity by removing suspended particles.

3.1.5. Resistivity

Resistivity measurements play a key role in assessing the effects of low-temperature plasma treatment on water quality [21]. As shown in Figure 6, initial resistivity levels were 1.21 KΩ-cm for well water, 3.06 KΩ-cm for tap water, and 2.98 KΩ-cm for river water. After 12 minutes of plasma treatment, resistivity ranged from 1.09 to 1.17 KΩ-cm in well water, 2.88 to 3.18 KΩ-cm in tap water, and 1.95 to 2.01 KΩ-cm in river water. Cold plasma treatment induces physical and chemical modifications, potentially improving water purity by reducing contaminants and increasing resistivity, which reflects lower conductivity and higher water quality [22].

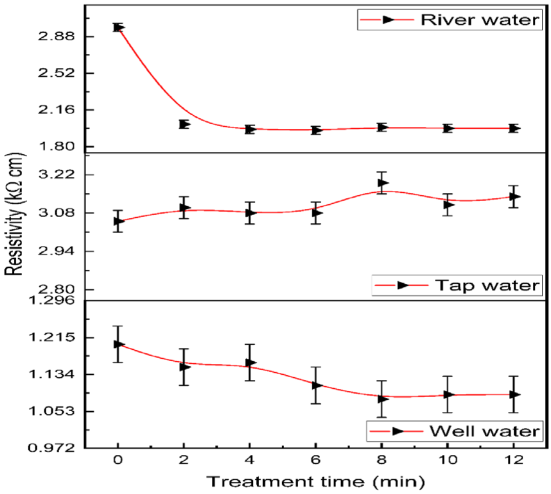


Figure 6: Variation of resistivity in well, tap, and river water samples with treatment time

3.1.6. Nitrate

Nitrate (NO_3^-), a nitrogen-oxygen compound commonly found in water as nitric acid salts, can pose health risks when converted to nitrite in the body. Non-thermal plasma treatment effectively alters nitrate levels through reactive oxygen and nitrogen species [22]. Initially, nitrate concentrations in well, tap, and river water were 6.42, 0.39, and 0.8 mg/L, respectively. After plasma treatment, levels increased to 6.56–8.16 mg/L in well water, 0.56–1.63 mg/L in tap water, and 2.68–3.60 mg/L in river water as shown in figure 7. This rise is attributed to plasma-induced oxidation, where hydroxyl radicals (. OH) and reactive nitrogen species (RNS) enhance nitrate formation. Additionally, plasma-driven breakdown of organic and inorganic matter increases nitrogen species availability, further contributing to elevated nitrate levels [23,24].

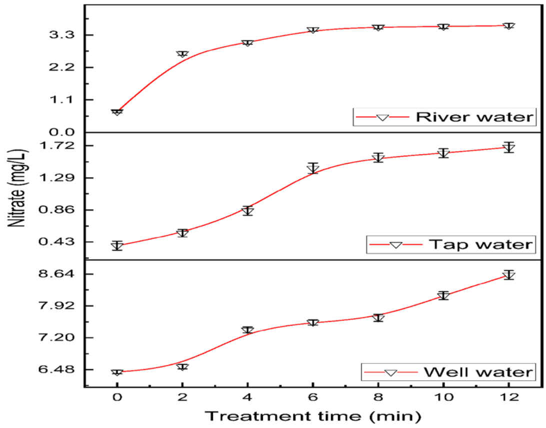


Figure 7: Variation of nitrate level in well, tap, and river water samples with treatment time

Ammonia

Ammonia (NH_3), a nitrogenous compound highly soluble in water, mainly exists as ammonium ions (NH_4^+) [25]. Its presence in water raises concerns due to its toxicity, contribution to eutrophication, and harmful effects on aquatic ecosystems. Plasma treatment has been investigated as an effective method to reduce ammonia concentrations by utilizing reactive species generated during plasma application to break down ammonia molecules. Figure 8 shows that the initial ammonia concentrations in tap and river water were below 0.01 mg/L. After plasma treatment, ammonia levels in tap water increased to a range of 0.01 to 0.76 mg/L, while river water concentrations ranged from 0.01 to 1.68 mg/L. In well water, ammonia concentrations remained nearly unchanged before and after plasma treatment, so it is not shown in the graph. The observed increase in ammonia levels post-treatment is likely due to the generation of reactive oxygen and nitrogen species, which interact with ammonia, leading to the formation of various degradation products [26].

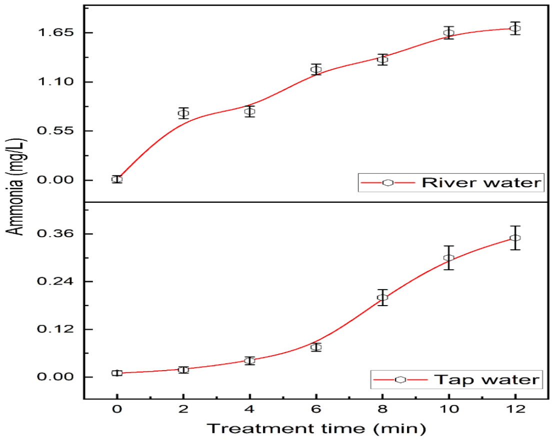


Figure 8: Variation of ammonia concentration in tap and river water samples with treatment time

4. Conclusion

This study highlights the effectiveness of non-thermal plasma technology in altering both the physical and chemical properties of water. Using a dielectric barrier discharge (DBD) plasma reactor, significant changes were observed in pH, electrical conductivity (EC), dissolved oxygen (DO), turbidity, resistivity, and various chemical parameters, including nitrate (NO_3^-) and ammonia concentrations. Cold plasma treatment lowered pH levels by generating reactive oxygen and nitrogen species (RONS), ensuring compliance with recommended water safety standards. The increase in EC indicated the formation of reactive ionic species, while the rise in DO levels demonstrated the potential for oxygenation in aquatic environments. The reduction in turbidity showcased plasma's ability to remove suspended particles, enhancing water clarity. Chemically, the accumulation of reactive species like nitrates and hydrogen peroxide underscored plasma technology's oxidative potential, playing a crucial role in disinfection and the removal of pathogens and organic contaminants. Overall, these findings establish non-thermal plasma technology as a sustainable and innovative approach to water treatment, effectively modifying key physicochemical parameters.

Author Contributions

HBB: Conceptualization, methodology, software, investigation, data curation, writing (original and final draft), writing (review & editing); **RPG/SD/AKS/SS/NK:** investigation, data curation and visualization; **DPS:** review & editing; All authors have read and agreed to the published version of the manuscript.

Data Availability

The data that supports the findings of the study are available from the corresponding author upon reasonable request.

Conflict of Interest

There is no conflict of interest for the publication of this article

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