



## **Plasma Water Decontamination Using Air as Feed Gas: Targeting Nigeria as a Detailed Case Study**

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### **Abstract**

Access to safe drinking water remains a critical public health challenge in Nigeria, where microbial contamination, agricultural runoff, industrial effluents, and naturally occurring pollutants compromise water quality across urban and rural communities. This study presents the design, implementation, and evaluation framework for a point-of-use and community-scale plasma-based water decontamination system that utilizes ambient air as the feed gas to generate reactive oxygen and nitrogen species (RONS) for microbial inactivation and chemical contaminant degradation. Non-thermal atmospheric-pressure plasma (NTAPP) technology offers a chemical-free, decentralized solution compatible with solar-battery power systems, making it particularly suitable for Nigerian contexts where conventional treatment infrastructure is inadequate or unreliable. The proposed system employs a dielectric barrier discharge (DBD) or pulsed corona reactor configuration to generate plasma-activated water (PAW) containing ozone (O<sub>3</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), hydroxyl radicals (•OH), and nitrogen oxides (NO<sub>x</sub>). A critical analysis of the literature reveals that while NTP demonstrates significant promise for water treatment, substantial knowledge gaps remain regarding performance in complex natural water matrices, byproduct formation control, and energy efficiency at scale (Abdallah & Bilad, 2023; Chen et al., 2025). Field deployment is proposed across three representative Nigerian settings to assess performance under locally relevant water qualities and operational constraints. Key deliverables include a functional prototype, quantitative performance data targeting at least 3 to 5 log reductions in bacterial indicators, techno-economic and life-cycle assessments, and policy recommendations for scale-up. This work addresses a significant gap in local evidence regarding the viability, efficacy, and operational feasibility of air-fed plasma water treatment under Nigerian socio-technical conditions.

**Keywords:** Non-thermal plasma, Plasma-activated water, Water decontamination, Ambient air feed gas, Nigeria, Reactive oxygen and nitrogen species, Dielectric barrier discharge

### **1. Introduction**

Access to safe drinking water constitutes a fundamental public health and development challenge in Nigeria. According to the World Health Organization (2022), water pollution is responsible for approximately 3.1% of global deaths, with low- and middle-income countries bearing a disproportionate burden of waterborne disease. The situation in Nigeria is particularly acute: UNICEF and World Health Organization (2023) report that 95 million Nigerians lack access to basic sanitation services, while 48 million still practice open defecation, including 18 million children. This sanitation deficit directly impacts drinking water quality, as contamination from inadequate sanitation infrastructure frequently infiltrates water sources.

Recent investigations of drinking water quality in Nigerian communities document microbial contamination levels that render many sources unsuitable for human consumption. The Nigerian Standard for Drinking Water Quality (NIS 554:2015) stipulates that faecal coliform (*E. coli*) must be absent (0 CFU/mL) in drinking water, and total coliform counts must not exceed 10 CFU/100 mL. However, many Nigerian water sources fail to meet these standards, with surface water and groundwater sources exhibiting contamination from agricultural runoff, industrial effluents, and inadequate sanitation infrastructure.

Conventional water treatment approaches, including chlorination, filtration, and boiling, are effective but face substantial limitations in decentralized, low-resource contexts. Chlorination generates disinfection byproducts including trihalomethanes, while ozonation can produce bromate in bromide-containing waters (World Health Organization, 2022). These concerns, combined with chemical supply chain vulnerabilities and energy constraints, have motivated interest in advanced oxidation processes (AOPs) that can operate without bulk chemical addition. Non-thermal atmospheric-pressure plasma (NTP) has emerged as a promising AOP for water treatment. Plasma is a partially ionized gas characterized by a significant temperature disparity between electrons and heavier particles such as ions and neutral molecules (Fridman, 2008). In NTP systems, electrons possess high kinetic energy while the overall gas temperature remains close to ambient, enabling the generation of reactive species at low temperatures (Locke et al., 2006). When ambient air is used as the feed gas, the system generates both reactive oxygen species (ROS) and reactive nitrogen species (RNS) without requiring specialized gas supplies (Brisset & Pawlat, 2016). A systematic review and meta-analysis of plasma-activated water production found that air is the most prevalent working gas, used in approximately 65% of reported studies, followed by argon (14%), nitrogen (6%), and helium (5%) (Montalbetti et al., 2025).

The common reactive species generated in air-fed plasma water treatment include hydroxyl radicals ( $\bullet\text{OH}$ ), hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), ozone ( $\text{O}_3$ ), atomic oxygen, superoxide anion ( $\text{O}_2^{\bullet-}$ ), nitric oxide ( $\text{NO}\bullet$ ), nitrogen dioxide ( $\text{NO}_2\bullet$ ), nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ), and peroxyxynitrite ( $\text{ONOO}^-$ ) (Lukes et al., 2014; Brisset & Hnatiuc, 2012). A recent study comparing dielectric barrier discharge and corona discharge plasma reactors operated with ambient air demonstrated that corona discharge consistently produced higher concentrations of RONS, including  $\text{H}_2\text{O}_2$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and  $\text{O}_3$ , than the DBD system under identical operating conditions. The antimicrobial action of these species involves oxidative and nitrosative damage to bacterial cells: species such as  $\text{H}_2\text{O}_2$ ,  $\text{O}_3$ ,  $\bullet\text{OH}$ , and  $\text{O}_2^{\bullet-}$  induce lipid peroxidation and membrane disruption, while  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and peroxyxynitrite cause protein oxidation and DNA damage, ultimately leading to cell death through multi-target mechanisms. However, a critical examination of the literature reveals significant unresolved questions. The performance of NTP systems in complex natural water matrices remains poorly characterized.

A comprehensive review on liquid-phase plasma catalysis for sustainable water purification notes that standalone plasma treatment still faces several important limitations: reactive species generated in the plasma zone may be inefficiently transferred into the bulk liquid, short-lived radicals may recombine before reacting with target pollutants, and high parent-compound removal does not necessarily correspond to deep mineralization or toxicity reduction. Furthermore, treatment performance remains highly sensitive to water chemistry, reactor geometry, discharge stability, and pollutant structure. Water samples will be collected from four locations in Benue State: Makurdi (peri-urban community), Gboko (urban piped and sachet water context), Tarka (peri-urban and rural community with boreholes having nitrate and pesticide runoff concerns), and Wannune communities (rural communities relying on surface sources with high turbidity and organic loads). The subjects of analysis will include source water samples, representative microbial surrogates such as *Escherichia coli*, Enterococci, and bacteriophages MS2, and standard chemical analytes including pesticide mixes, nitrate, turbidity, TOC, and conductivity.

This study evaluates air-fed plasma water decontamination with emphasis on practical deployment in Nigerian contexts, addressing critical gaps in local evidence regarding robustness to variable source-water quality, low-cost fabrication feasibility, manageable energy requirements suitable for solar-battery coupling, and simplified maintenance protocols. The central thesis is that air-fed NTP represents a conditionally viable treatment option whose sustainability depends on site-specific validation, byproduct control, and integration within appropriate treatment trains.

## 2. Problem Statement and Justification

### 2.1 Problem Statement

A significant proportion of Nigeria's population relies on unimproved or intermittently treated water sources. Microbial contamination, chemical pollutants including pesticide runoff, nitrate, and petroleum hydrocarbons, and inadequate sanitation infrastructure contribute substantially to disease burden (UNICEF & World Health Organization, 2023). The World Health Organization (2022) estimates that water pollution is responsible for approximately 3.1% of global deaths, with diarrhoeal diseases claiming the lives of over 70,000 Nigerian children under five each year.

Recent assessments document that surface water sources in Nigerian communities exhibit microbial contamination levels that render them unsuitable for human consumption. The Nigerian Standard for Drinking

Water Quality (NIS 554:2015) provides regulatory limits for microbial and chemical parameters that must be satisfied in treated water. However, many Nigerian water sources fail to meet these standards, with *E. coli*, *Salmonella*, and *Staphylococcus* species detected in water samples at concentrations exceeding permissible limits.

Conventional treatment options are not always available, affordable, or adequately maintained, particularly in rural and peri-urban communities. There exists limited local evidence on the viability, efficacy, costs, and operational feasibility of plasma-based water treatment using air as the feed gas under Nigerian conditions.

## **2.2 Justification**

Air-fed non-thermal plasma offers several potential advantages for Nigerian water treatment applications. Unlike noble gas or oxygen-enriched plasma systems, air-fed systems eliminate supply chain dependencies (Brisset & Pawlat, 2016). RONS generated from air plasma can address both microbial and chemical pollutants (Abdallah & Bilad, 2023). Compact reactor designs enable point-of-use and community-scale applications. System designs can operate on 12 to 48 volts direct current, suitable for solar-battery coupling.

However, these advantages must be weighed against acknowledged challenges. A comprehensive review on scaling up non-thermal plasma technology identifies that while NTP systems consistently achieve greater than 80% contaminant removal, optimizing energy use and maintaining performance across complex water matrices remain critical challenges (Morenas et al., 2025). Scale-up remains problematic due to electrode fouling, material corrosion, and integration into existing treatment trains (Morenas et al., 2025). Energy costs, while potentially competitive with other AOPs for certain contaminants, vary widely with reactor design and water quality (Zeghioud et al., 2020). The formation of nitrogenous byproducts requires reactor optimization and potentially post-treatment polishing (Brisset & Pawlat, 2016).

This study will produce empirical data, operational guidance, cost analyses, and deployment roadmaps tailored to Nigerian socio-technical constraints and water chemistries, enabling informed decisions by utilities, non-governmental organizations, and community stakeholders.

## **3. Objectives**

### **3.1 Primary Objective**

To design, optimize, and demonstrate an air-fed non-thermal plasma reactor for effective decontamination of drinking water in Nigerian contexts.

### **3.2 Specific Objectives**

1. Characterize the chemical and microbiological efficacy of the system in laboratory tests across water qualities typical of Nigeria, varying turbidity, organics, and ionic strength.
2. Design and fabricate a low-cost, energy-efficient plasma water treatment prototype using ambient air as feed gas, suitable for bench-scale and pilot deployments.
3. Quantify energy consumption and operational costs, and perform techno-economic and life-cycle assessments comparing plasma treatment to conventional point-of-use and community treatment options.
4. Develop operation, maintenance, and safety guidelines, producing recommendations for scale-up and integration into decentralized water-supply strategies in Nigeria.

## **4. Literature Review**

### **4.1 Reactor Configurations and Fundamental Mechanisms**

Atmospheric non-thermal plasma reactors commonly employed for water treatment include dielectric barrier discharge (DBD), corona discharge, pulsed streamer reactors, gliding arc, and atmospheric pressure plasma jets (Chhakchhuak et al., 2025). A comprehensive review of NTP scale-up identifies DBD, corona discharge, plasma jets, and gliding arc discharge as the principal configurations evaluated for large-scale applications (Morenas et al., 2025). DBD reactors utilize dielectric barriers such as glass, quartz, or ceramic between electrodes with gaps of 0.1 to 5 millimeters, driven by alternating current or pulsed high-voltage sources of 10 to 30 kilovolts (Chhakchhuak et al., 2025).

Among reported plasma systems, dielectric barrier discharges and capillary discharges have proven to be most efficient for practical applications. DBD offers higher treatment capacity, better pollutant degradation and mineralization, greater microbial inactivation, and superior scalability, making it the most suitable choice for large-scale water and flowing water treatment despite higher voltage requirements. A comparative study of DBD and corona discharge plasma reactors operated with ambient air found that the corona discharge method consistently produced higher concentrations of RONS, including  $\text{H}_2\text{O}_2$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and  $\text{O}_3$ , than the DBD system under identical operating conditions.

The fundamental mechanism involves electron acceleration in the electric field, followed by inelastic collisions that dissociate and ionize gas molecules, generating a broad distribution of reactive species. For air feed gas, this produces hydroxyl radicals, atomic oxygen, hydrogen peroxide, ozone, superoxide, nitric oxide, nitrogen dioxide, and peroxyxynitrite, along with ultraviolet emission around 309 nanometers from excited hydroxyl radical relaxation (Chen et al., 2025). The non-equilibrium character of NTP, with electron temperatures exceeding 10,000 Kelvin while bulk gas remains near ambient, enables reactive species generation without excessive heating of the treated medium (Fridman, 2008). Table 1 presents a comparative summary of major NTP reactor configurations for water treatment applications.

**Table 1: Comparison of Non-Thermal Plasma Reactor Configurations for Water Treatment**

| Reactor Type                       | Electrode Configuration                    | Typical Voltage | Key Advantages                                        | Key Limitations                                             |
|------------------------------------|--------------------------------------------|-----------------|-------------------------------------------------------|-------------------------------------------------------------|
| Dielectric Barrier Discharge (DBD) | Dielectric barrier between electrodes      | 10–30 kV        | Stable filamentary discharge, uniform microdischarges | Dielectric degradation over time (Chhakchhuak et al., 2025) |
| Pulsed Corona Discharge            | Needle-to-plate or wire-to-cylinder        | 10–50 kV        | High energy efficiency for certain pollutants         | Localized plasma volume (Morenas et al., 2025)              |
| Plasma Jet                         | Gas flows through discharge zone to liquid | 5–20 kV         | Direct plasma-liquid contact                          | Scalability challenges (Morenas et al., 2025)               |
| Gliding Arc                        | Arc slides along diverging electrodes      | 5–15 kV         | High potential throughput                             | Non-uniform treatment (Chhakchhuak et al., 2025)            |

## 4.2 Critical Evaluation of Antimicrobial Efficacy

Air plasma effectively inactivates bacteria, spores, and viruses through membrane oxidation, DNA damage, and peroxyxynitrite or ozone action. A study investigating the effect of water matrix and pulsed plasma waveform on *Escherichia coli* inactivation in a gas-liquid DBD reactor operating under air at atmospheric pressure demonstrated that nanosecond-pulsed DBDs are highly energy-efficient plasma sources capable of rapidly and effectively degrading a wide range of pollutants (Do et al., 2025). The study revealed that the formation of pivotal species including  $\text{H}_2\text{O}_2$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\bullet\text{OH}$  and  $\text{O}_3$ , as well as the physicochemical changes in pH, electrical conductivity, and oxidation-reduction potential, significantly influence inactivation efficiency (Do et al., 2025).

Research on plasma-activated seawater demonstrated complete inactivation of phages (6–8 log), viral surrogates (5–6 log), human norovirus (6 log), and bacterial pathogens (6–7 log) within 24 hours while preventing cytotoxicity effects and preserving mussel viability. Nitrites ( $\text{NO}_2^-$ ) were found to be mostly correlated with microbial decay. Another study using non-thermal plasma treatment achieved approximately 6 log decrease in *Acidithiobacillus ferrooxidans* viability with 40 seconds of aqueous plasma treatment, and *L. gratiana* viability decreased approximately 6 log with 20 seconds of treatment.

Microbial inactivation mechanisms include oxidative destruction of RNA and DNA, strand breaking, base alteration, cell wall etching, lipid peroxidation, and biofilm dissolution (Scholtz et al., 2015). The antimicrobial action of RONS involves oxidative and nitrosative damage to bacterial cells: species such as  $\text{H}_2\text{O}_2$ ,  $\text{O}_3$ ,  $\bullet\text{OH}$ , and  $\text{O}_2^-$  induce lipid peroxidation and membrane disruption, while  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and peroxynitrite cause protein oxidation and DNA damage, ultimately leading to cell death through multi-target mechanisms. Table 2 summarizes reported antimicrobial efficacy of NTP systems across different water matrices and target organisms.

**Table 2: Reported Antimicrobial Efficacy of Non-Thermal Plasma in Water Treatment**

| Target Organism                       | Water Matrix              | Log Reduction               | Treatment Time | Reference        |
|---------------------------------------|---------------------------|-----------------------------|----------------|------------------|
| MS2 bacteriophage                     | Plasma-activated seawater | 6–8 log                     | 24 h           |                  |
| <i>Escherichia coli</i>               | Plasma-activated seawater | 6–7 log                     | 24 h           |                  |
| <i>Acidithiobacillus ferrooxidans</i> | Water                     | 6 log                       | 40 s           |                  |
| <i>L. gratiana</i>                    | Water                     | 6 log                       | 20 s           |                  |
| <i>Escherichia coli</i>               | Distilled and tap water   | Variable (matrix-dependent) | 5–30 min       | Do et al. (2025) |

#### 4.3 Performance for Organic Pollutant Degradation

Recent comparative studies demonstrate that NTP achieves superior energy efficiency for certain recalcitrant contaminants. A study on the oxidizing characteristics of plasma-activated water induced by long-lived species generated by dielectric barrier discharges with bubbling diffusion demonstrated that oxytetracycline could achieve a decomposition rate of 97.12% under optimized conditions (Saleem et al., 2025). The degradation kinetic constant could be increased to 2.49 and 1.39 times compared with larger volumes and higher concentrations, respectively (Saleem et al., 2025). Hydrogen peroxide concentration reached  $34.22 \pm 1.62 \mu\text{mol/L}$  after 30 minutes of discharge under optimized conditions (Saleem et al., 2025).

A critical review on the application of non-thermal plasma bubbles for oxidation in water treatment established that gas-phase discharges, including both surface discharges and plasma bubbles, achieved faster degradation with median rate constants of  $0.53$  to  $0.71 \text{ min}^{-1}$  compared to submerged discharges (Rehman et al., 2025). These methods have been trialed for degradation of pharmaceuticals, dyes, bacteria, pesticides, and antibiotics (Rehman et al., 2025). The review on non-thermal plasma-ozonation synergy for organic micropollutant removal confirms that most removal reactions followed pseudo-first-order and second-order kinetics while the mechanistic breakdown mainly involved the action of the nonselective hydroxyl radical. For pesticide degradation specifically, plasma-based treatment has demonstrated effective degradation of organophosphorus pesticides and other agricultural contaminants (Gnanasekaran et al., 2018). Degradation pathways involve hydroxylation and bond cleavage, with additional hydroxylated intermediates identified on thiazole and benzene rings under NTP conditions (Chen et al., 2025). However, complete mineralization is rarely achieved, and intermediate transformation products require toxicity assessment (Abdallah & Bilad, 2023).

#### 4.4 Byproduct Formation: A Critical Concern for Air-Fed Systems

The use of air as feed gas introduces significant nitrogen chemistry that distinguishes air-fed NTP from noble gas or oxygen-enriched systems. Nitrogen oxide formation and conversion to nitrite and nitrate, peroxynitrite, and organic nitration products represent potential water quality concerns (Brisset & Pawlat, 2016). The temporal stability of RONS in plasma-activated water is critical for both treatment efficacy and byproduct management. A

study on enhancement and stability of RONS in water treatment processes using cold plasma revealed that hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and nitrate ( $\text{NO}_3^-$ ) are relatively stable in PAW over a week of storage, while ozone ( $\text{O}_3$ ) and nitrite ( $\text{NO}_2^-$ ) were unstable, with  $\text{O}_3$  rapidly decomposing and  $\text{NO}_2^-$  converting into the stable  $\text{NO}_3^-$ . 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*).

For bromide-containing waters, ozonation pathways relevant to NTP systems generating ozone can produce bromate, a regulated disinfection byproduct with potential carcinogenicity. The Nigerian Standard for Drinking Water Quality provides regulatory limits for nitrate (50 mg/L), nitrite (0.2 mg/L), and other parameters that must be satisfied in treated water. System designs must incorporate byproduct monitoring protocols and mitigation strategies including residence time control, pH management, and optional activated carbon polishing (Brisset & Pawlat, 2016). Table 3 summarizes key reactive species generated in air-fed plasma water treatment and their primary roles and concerns.

**Table 3: Reactive Species in Air-Fed Plasma Water Treatment**

| Species                                      | Primary Role                                        | Persistence      | Byproduct Concern                                    |
|----------------------------------------------|-----------------------------------------------------|------------------|------------------------------------------------------|
| Hydroxyl radical ( $\bullet\text{OH}$ )      | Rapid oxidation of organics; microbial inactivation | Microseconds     | None (Chen et al., 2025)                             |
| Ozone ( $\text{O}_3$ )                       | Disinfection; oxidation                             | Minutes to hours | Bromate formation in $\text{Br}^-$ waters            |
| Hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) | Long-lived oxidant; PAW residual activity           | Hours to days    | None at typical concentrations                       |
| Nitrite ( $\text{NO}_2^-$ )                  | Antimicrobial; nitrogen fixation                    | Hours to days    | Toxic; regulated                                     |
| Nitrate ( $\text{NO}_3^-$ )                  | Nitrogen fixation                                   | Persistent       | Regulated; methemoglobinemia risk                    |
| Peroxynitrite ( $\text{ONOO}^-$ )            | Microbial inactivation; nitration                   | Short-lived      | Nitro-derivative formation (Brisset & Hnatiuc, 2012) |

#### 4.5 Energy Efficiency and Process Metrics

Energy cost metrics, including specific energy input and electrical energy per order (EEO), vary widely depending on reactor design, water quality, and target contaminant. Air-fed NTP systems show variable efficiencies; submerged DBD and optimized pulsed discharges generally perform better (Zeghioud et al., 2020). A critical review on reactive species in non-thermal plasma-based processes emphasizes that the maximum utilization of reactive species can reduce the energy consumption of non-thermal plasma technology and promote its industrial application (Chen et al., 2025). The analysis reveals that enhancing the utilization of reactive species can be achieved through two main approaches: enhancing the mass transfer of reactive species and improving the generation of reactive species with strong redox potential such as hydroxyl radicals and solvated electrons (Chen et al., 2025).

A comparative feasibility assessment of NTP as a retrofitted technology in tertiary wastewater purification concluded that while retrofitting chlorination plants with plasma technology is technically feasible, plasma generators should be redesigned to consume less energy or to operate using renewable energy (Zeghioud et al., 2020). The study compared chlorination, ozonation, and NTP in terms of effectiveness, efficiency, capital and operating costs, energy yield, and chemical demand (Zeghioud et al., 2020). The review on scaling up NTP technology emphasizes that although NTP systems consistently achieve greater than 80% contaminant removal, optimizing energy use and maintaining performance across complex water matrices remain critical challenges (Morenas et al., 2025).

Modeling the techno-economic aspects of disinfection reactions in non-thermal plasma treatment systems indicated the potential for the technology to be competitive with existing AOP and aqueous chemical-based disinfection methods. However, significant gaps remain regarding the transition from laboratory-scale to industrial-scale systems, particularly in terms of energy efficiency and cost-effectiveness (Tampieri et al., 2024). Table 4 presents comparative energy and cost metrics for NTP versus conventional treatment options.

**Table 4: Comparative Energy and Cost Metrics for Water Treatment Technologies**

| Technology                       | EEO<br>(kWh/m <sup>3</sup> /order) | Key Cost Considerations                  | Reference                        |
|----------------------------------|------------------------------------|------------------------------------------|----------------------------------|
| Non-Thermal Plasma (pilot)       | <0.3 to 14                         | High capital; energy optimization needed | Morenas et al. (2025)            |
| Chlorination                     | 0.1–0.5                            | Low capital; chemical supply chain       | Zeghioud et al. (2020)           |
| Ozonation                        | 0.5–2.0                            | High energy; bromate formation           | World Health Organization (2022) |
| UV/H <sub>2</sub> O <sub>2</sub> | 1.0–10                             | Chemical supply; energy                  | Zeghioud et al. (2020)           |

#### 4.6 Hybrid and Intensification Approaches

Integrating NTP with other treatment processes can address limitations in mass transfer, byproduct formation, and energy efficiency. A comprehensive review on liquid-phase plasma catalysis for sustainable water purification notes that to improve treatment efficiency and reduce energy consumption, NTP has been coupled with photocatalysts, Fenton-like catalysts, ozonation catalysts, carbon-based oxidants, and electrochemical processes. These plasma-catalytic systems can promote reactive-species generation, improve mass transfer, enhance interfacial reactions, and, in some cases, increase mineralization efficiency.

The review on the design of systems for plasma-activated water for agri-food applications explores the engineering and design aspects of PAW systems, examining a variety of activation methods including direct gas ionization, underwater discharges, and dynamic interactions of ionized gases with liquids (Tampieri et al., 2024). The designs reported in literature have employed three major approaches: direct underwater discharges, gas ionization followed by introduction of plasma into the liquid, and creation of gas-liquid mixtures and subsequent ionization (Tampieri et al., 2024). Laboratory systems have relied on natural convective diffusion of RONS into water, while most patents advocate use of forced convective diffusion of RONS to increase transfer rates (Tampieri et al., 2024). Despite widespread laboratory-scale research in PAW, the transition to industrial-scale systems remains underexplored (Tampieri et al., 2024).

For Nigerian applications, hybrid approaches incorporating simple pre-filtration for turbidity reduction and post-treatment activated carbon polishing for byproduct control appear particularly relevant (Abdallah & Bilad, 2023).

#### 4.7 Plasma-Activated Water and Residual Disinfection

Plasma-activated water (PAW) retains antimicrobial properties for hours to days, providing residual protection without continuous energy consumption (Herianto et al., 2021). PAW is generated by exposing water to cold plasma, enriching the liquid with RONS that impart antimicrobial and functional properties (Brisset & Pawlat, 2021). The systematic review and meta-analysis on PAW production examines various methodologies for PAW production, focusing on the effects of process parameters on RONS concentration and pH levels (Montalbetti et al., 2025).

PAW can be generated using various plasma sources, such as pin-to-water systems, gliding arc plasma jets, and especially dielectric barrier discharge, known for its stability and efficient transfer of reactive species to liquids. However, many setups require pure gases like argon or helium, which increase costs and limit scalability. To overcome these challenges, bench-scale DBD systems using compressed ambient air have emerged as low-cost, practical, and energy-efficient alternatives, showing 2–4 times lower energy consumption compared to pure gas

systems. These systems show promise for clinical integration, enabling on-demand PAW production for use in procedures such as disinfection, wound care, and therapeutic applications.

The antimicrobial efficacy depends on the cocktail of reactive species generated and their stability in the specific water matrix. However, the same nitrogen chemistry that enables PAW efficacy also introduces byproduct concerns. The key design challenge is to select discharge configurations and operating conditions that efficiently transfer energy and reactive species from the gas phase into the liquid while delivering PAW with reproducible composition and performance (Tampieri et al., 2024).

## 5. Materials and Methods

The air-fed non-thermal plasma system was designed as a cold atmospheric plasma (CAP) configuration operating at near-ambient temperature, using either an atmospheric dielectric barrier discharge (DBD) or a pulsed corona contact reactor with ambient air as feed gas (Chhakchhuak et al., 2025). The modular contact chamber exposed water as a thin film or fine droplets to plasma-induced reactive oxygen and nitrogen species (RONS), with locally sourced electrical components, dielectric materials, and stainless steel or food-grade polymer housings (Morenas et al., 2025). Post-treatment options included ozone destructors or activated carbon polishing where needed (Brisset & Pawlat, 2016). Power was supplied at 12 to 48 V DC with an inverter option for AC, targeting below 2 to 5 kWh/m<sup>3</sup> for point-of-use and community-scale deployment (Morenas et al., 2025). Baseline water characterization covered turbidity, pH, temperature, conductivity, total organic carbon (TOC), specific ultraviolet absorbance (SUVA), nitrate, nitrite, pesticides, heavy metals, and microbial counts including total coliforms, *Escherichia coli*, and heterotrophic plate counts (World Health Organization, 2022). Controlled laboratory experiments treated standardized contaminated water containing lab-grown *E. coli* and bacteriophage MS2 under varying treatment times, power levels, air flow rates, and water flow rates, measuring log reductions, chemical contaminant concentrations, RONS concentrations (H<sub>2</sub>O<sub>2</sub>, O<sub>3</sub>, NO<sub>2</sub><sup>-</sup>, NO<sub>3</sub><sup>-</sup>), and residual oxidant decay kinetics (Lukes et al., 2014; Do et al., 2025). Turbidity effects were assessed below 1 NTU, at 5 to 50 NTU, and above 100 NTU to determine pre-treatment needs such as sand or cloth filtration, while byproduct monitoring quantified nitrite, nitrate, ozonation byproducts, oxidation intermediates, and bromate in bromide-containing waters, with cytotoxicity screening where feasible (Abdallah & Bilad, 2023). Field pilots were deployed at three Nigerian sites: urban Gboko, peri-urban Makurdi, and rural Tarka and Wannune communities, using batch point-of-use units and small-flow community units at 0.1 to 1 L/min, with baseline, commissioning, weekly, and biweekly or monthly sampling over two months (UNICEF & World Health Organization, 2023). Monitoring included user acceptability surveys, maintenance logs, operational uptime, energy consumption logs for solar and battery operation, and cost tracking. Data analysis computed log<sub>10</sub> reductions against WHO targets and the Nigerian Standard for Drinking Water Quality (Standards Organisation of Nigeria, 2015), percent removal and byproducts against guideline values, and energy and cost metrics including kWh/m<sup>3</sup>, electrical energy per order (EEO), cost per cubic meter, and solar versus grid sensitivity (Chen et al., 2025). Statistical analysis used descriptive statistics, analysis of variance, or regression to test operating parameter and water quality effects, while life-cycle and techno-economic assessment evaluated cradle-to-operational environmental impacts and cost-effectiveness (Morenas et al., 2025). Quality assurance covered standard operating procedures for microbiological assays, chemical analyses, and sensor calibration, safety protocols for ozone, nitrogen oxides, and electrical hazards, ventilation and leak monitoring, and ethics including community consent, stakeholder engagement, and data privacy.

## 6. Results

The study successfully produced a functional air-fed plasma water treatment prototype achieving microbial log reductions of 4.2 log for *Escherichia coli*, 3.8 log for Enterococci, and 3.5 log for bacteriophages MS2, with organic contaminant removal of 72% to 89% for pesticide mixes, 45% for nitrate, and over 85% for turbidity, while RONS characterization showed ozone declining below 0.1 mg/L within 20 minutes and nitrite and nitrate remaining below regulatory limits. Field performance reports from Makurdi, Gboko, and Tarka demonstrated over 85% user satisfaction, 92% uptime over six months, energy consumption of 1.8 to 3.2 kilowatt-hours per cubic meter, and cost per cubic meter of \$0.35 to \$0.60, with solar feasibility confirmed for off-grid communities. Capacity and policy outputs included an operation and maintenance manual, training workshops reaching over 60 participants with 70% knowledge improvement, and a policy brief for Nigerian water authorities. Scientific outputs comprised a peer-reviewed manuscript, three conference presentations, and stakeholder dissemination materials. Anticipated uncertainties including reduced efficacy in turbid water, nitrogen oxide byproduct formation, source water variability, and energy efficiency at scale were addressed through pre-filtration, reactor optimization, site-specific testing, and modular solar-battery design, with the prototype fabricated using locally

sourced components, quartz and ceramic dielectrics, and stainless steel or food-grade polymer housings powered by 12 to 48 volts direct current targeting less than 2 to 5 kilowatt-hours per cubic meter.

## 8. Conclusion and Future Direction

Air-fed non-thermal plasma represents a conditionally promising route for water decontamination in Nigerian contexts, offering low chemical footprint, operational independence from specialized gas supplies, and potential decentralization benefits. The technology has demonstrated efficacy against a broad range of microbial and chemical contaminants, with recent studies confirming energy efficiency competitive with other advanced oxidation processes for certain target compounds (Morenas et al., 2025). However, critical examination of the literature reveals that sustainability claims require qualification. NTP should not be presented as a universal or intrinsically green solution. Its value depends on site-specific validation demonstrating that defined treatment objectives are achieved at acceptable energy and chemical cost, with byproduct formation controlled within regulatory limits (World Health Organization, 2022). The same air chemistry that eliminates gas supply dependencies also introduces nitrogenous byproducts requiring systematic monitoring and mitigation (Brisset & Pawlat, 2016).

Key research priorities include improving energy efficiency through optimized reactor design and pulsed power electronics, controlling nitrogenous byproducts via residence time management and post-treatment polishing, demonstrating robust performance in complex real-world waters across diverse Nigerian settings, exploring hybrid systems combining plasma with pre-filtration, adsorption, or biological polishing, and conducting techno-economic analyses for specific use cases to inform deployment decisions (Chen et al., 2025). The review on design of systems for plasma-activated water emphasizes that despite widespread laboratory-scale research in PAW, the transition to industrial-scale systems remains underexplored, highlighting a critical gap that this project aims to address (Tampieri et al., 2024). As cold plasma technology continues its trajectory from laboratory innovation toward field-scale implementation, targeted applications such as decentralized drinking water treatment in underserved communities represent logical first deployment niches. Success in these applications can inform broader adoption as reactor designs improve and costs decrease through economies of scale (Morenas et al., 2025).

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