A Novel Solar-Powered Cold Plasma Ozonation System for Point-of-Use Drinking Water Treatment

Report
to the Water Research Commission

by

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WATER
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EXECUTIVE SUMMARY

BACKGROUND

There are various types of water contaminants (physical, chemical, biological, etc.), and different methods are employed to eliminate these contaminants from water depending on the intended water use. In South Africa, prevalent contaminants reported in literature are generally classified as inorganic chemicals, polycyclic aromatic hydrocarbons (PAHs), micropollutants, nutrients and microorganisms. This project examined drinking water quality from a holistic viewpoint by conducting several tests on untreated water and treated water following the guidelines of the World Health Organisation (WHO) and South African National Standard (SANS) 241. However, based on subsequent findings regarding several of the heavy metals in compliance with the limit set by WHO, the project focused on microorganisms and, more specifically, bacteria (or bacteriological quality) in the water. In this respect, destruction of *Escherichia coli* (E. *coli*) and total coliforms has been investigated in accordance with the WHO standard. The investigation of the destruction of microorganisms is further premised and underpinned by the fact that microbial pollutants are listed in different areas of South Africa as among the main pollutants in rural and peri-urban communities. The potential for the destruction of microorganisms using plasma-based systems is well-established. However, most studies focus on simulated water and rarely carry out research on real water where there are several organic matters and inorganics that could reduce the efficacy of the system. This indeed is the strength of this research project, and the investigations in different real water bodies are elaborated in this report. To achieve this, continuous literature review, reactor/process design and construction, user perspectives evaluation and system process evaluation against SANS 241:2015 and WHO guidelines were carried out.

This final report describes all the activities undertaken on the project entitled "A Novel Solar-Powered Cold Plasma Ozonation System for Point-of-Use Drinking Water Treatment" supported by the Water Research Commission (WRC) of South Africa under WRC Project No.: C2022-2023-00897 in the period 2022 to 2025. The research station was located at the University of Pretoria, Department of Chemical Engineering, with technical and scientific knowledge sharing and support from Swansea University, UK.

OBJECTIVES

The objectives of the project were to:
  (i)   design, construct and operate the solar-powered plasma-ozonation system at laboratory scale for surface water treatment,
  (ii) evaluate user participation with respect to technology acceptability, design and usability of the point-of-use (POU) device,
  (iii) study the effect of reactor operating conditions on the performance (such as energy use, treatment time, and disinfection of contaminants) of the system,
  (iv) evaluate the efficacy of point-of-use solar-powered cold plasma-ozonation technology on real water treatment considering the WHO's water quality standard & benchmark with well-established methods, with respect to cost per volume of treated water and energy consumption during the treatment.

This report presents an overview of all the concluded investigations, based on the aforementioned objectives, in this project. Each chapter of this report further details the respective investigations carried out in the project. Other useful results of performance and water quality analyses that are not included in the main body of this report are presented as appendices to this report as typical results of various experiments carried out.

INCEPTION AND LITERATURE REVIEW

After the project started, the survey of pertinent literature was initiated and continued throughout the period of the project. The sources included major databases such as Scopus, Web of Science, PubMed and other online resources for grey literature. Initially, the search window was limited to the period 2003 to 2022 (20 years), then extended in the course of the project to the end of 2024. The spectrum of information included cold or non-thermal plasma, ozonation, and water treatment, and enormous volumes of manuscripts were reviewed

to extract relevant ideas to execute the project objectives. The information guided the design, construction and operation of the plasma reactor and the system/device performance evaluation with respect to water treatment at the household level to inactivate microbiological contaminants. The survey of literature revealed that plasma-ozonation (PO) had not been studied and tested as a point-of-use technology (Pooi and Ng, 2018), and even then, investigators who attempted to study and test a solar-powered decentralised drinking water ozonation system utilised microplasma to produce ozone (Hendrickson et al., 2020). This project set out to investigate the application of a solar-powered plasma-ozonation system based on dielectric barrier discharge (DBD) as a point-of-use water treatment system. Also, the research by (Magureanu et al., 2016; Vanraes et al., 2017; Wardenier et al., 2019) concentrated on micropollutants and organic compounds; however, our goal was to implement the coupled PO technique and reactor system to successfully improve the quality of drinking water from surface (and groundwater) water sources by ensuring that the treated water meets the standard of the WHO and SANS 241:2015.

DESIGN, CONSTRUCTION AND OPERATION

With respect to design, construction and operation, two reactor modules (R1 and R2) have been designed for a range of operational options and functions, without the same material and operating principle but with different functioning modes. Both R1 and R2 are dielectric barrier discharge plasma reactors consisting of borosilicate glass tubes with copper tape wrapped around each of the tubes and stainless-steel electrodes (R2-spiked and R1-unspiked). R1 is of smaller size: 30 mm (outer diameter) x 300 mm (length) x 2.3 mm (wall thickness) glass, specifically configured to study ozone dosage and powered by a high voltage pulsed direct current power supply unit (HV Pulsed DC PSU). R2 (main reactor) is 40 mm (outer diameter) x 300 mm (length) x 2.3 mm (wall thickness) powered by a high voltage alternating current power supply unit (HV AC PSU) that can draw power from either the solar energy system or from electrical socket (grid).

The solar energy system designed and installed by GreenHouse Energy Consulting, South Africa, mainly consists of solar panels (on the rooftop), an inverter, a storage battery, a charge controller and other necessary controls all fitted in one unit/box (except panels). R2 feed gas is oxygen (> 93% purity, rated at 10 L/min, with a higher purity of 95% at 5 L/min), a pressure swing adsorption (PSA) oxygen concentrator (OC), eliminating the expensive and unsustainable oxygen cylinder (of R1). The operation process of R2 has been configured and engineered for a range of operating modes, but mainly to fit the primary function of plasma-ozonation. With just simple control valves, it can do ozonation alone (batch mode), plasma alone (or only) – continuous flow mode, plasma-ozonation and plasma alone – single pass mode in continuous recirculation of the produced ozone. The other process components include an oscilloscope, a peristaltic pump, flow meters and connecting tubing.

USER PARTICIPATION EVALUATION – ACCEPTABILITY, DESIGN AND USEABILITY

The user participation involved engaging the community (Hammanskraal community, City of Tshwane (CoT), South Africa (SA)) to mainly raise awareness of untreated water effects and introduce plasma-ozonation HWT technology. This was carried out through a focus group discussion (FGDs) of 14 members, through interactive open discussions and questionnaire transmission and to evaluate user acceptability, design and useability or the willingness to use/adopt the technology. The current system design consists of a solar-powered plasma reactor (R2) in a container/housing unit of size 3 m (Length, L) x 2 m (width, W) x 2.4 m (height, H), described as a community module was introduced to the community and was the basis of the engagements and responses.

The engagements established that (i) the community was willing and accepted to test and use the technology in their area, (ii) was open to using the green energy-powered POU water treatment technology, and (iii) On design, in addition to the community module (a container/housing unit, 3 m (L) x 2 m (W) x 2.4 m (H)), they ideated to have an individual household tap module, which may not fit in the current project parameters of time and resources.

SYSTEM PERFORMANCE EVALUATION

The performance evaluation was undertaken by investigating the effect of experimental conditions on reactor efficiency/efficacy and the treatment efficiency/efficacy of the technology based on WHO criteria and SANS 241.

a) Effect of experimental conditions on reactor efficiency/efficacy

For experimental conditions, the study utilised a smaller reactor R1 (30 mm x 300 mm x 2.3 mm borosilicate glass tube). The gas flow rate (in L/min), voltage (in kV) and Frequency (in kHz) were investigated as the three main independent variables influencing the concentration of ozone produced. The activities included: calibration of the Rotameter (oxygen flow regulator), plasma ozone quantification and establishing optimal reactor operating conditions for optimal ozone production. An initial parametric screening was conducted using the one-factor-at-a-time (OFAT) approach. Afterwards, a full experimental design was carried out using the response surface methodology – Box Behnken (RSM BB) approach, where the RSM BB experiment with 3 factors, each with 3 levels and ozone concentration as the response, was utilised. It was concluded that the optimal conditions for ozone production were at a flow rate = 1.64 L/min, voltage = 22 kV and Frequency = 2 kHz for samples at 20°C for the smaller reactor R1. Also, only the operating frequency was of statistical significance based on the response surfaces. The results also depicted the importance of temperature in the generation/solubility and half-life of ozone due to the reason that, with higher frequencies, more heat is generated. These results gave valuable ideas for determining suitable conditions for studying reactor R2 to treat real surface water.

b) Treatment efficiency/efficacy of the technology based on WHO criteria and SANS 241 (with R2)

The investigations utilising R2 were carried out to analyse the system's treatment efficiency/efficacy, and these included; (i) surface water treatment from a nearby more urban stream (LC De Villiers, Sports Centre) – treatment was carried out two times, (ii) surface water (Mutshedzi River) and groundwater (Manyii and Mamvuka springs) located in Limpopo province, in rural areas and (iii) water treatment plant (WTP) water and community tap (TAP) water served by the plant. Microbiological quality parameters were the major focus for characterising the reactor's (R2) efficiency/efficacy, given that most of the other quality parameters were below the upper range provided by WHO, as highlighted in Appendix B.

(i) LC De Villiers, Sports Centre – Using R2

The LC De Villiers Sports Centre stream initial testing and treatment (with R2) showed that most parameters in the plasma-treated sample complied with the SANS 241: 2015 and WHO guidelines. However, the high E. *coli* load of 770 MPN/100 mL was reduced to 6 MPN/100 mL after 30 minutes of treatment, which did not comply with the undetectable levels (0 or < 1 MPN/100 mL) required (WHO and SANS 241: 2015). The nitrates also increased from 0.9 mg/L (untreated water) to 6.0 mg/L (treated water), possibly due to system connections that could allow air ingress into the system. A second sample was therefore collected and studied with improved experimental parameters; mainly, treatment time was increased. The results show that in 60 minutes, the detected 450 colonies of E. *coli*/100 mL in raw water were eliminated. Also, the raw water total coliform load of 24000 colonies /100 mL was fully removed. This implies the plasma technology can improve the microbiological quality of drinking water with increased time.

However, the challenge that will continue to be under study in a different project arrangement is the issue of the nitrites, which increased in the first test, and a similar trend persisted in the second testing. The nitrates increased from <0.5 mg/L in raw water (untreated) to 11.62 mg/L after treatment. The nitrites also followed the same trend as nitrates. This aspect will further be investigated in the future to obtain a solution as a research problem follow-up.

(ii) Surface water (Mutshedzi River) and groundwater (Manyii and Mamvuka springs) – Using R2

These highly polluted sources were experimentally studied utilising the solar-powered HV AC PSU feeding the reactor R2, and the plasma performance has been compared to other HWT methods but with focus on chlorine

tablet and boiling (**Tables 0-1 and 0-2**). For Mutshedzi River, plasma reduced the initial E. *coli* and total coliform loads of 11400 CFU/100 mL and 73150 CFU/100 mL to 2 CFU/100 mL (99.99% removal) and 11 CFU/100 mL (99.985% removal), respectively, in 60 minutes. Chlorine tablet was better, but plasma was better than boiling.

Table 0-1: Treatment options for E coli and total coliforms in Mutshedzi River (P7).

Treatment Option	E-coli				Total Coliforms			
	Initial E coli (CFU/100 mL)	Final E coli (CFU/100 mL)	Percentage removal (%)	Log reduction	Initial total coliform (CFU/100 mL)	Final total coliform (CFU/100 mL)	Percentage removal (%)	Log reduction
Boiling	11400	14	99.88	2.91	73150	34	99.950	3.35
Chlorine tablet	11400	0	100	5.06	73150	4	99.995	4.86
Plasma	**11400**	**2**	**99.99**	**3.76**	**73150**	**11**	**99.985**	**3.82**

Table 0-2: Water purification methods applied for Manyii and Mamvuka springs

Pollutant	Manyii Spring					Mamvuka Spring (S2)				
	Method	Initial (CFU/100 mL)	Final (CFU/100 mL)	% Removal	Log Reduction	Method	Initial (CFU/100 mL)	Final (CFU/100 mL)	% Removal	Log. Reduction
E. coli	Chlorine Tablets	3145	0.1	100	4.5	Chlorine Tablets	1975	9	99.54	2.34
	Boiling	3145	17	99.46	2.27	Boiling	1975	0.1	99.99	4.3
	Plasma	**3145**	**0**	**100**	**Complete removal**	**Plasma**	**1975**	**0**	**100**	**Complete removal**
Total Coliforms	Chlorine Tablets	14745	6	99.96	3.39	Chlorine Tablets	10575	9	99.91	3.07
	Boiling	14745	173	98.83	1.93	Boiling	10575	104	99.02	2.01
	Plasma	**14745**	**26**	**99.82**	**2.75**	**Plasma**	**10575**	**0**	**100**	**Complete removal**

Plasma completely inactivated E. coli from Manyii and Mamvuka springs (**Table 0-2**). The initial high E. *coli* contaminant loads of 3145 CFU/100 mL (Manyii) and 1975 CFU/100 mL (Mamvuka) were reduced to **0** CFU/100 mL after 60 minutes of plasma action. In this case, plasma stands out as an HWT/POU treatment method, followed by chlorine tablet. Note that boiling, a common HWT method, did not kill all the pathogens in Manyii spring (17 CFU/100 mL out of 3145 CFU/100 mL remained).

(iii) Water treatment plant (WTP) and community tap (TAP) with R2

The purpose of testing the WTP and TAP water was to examine the effect of plasma treatment on treated water ready for the distribution network and at the tap outlet for consumption. The analytical results on untreated WTP and TAP water showed the microbiological quality on total coliforms for both WTP and TAP water samples, recording 14 colonies/100 mL (WTP) and 1 colony/100 mL (TAP). Although most physicochemical parameters were compliant with SANS 241, for both WTP and TAP, the electrical conductivity, colour, total organic carbon (TOC) and ammonia were all above the permissible limits.

However, after plasma treatment, the analytical results show that the pH is compliant according to SANS 241: 2015; however in both cases, it increased for WTP from 7.54 to 8.76 and for TAP from 8.03 to 8.79 before and after plasma treatment. Plasma alone further reduced electrical conductivity (in WTP & TAP), colour in TAP, total organic carbon (TOC) in both WTP & TAP, and eliminated total coliforms in WTP. However, the challenge lies in the increase in nitrate from <0.13 mg/L (WTP) and <0.13 mg/L (TAP) before plasma treatment to 41.14 mg/L (WTP) and 40.27 mg/L (TAP), respectively, after plasma treatment. A similar trend was observed with the nitrite. A similar issue was observed during the treatment of LC De Villiers stream water. This has been marked for further investigation in future under a different project arrangement.

(iv) Remark on plasma device and process performance evaluation with R2

The achievement of reducing high loads of E. *coli* (Manyii spring: 3145 CFU/100 mL and Mamvuka spring: 1975 CFU/100 mL) to 0 CFU/100 mL (in both) and total coliforms in Mamvuka spring from 10575 CFU/100 mL to 0 CFU/100 mL (100% removal) characterises a highly performing and efficient reactor and process. Even with the inability to fully remove E. *coli* and total coliforms in some cases, > 99% removal was achieved. Increasing the plasma action time up to 90 minutes (1 hr 30 mins) is likely to remove the remaining pathogens.

The plasma device achieved complete inactivation of E. *coli* from a surface and groundwater sample and achieved up to > 3.7 Log removal value (LRV) in a bacteria-laden surface water source (river) containing 11400 CFU/100 mL of E. *coli*. The complete removal ability implies that the device complies with the WHO protocol that requires that the HWT technology be able to remove bacteria up to: (i) log10 reduction ≥ 4, which implies comprehensive protection and is classified as 3-star performance (very high pathogen removal) and (ii) log10 reduction ≥ 2 meaning comprehensive protection and is classified as 2-star performance (high pathogen removal) (WHO, 2019). This means the designed device (R2) and process comply with these WHO HWT technologies requirements.

GENERAL REMARKS

This project set out key aims, which informed the selection of methods to achieve such aims. The first goal was to design, construct and operate a solar-powered plasma-ozonation system at a laboratory scale for surface and groundwater treatment. A plasma reactor powered by solar has been constructed at a laboratory scale and tested by treating real ground and surface water. The community opinions were sought on the proposed technology, and these gave valuable recommendations for having two devices/processes: one that can serve a community (designed in this project) and a smaller device that can fit on a household tap. This community involvement facilitated the realisation of the second project aim. The third aim was to study the effect of the operating conditions of the reactor on its performance, bearing in mind the energy consumption, treatment duration, and contaminant removal. The conditions that favour the production of plasma oxidants, particularly long-lived ozone, were studied. These ideated the decision and choice of the operating conditions used in real water treatment using the plasma reactor. However, against the third objective of this project, the evaluation of energy consumption during the treatment was deemed unnecessary because we assumed that the system was green since energy consumed was obtained from solar energy. The fourth project goal was to evaluate the reactor/process on real water based on WHO performance criteria and benchmark the results with other technologies on cost per volume of water treated and energy efficiency. To this aim, the system has been evaluated on both SANS 241:2015 and WHO guidelines on the removal of microbiological contaminants and compared with well-established methods including chlorination and boiling. Among the key performance observations was the reactor's compliance with the WHO protocols for HWT technologies, which should achieve Log10 reduction ≥ 4 as the highest for bacteria reduction by the technology (WHO, 2019). Furthermore, all the other water quality parameters in the real surface and groundwater remained within the WHO and SANS 241:2015 guidelines after treatment with the plasma-ozonation system.

CONCLUSIONS AND RECOMMENDATIONS

In this project, a plasma-ozonation reactor unit has been designed and evaluated for the treatment of surface water and rural groundwater. The process has been configured to carry out various treatment processes, including plasma, plasma-ozonation and ozonation. Opinions were sought from a selected community about the device in the context of acceptability, design and useability, and recommendations have been made for further research and design improvements.

The actionable insights of the project point mainly to the idea of having two device set-ups, as highlighted during user participation evaluation. The system introduced to the community consists of a plasma-ozonation reactor device, R2: 40 mm (diameter) x 300 mm (length) x 2.3 mm (thick) borosilicate glass tube with other components, in a housing unit/container of dimensions 3 m(L) x 2 m (W) x 2.4 m (H). This has been described as a community module. It is therefore recommended in future to design and evaluate a small plasma reactor fixed on the tap (individual household module) and powered by a small solar panel that can treat water in a single water pass in the plasma region or engineered for multiple passes. However, this is still farfetched because it is out of the scope of the current project and not feasible within the limited time and resources provided for this project. This could be considered as future endeavours for scale-up and techno-economic feasibility studies. Furthermore, socio-economic studies and more environmental impact studies of utilising the system, especially in rural communities, should be considered. Overall, the developed plasma-ozonation system can be said to be between a Technology Readiness Level (TRL) of 4 and 5. Therefore, moving the project to a TRL of 6 and 7 will be the next phase of the solar-powered plasma ozonation system.

ACKNOWLEDGEMENTS

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ACRONYMS & ABBREVIATIONS

AC	Alternating Current
AOPs	Advanced Oxidation Processes
AOT	Advanced Oxidation Technologies
ANOVA	Analysis of Variance
ASWSD	Accelerating sustainable water service delivery
Avg or Ave.	Average
BBD	Box Behnken design
BOD	Biological Oxygen Demand
BSF	Biosand filtration
CCD	Central Composite Design
CFU	Colony forming units
COD	Chemical Oxygen Demand
CoT	City of Tshwane
CP	Cold Plasma
DC	Direct Current
DBD	Dielectric Barrier Discharge
DBPs	Disinfection by-products
DI	Deionized water
DO	Dissolved Oxygen
DoE	Design of Experiments
DSTI	Department of Science Technology and Innovation
DW	Drinking water
EC	European Commission
E. coli	Escherichia coli
EPL	Environmental Pollution Laboratory
FGD	Focus Group Discussions
GDP	Gross Domestic Product
HAAs	Haloacetic Acids
HRT	Hydraulic Residence Time
HSW	Household Stored Water
HV PSU	High voltage power supply unit
kWh	kilowatt hour
LCA	Life Cycle Assessment
LDCs	Least Developed Countries
LRV	Log Removal Value
MHCD	Micro-hollow cathode discharge
min	minutes
MLD	Mega litres per day

MPN	Most Probable Number
MPO	Microplasma ozonation
NTP	Non-thermal Plasma
NTU	Nephelometric Turbidity Units
OC	Oxygen concentrator
OFAT	One-factor-at-a time
O&M	Operation and maintenance
POU	Point-of-use
PAHs	Polycyclic Aromatic Hydrocarbons
pH	Hydrogen potential
PSA	Pressure swing adsorption
qPCR	quantitative Polymerase Chain Reaction
QMRA	Quantitative Microbial Risk Assessment Method
RO	Reverse Osmosis
ROS	Reactive oxygen species
RONS	Reactive oxygen nitrogen species
RSA	Republic of South Africa
RSM	Response surface methodology
s	seconds
SANS	South African National Standards
SD	Standard Deviation
SDGs	Sustainable Development Goals
Std. dev.	Standard Deviation
SW	Surface Water
TDS	Total Dissolved Solids
THMs	Trihalomethanes
TOC	Total Organic Carbon
TSS	TSS – Total Suspended Solids
SoDis	Solar Disinfection
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
US EPA	United States Environment Protection Agency
UV	Ultraviolet
UNICEF	United Nations Children's Fund
VOC	Volatile Organic Compound
WHO	World Health Organisation
WRC	Water Research Commission of South Africa
WTP	Water Treatment Plant

GLOSSARY

Disinfection	Removal or reduction of harmful microorganisms from water
Chlorination	Process of adding chlorine or chlorine compounds to water to kill harmful microorganisms
Ozone	Molecule consisting of three oxygen atoms
Ozonation	Treating water with ozone
Oxidation	Loss of electrons involving reaction with oxygen
Log removal value	Is the logarithm to base 10 of the ratio of initial and final concentration
Non-thermal plasma	Partially ionised plasmas for which temperature of the (light, charged) electrons is exceedingly more than that of ions and neutrons
Plasma	Ionised gas
Point-of-use	at the location where water is used
Plasma-ozonation	Treating water with ionised gas in combination with ozone gas
Reactive oxygen species	Oxygen-based oxidants in plasma
Reactive nitrogen species	Nitrogen-based oxidants in plasma
Synergy	Combination of processes
Sedimentation	Settling of particles out of water at the bottom of the vessel
Thermal plasma	Ionized gas in which electrons, ions, and neutral particles exist in equilibrium and is characterised by high temperature
Ultra-violet radiation	Electromagnetic radiation with wavelength in range 200 - 400 nm

CHAPTER 1: BACKGROUND

1.1   INTRODUCTION

This manuscript gives a full account of the project "A Novel Solar-Powered Cold Plasma Ozonation System for Point-of-Use Drinking Water Treatment", supported by the Water Research Commission (WRC) of South Africa under WRC Project No. C2022-2023-00897 in the period 2022 to 2025. The project was implemented by the University of Pretoria, Department of Chemical Engineering and with knowledge sharing and support from Swansea University, UK. The work done in the project is summarised in **Table 1.1.** The project progress was continuously documented in five (5) progress reports, representing the 5 respective deliverables as outlined in **Table 1-2.** Each deliverable had certain tasks defined by the project objectives. This document therefore presents all prior work in the progress reports (PRs), including addresses to comments on the experimental results presented during progress. The project was rationalised under the global themes of climate change, water-energy food-nexus, water quality and health, but centred on innovations in water treatment technologies, for which a point-of-use (POU) plasma-based water treatment device has been developed, tested and documented as planned in the project proposal.

This research was part of the global efforts to increase the provision of drinking water, which is a milestone in the fight against poverty and prevention of water-related illnesses. Moreover, the role of clean water availability was significantly observed in the fight against the COVID-19 pandemic (United Nations, 2022). In South Africa, where the project was based, some of the rural communities employ the traditional physical methods of purifying water, such as boiling and addition of chemicals, especially chlorine (chlorination). Purification aims at killing the disease-causing microorganisms (the pathogens) to make water fit for drinking and domestic use. The demerits associated with such methods motivate the need for a novel decentralised advanced treatment technology to define a better future (or hope) for the rural communities of South Africa and elsewhere in the world. Boiling, for example, though effective, may not be sustainable, while well-established chlorination has associated disinfection by-products (DBPs) that can be toxic. Thus, in this project, a non-thermal (NTP) plasma-ozonation system that consists of a solar-power supply unit, a plasma unit producing reactive ozone (O_3), and a water treatment vessel, has been investigated.

The project goals, planning and conceptualisation, experimental investigations, key results and documentation have been presented in the proceeding sections of the report. This includes other pertinent project aspects such as user participation evaluation where community opinions and inclusion were accounted for to comply with common practice norms of developing household water treatment (HWT)/point-of-use (POU) devices.

1.2   PROJECT AIMS AND OBJECTIVES

The overall goal of the project was to design and demonstrate the potential of a point-of-use solar-powered cold plasma coupled ozonation process for the removal of harmful contaminants in surface and groundwater to drinking water quality.

In general, the project was specifically focused on achieving the following goals that describe the main aim of the study and associated investigations:

a) To design, construct and operate the solar-powered plasma-ozonation system at laboratory scale for surface water treatment.

b) To study the effect of reactor parameters (ozone dosage and air/oxygen inlet flow rate) on treatment time and disinfection of contaminants.

c) Evaluate the efficacy of point-of-use solar-powered cold plasma-ozonation technology on real water based on the WHO performance criteria & benchmark with well-established methods with respect to cost per treated water volume.

d) Evaluate user participation with respect to technology acceptability, design and usability of the point-of-use (POU) device.

1.3 SCOPE AND LIMITATIONS

The main focus was to employ solar-powered cold plasma-ozonation to treat surface water (and groundwater) at the point-of-use (POU). In South Africa, studies by (Bezuidenhout et al., 2002, Fatoki et al., 2002, Fatoki and Awofolu, 2004, Abiye and Leshomo, 2012, Edokpayi et al., 2016) have provided evidence that the prevalent pollutants in water sources are generally classified as inorganic chemicals, polycyclic aromatic hydrocarbons (PAHs), micropollutants, nutrients and microorganisms. The researchers, (Verlicchi and Grillini, 2020b) have agreed with this categorisation.

However, the disease-causing microorganisms (pathogens) are a global challenge at the point-of-water use and community water sources, where, in most cases, no treatment is applied. Many global researchers and investigators have given empirical evidence of this challenge by reporting the presence of faecal coliforms and *Escherichia coli* (E. *coli*) pathogens (Bain et al., 2014, Mahmud et al., 2019, Otekpo, 2020) at household level (i.e., POU) and in community water sources. This focus on microorganisms is further premised and underpinned by the fact that microbial pollutants are listed in different areas of South Africa as among the main pollutants in rural and peri-urban communities. For example, E. *coli* and total coliforms were detected in street taps and point-of-use (POU) household storage units during the study by (Luvhimbi et al., 2022) in the assessment of water quality and human risk evaluation of drinking water from source to POU in Thulamela Municipality, Limpopo Province of South Africa. In addition, access to safe water coupled with good sanitation is essential in stopping and managing the spread of cholera, an acute diarrhoea illness caused by consuming food or water contaminated with the bacterium *Vibrio cholerae* (WHO, 2022a). This fact is further substantiated by last year's (2023's) cholera outbreak in Hammanskraal, a community in the north of Pretoria in South Africa (Reliefweb, 2023).

Thus, the cold plasma-ozonation technology aims at inactivating the microbiological pollution indicators (E. *coli* and total coliforms) in drinking water at the POU to control diarrhoea and other waterborne diseases in South African communities. Plasma technology offers good promise because many authors have remarked on its diverse applications and high ability to inactivate microorganisms (Dolezalova and Lukes, 2015, Girgin Ersoy et al., 2019, Rodsong et al., 2021, Kalakonda et al., 2022).

1.4   LAYOUT OF FINAL REPORT

This manuscript has been organised in the following chapters covering the work done, the project objectives and outcomes:

Executive Summary – provides an overview of the report, the general project goal, major tasks undertaken and outcomes with reference to the project objectives and the key recommendations.

Chapter 1: **Introduction** – gives the project background, objectives, achieved outcomes and a brief layout of the report.

Chapter 2: **Literature Review** – purposely carried out to build knowledge, establish the scientific gap and determine project delivery focus and strategy;

Chapter 3: **System Design and Construction** – describing the process of conceptualisation, including the components, materials utilised and preliminary performance evaluation.

Chapter 4: **User Participation Evaluation** – In terms of technology acceptability, design and system usability.

Chapter 5: **System Performance Evaluation** – In the context of treatment technology efficiency /efficacy based on WHO drinking water guidelines and SANS 241 criteria and WHO criteria for household water treatment devices (HWTDs);

Chapter 6: **Conclusions and Recommendations**– summarising the entire project, outlining the methods, the major outcomes and future perspectives or a glimpse of the future based on the level of achievement of the project objectives.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This focused on studying information from various credible sources. This contributed to the initial body of knowledge build-up for a planned novel point-of-use (POU) water treatment facility to impact the well-being of communities where it would be implemented. It is much appreciated that plasma technology and its application to water purification are relatively new, with relatively less scholarly information in comparison to other water treatment technologies. However, many authors remarked on the diverse applications of plasma technology and its advantages in terms of high pollutant removal efficiency, simplicity, high energy efficiency and environmental friendliness, among others (Locke et al., 2006, Zeghioud et al., 2020, Aggelopoulos, 2022). This showed that technology has high promise in water purification and wastewater treatment and offers an opportunity to investigate.

The literature review examined the major and relevant articles from available databases as presented in the preceding sections. This guided the design improvements, experimental procedures, analysis and interpretation of the investigations. Literature sources that could contribute to the knowledge required to develop the facility to treat water for drinking purposes at the POU using plasma-ozonation technology were filtered from search results from established, credible and popular search databases. The search focused on peer-reviewed literature and with relevant complements from grey literature. The online search engines/databases employed included: Scopus, Web of Science, PubMed and other online resources for grey literature (mainly information produced by bodies such as government, business, industry and academia whose principal activity not generally published) were reviewed.

The strategy included, first, identification of key search terms/keywords and then combining the keywords with operators such as "AND" and "OR". In a few cases, the truncation symbol, an asterisk (*), was used in the database under focus to get different alternatives related to the topic of focus.

The search window in all databases was initially limited to the 2003 to 2022 period (20 years), but later extended up to the project conclusion to complement the information in this section. The intended research was centred on "plasma ozonation as a point-of-use" water treatment, with attention on bacteriological quality of surface and groundwater. The following search terms and combinations were used:

- "plasma"
- "plasma + ozonation"
- "advanced oxidation processes"
- "ozonation" + "microorganisms"
- "plasma" + "water treatment"
- "plasma" + "water treatment" + "point of use"
- "plasma" + "ozonation" + "water treatment"
- "plasma" + "ozonation" + "point of use" + "water treatment"
- "plasma" + "ozonation" + "microorganisms"
- "plasma" + "ozonation" + "pathogens"
- "microplasma" + "ozonation" + "water treatment"

- "microplasma" + "ozonation" + "microorganisms"
- "microplasma" + "ozonation" + "disinfection"
- "plasma" + "reactor"
- "non-thermal" + "plasma" +" "reactor" +" ozonation"
- "cold" + "plasma" + "ozonation" + "water treatment"

Grey literature was further explored using the combination of the search terms, in the form of phrases, utilising the listed search terms as follows:

- plasma ozonation in water treatment
- plasma ozonation as point-of-use water treatment
- microplasma ozonation for water disinfection at point of use
- non-thermal plasma reactor ozonation.

2.2 DRINKING WATER TREATMENT TECHNOLOGIES AND QUALITY MANAGEMENT

Generally, water treatment for drinking purposes is accomplished with technologies including coagulation, sedimentation, filtration and disinfection, with each process modifying the water quality to a better state than the previous one. Disinfection in centralised systems is achieved through mechanisms like chlorination, ozonation, ultraviolet (UV) radiation and membrane processes such as reverse osmosis (RO). Each of the methods has merits and drawbacks, as explained by (Benotti and Brownawell, 2009, Abdel-Raouf et al., 2012, Awaleh and Soubaneh, 2014, Weng and Pei, 2016). Water from the treatment plant or after any of the mentioned is normally examined to check compliance with known national, regional, or global standards as per the requirements of each country.

2.2.1 Drinking Water Quality Regulation in South Africa

Several countries and regions have set standards upon which the quality of drinking water is evaluated to be rendered fit for that purpose. The EC Drinking Water Standards, UK Standards and US EPA Standards do operate in their area of authority as specified. In addition, WHO periodically publishes drinking water guidelines containing guideline values of different water quality parameters/contaminants that are utilised by many nations in addition to their respective national standards.

In South Africa, the South African National Standards 241 (SANS 241) provide standard limits of parameters to characterise drinking water quality. The current edition SANS 241, 2015 (Edition 2) is under review, but has been utilised in the project together with the WHO guidelines for the different parameters. In addition, the Blue Drop Regulation implemented through the Blue Drop Certification programme, during which an audit on the water supply system in the municipality is carried out, further motivates compliance with the recommended water quality standard. The outcomes of the audit serve as a prompt for refocusing essential regulatory and support measures to address non-compliance (WRC, 2015).

The point-of-use (POU) or household water treatment (HWT) technologies are implemented at the location where the water will be utilised. The Department of Science and Technology and Council for Scientific and Industrial Research implemented an initiative about accelerating sustainable water service Delivery (ASWSD)

in Eastern Cape, Limpopo and Mpumalanga. The POU technology was based on a ceramic household filter. The goal was to accelerate provision of drinking water to the unserved or underserved rural communities in those areas (DSTI, n.d).

The current project aimed to design and implement a plasma-ozonation POU system to inactivate microbiological contaminants in water. However, there are no guidelines or protocols in South Africa for performance evaluation of POU devices or systems. The WHO established a basis for assessing the microbiological performance of HWT (or POU) devices and has developed the international scheme to evaluate HWT technologies. The scheme provides a harmonised testing protocol and outlines the microbial groups and recommended reduction needs. The protocol provides that the household water treatment technology be able to remove bacteria up to: (i) $\log_{10}$ reduction ≥ 4 which implies comprehensive protection and is classified as 3-star performance (very high pathogen removal) (ii) $\log_{10}$ reduction ≥ 2 meaning comprehensive protection and is classified as 2-star performance (high pathogen removal), (iii) meets at least 2-star criteria for two classes of pathogens (targeted protection) and (iv) fails to meet WHO performance criteria (which implies little or no protection) (WHO, 2016b, WHO, 2019).

2.3 PLASMA TECHNOLOGY AND APPLICATIONS

2.3.1 Plasma Technology

When a (neutral) gas is supplied with energy, plasmas are produced, described as the fourth state of matter, in addition to solid, liquid and gas (Nandkumar, 2014). Plasmas consist of electrons, ions (positive and negative) and neutral species (Mo and Tamo\vsiūnas, 2012). The energy can be supplied in a number of ways such as thermal energy or via energetic beams (Conrads and Schmidt, 2000). During plasma generation, radiation emission occurs in the ultraviolet (UV), visible and infrared regions of the electromagnetic spectrum (Sakudo et al., 2019). A plasma generation system generally consists of a gas carrier, a high voltage power supply and electrode materials; and regarding generation conditions, classified as either thermal (equilibrium) plasma or non-thermal (non-equilibrium) (Murugesan et al., 2020a). Thermal plasma is generated at extreme temperatures and high pressure with the aid of an electrical power source which is either direct current (DC) or alternating current (AC) or by electromagnetic sources (microwave or radio frequency), and all the reactive species (such as ozone, hydroxyl radicals and hydrogen peroxide) are in thermodynamic equilibrium due to the gas temperature of the constituents being uniform (Murugesan et al., 2020a, Cubas et al., 2021).

The non-thermal plasma (NTP) or cold plasma (CP) consists of partially ionised plasmas for which the temperature of the (light, charged) electrons is exceedingly higher than that of ions and neutrons. The thermodynamic state and physical processes of the NTP result in low gas temperature, qualifying it for biological applications, including degradation of pathogens in water for domestic applications (Taylor and Pirzada, 1994, Nehra et al., 2008, Sakudo et al., 2019). **Table 2-1** presents the classification of plasma. An important observation is that treatment by CP is achieved at room (or ambient) temperature with adequate/acceptable disinfection efficacy and with minimal possible damaging impacts on biological tissues (Šimončicová et al., 2019). The current project is centred on the applications of NTP or the CP.

Table 2-1. Plasma classification (Taylor and Pirzada, 1994, Nehra et al., 2008, Sakudo et al., 2019)

Plasma Classification	Temperature (K)	Electron density (m^{-3})	Discharge type	Examples
Thermal plasma (Quasi-equilibrium plasma)	$T_e \approx T_i \approx T_n \approx T_g \leq 2 \times 10^4$	$n_e \geq 10^{20}$	Arc plasma, Plasma torch, Radio-frequency (RF) Plasma, Microwave plasma etc.	Radiation, welding and cutting, Waste treatment, Material processing, etc.
Non-thermal plasma (Non-equilibrium plasma)	$T_e \geq T_i \geq T_n \approx T_g = 300–1000$	$n_e \approx 10^{10}$	Glow discharge, Corona discharge, atmospheric pressure plasma jet (APPJ), dielectric barrier discharge (DBD), micro-hollow cathode discharge (MHCD), Plasma needle, Low-pressure plasma etc.	Ozonizer, Plasma medicine, Volatile organic compound (VOC) treatment, Plasma agriculture, Surface modifications (coating, etching, activation, cleaning, nitration, etc.), Illumination (plasma screen, fluorescent lamps, etc.)

T_e = electron temperature, T_i = ion temperature, T_g = gas temperature, T_n = neutron temperature and n_e = electron density

2.3.2 Plasma Applications in Water Treatment

Plasma technology has a wide range of applications, ranging from sterilisation of medical devices, agricultural applications such as improving crop yields, food preservation (or food safety) and water treatment. With 90% of the sewage in least developed countries (LDCs) conveyed untreated to water bodies (UNESCO), rural communities in such countries have higher chances of bacterial contamination in sources for drinking water, and in many cases, up to the point of use, in the household. Bacterial contamination of water for drinking and other domestic applications is among the major water problems sub-Saharan Africa faces, with unimproved sources serving as reservoirs of pathogens, mainly E. *coli* (Gwimbi et al., 2019).

NTP (non-thermal plasma) or CP (cold plasma) technologies promise success in water decontamination, with commendable abilities in the degradation of organic and inorganic pollutants by the plasma-generated reactive chemical species such as atoms, electrons, ions, and charged particles. The formation of the reactive species, including the reactive oxygen species (ozone, singlet oxygen, superoxide ion, peroxyl, alkoxyl, etc), UV light and free radicals during the discharge operation facilitates the efficient destruction of contaminants in water (Sakudo et al., 2019, Šimončicová et al., 2019, Murugesan et al., 2020b).

NTP as an AOP has proven efficient in the removal of E. *coli* and literature shows that with high voltage, characterised by a stronger electric field that is capable of generating (adequate) oxygen species (such as ozone), the E. *coli* deactivation is efficient (Rodsong et al., 2021). This optimistically implies that NTP can effectively destroy the coliform bacterial group in the water, including E. *coli*, given the right plasma reactor setup (or configuration). The goal is to utilise the generated reactive ozone (O_3) for the deactivation of pathogenic microbiological contaminants in drinking water at the point-of-use.

2.4 PLASMA-OZONATION AS A POINT-OF-USE DRINKING WATER TECHNOLOGY

2.4.1 Point-of-Use Treatment Methods

In general, point-of-use (POU) systems and technology have been investigated for the removal of different types of contaminants from water and have proven effective, from as early as the late 1980s to the present, with different (low-cost) technologies and purification mechanisms. Literature shows that earlier and some recent research on POU water treatment, such as (Fox, 1989, Norton et al., 2009, Tantawy et al., 2022) employed other mechanisms than plasma-ozonation to remove physicochemical and inorganic contaminants. A review of POU water treatment technologies is discussed in the proceeding section to appreciate and justify the intended research/study. This, therefore, vindicates the novelty of the intended research in water purification technology for which the performance of solar-powered non-equilibrium plasma-generated ozone (O_3) is sought.

2.4.1.1 Review of low-cost POU water treatment systems for developing communities

The review was based on the paper:

Pooi, C.K., Ng, H.Y., 2018. Review of low-cost point-of-use water treatment systems for developing communities. npj Clean Water 1, 11. https://doi.org/10.1038/s41545-018-0011-0.

a) Goal and motivation

The assessment carried out by (Pooi and Ng, 2018) on low-cost POU water purification systems gives a more robust delineation of the POU systems in low-income communities. The paper gave descriptions of the various technologies applicable to developing/least developed countries (LDCs), in a past decade (reference year as 2018).

The study was motivated by the fact that a relatively big percentage (more than 30%) of people in LDCs had no access to improved drinking water (WHO, 2015) and substantiated by more recent data showing that just 39% of the population in Africa used safely managed water in 2020 (WHO and UNICEF, 2022). The continued use of unimproved water makes people more vulnerable to waterborne illnesses such as diarrhoea and their symptoms. For example, (as noted in the paper) in 1996, South Africa (RSA) spent up to R 3.0 billion, up to 1% of RSA's gross domestic product (GDP), as total social costs to combat diarrhoea. Additionally, because of the high capital and investment costs associated with centralised systems, which make them unaffordable for underdeveloped nations, onsite treatment and storage systems (i.e., POU systems) are the only practical alternatives.

b) Treatment methods employed

The established conventional water treatment methods, such as coagulation, flocculation, filtration and disinfection (depending on raw water contamination levels), provide an acceptable reference for the development and evaluation of new technologies. The methods (listed below) emphasised by (Pooi and Ng, 2018), employ the impurities removal mechanisms similar to the conventional systems, this time as decentralised systems at the POU.

- Flocculant/disinfection system as PUR sachets (P&G) deployed in Western Kenya (Crump et al., 2004).

- Biosand filtration (BSF) – better performance with iron-coated sand (Ahammed and Davra, 2011), deployed in countries (town): Honduras, Ghana (Tamale), etc.

- Membrane filtration – (pressure driven and external driving force needed, such as electrical pumping); deployed in Asia (various technologies), and some models need no power or chemicals, such as Skyhydrant (with up to > 6 log removal for coliform).

- Solar Disinfection (SoDis) (Berney et al., 2006).

- Wind-powered electrocoagulation.

- Nanotechnology (Titanium dioxide nanoparticles with photocatalysis and silver nanoparticles).

c) Key findings

The authors described the performance of each treatment method in the removal of waterborne disease-causing microorganisms. **Table 2-2** summarises the methods and the reported key outcomes bearing on the contaminant removal efficiency. Much appreciation is given to combined/coupled processes such as filtration and disinfection.

Table 2-2. POU methods in developing countries (Pooi and Ng, 2018).

POU Method /Processes /Aspect	Any field deployment /testing	Water quality parameter (s)	Key results/ performance removal efficiency	Challenging Parameters for POU method (s)
All POU methods		• Escherichia coli (E. *coli*), • Turbidity,	• Overall satisfactory performance in the removal of E. *coli* (and pathogens), • Reduced turbidity.	• Heavy metals and other inorganic substances
Flocculant/disinfection system (Ferric sulphate/calcium hypochlorite) as PUR sachets (P&G)	Western Kenya	• E. *coli*, • Turbidity,	• A high dose resulted in an E. *coli* concentration of 0 mg/L, • Low dosage in high turbid water failed on drinking water quality standards, • Diarrhea reduction per person in Guatemala of 23.8%, • Vietnam case study, >5 log virus removal and 4 log removal and 3.6 log removal were also achieved for Cryptosporidium and Giardia, respectively. • >99% arsenic removal and >8.2 log removal of E. *coli* (Souter et al., 2003)	Not stated (NS)
Biosand filtration or Biosand filter (BSF)	Cambodia	• Turbidity • E. *coli*	• E. *coli* removal at 63% (new POU BS) & at 98% (mature filter), • Treated water not compliant with WHO standards, • Better performance with iron-coated sand achieving > 2 log removals on > 10^3 CFU/mL pollution levels, • Poor performance at higher flow rates. • Virus removal 1.3 log removal (echo virus) • Long filter life - up to 8yrs Cambodia.	Not stated (NS)
Membrane filtration (Various products from different manufacturers)	Asia	• E. *coli,* • Bacteria. • Coliforms • Viruses	• Achieves in general from >3 log removals to >7 log removals for all pathogens reported, • no power or chemicals with some models e.g., Skyhydrant (>6 log removal)	Not stated (NS)

POU Method /Processes /Aspect	Any field deployment /testing	Water quality parameter (s)	Key results/ performance removal efficiency	Challenging Parameters for POU method (s)
Solar Disinfection (SoDis) Depending on UV & Temperature)		• Vibrio cholerae, • E. *coli.* • Turbidity	• Temperature - Vibrio cholerae & E. *coli* inactivation at 40°C & 45°C respectively. • 6-log E. *coli* removal with turbid well water (up to 100 NTU). (Keogh et al., 2015)	• Unable to remove chemicals
	Field studies in Kenya, India, Bolivia & Cambodia		• Between 6% and 63% reduction in diarrhea episodes in field study countries.	Not stated (NS)
Wind powered electrocoagulation (Jeon et al., 2016)		• Microalgae • Dissolved dye	• 90% removal of microalgae & 97% removal of dissolved dye from synthetic water in 72 hours • Possible removal of pathogens & chemicals	Not stated (NS)
Nanotechnology (Titanium dioxide nanoparticles - photocatalysis and silver nanoparticles). • Solarbag (by paralytics)		• E. *coli*	• Reduced below detection in 4h (titanium dioxide immobilised in water). • Silver nanoparticles (AgNP) have antimicrobial properties • Tata Swach, a water filter using rice husk ash with AgNP, is able to achieve 1 log E. *coli* removal, • Folia filter using copper and silver nanoparticle achieved • 6 log E. *coli* removal was achieved with 1.6 mg AgNP/g filter paper & field studies up to 4 log E. *coli* removal.	Not stated (NS)

d) Research gaps

Generally, the following gaps were identified in the reviewed paper:

- The application of plasma ozonation technology as a POU is not described in the compilation by (Pooi and Ng, 2018).
- Investigation into the combination of one or more technologies with plasma ozonation.
- There is no information about taste reported for flocculant/disinfection system (PUR sachets).
- With a BSF, there was variability in flow rate and the filter bed needs to ripen for better performance.
- Membrane filtration – requires electricity; however, some improvements have been made for POU, and no combination with plasma ozonation for synergetic influence.
- Solar disinfection (SoDis). The performance depends on temperature and the intensity of the sun. The turbidity of the water can impact the efficacy and it is unable to remove chemicals.
- No extensive information about the long-term effects of titanium dioxide nanoparticles and silver nanoparticles (Lin et al., 2017) though at high concentrations, they are reported to be toxic to marine life (Fabrega et al., 2011).

e) Relevance to project aims and objectives

- Project aim and objective 1: Opportunity to test the plasma-ozonation technology.
- Project objective 1: Synergetic effect such as a combination of membrane filtration and plasma-ozonation.
- Project objective 2: Dosage is important – as observed in the flocculant/disinfectant system with PUR sachets and contact time.

2.4.2 Plasma-ozonation in Water Treatment

The limited published studies and scientific investigations usually indicate that using ozonation will be successful and that synergetic process setups will result in larger beneficial impacts. To establish the scientific foundation for experimentation and testing of the plasma reactor at the deployment community site, a critical analysis of a few peer-reviewed works with an impact on the uses of plasma-ozonation in water treatment is presented.

2.4.2.1 Solar Powered Microplasma-Generated Ozone

The review was based on the paper:

Dorevitch, S., Anderson, K., Shrestha, A., Wright, D., Odhiambo, A., Oremo, J., Heimler, I., 2020. Solar Powered Microplasma-Generated Ozone: Assessment of a Novel Point-of-Use Drinking Water Treatment Method. Int. J. Environ. Res. Public Health 17. https://doi.org/10.3390/ijerph17061858

a) *Study motivation*

The following were the study's cited motivating factors: (i) low-income countries have less financial capacity to meet the investment (capital) and maintenance (and operation) costs of centralised treatment facilities (Rodriguez et al., 2012), (ii) the exceptionally high cases of diarrhea among children (<5 years of age) in low and middle sociodemographic index countries associated with over 200,000 children's deaths (IHME, 2015) and (iii) developments in microplasma technology with the capability of reducing the electrical field strengths necessary for ozone generation (Eden et al., 2013, Kim et al., 2017), for example, a single chip (microchannel array) can be 3 times more efficient than the conventional dielectric barrier discharge (DBD) or corona ozone reactors, with respect to ozone production.

This review largely focused on the characteristics of microplasma ozonation and the factors that affect the goal of disinfection.

b) *Study methods employed*

(Dorevitch et al., 2020) explain that the first stage of the method was evaluated in Chicago in the United States of America (USA) for which the POU ozonation performance on the destruction of pathogens (bacteria and viruses) was tested on wastewater. Following the success in Chicago, further studies were carried out in Kenya on surface water (SW), household stored water (HSW), and drinking water (DW). The user community's opinions of the microplasma ozonation system were assessed in addition to the water quality (turbidity and E. *coli*). The key elements of the investigations are summarised below:

- Use of EP Purelife 1000 Ozone generator with a capacity rate of: 0.2-0.3 gm/hr and air/ozone flow rates of 2 Litres/min. The air/ozone mix was transferred to water to be disinfected by means of a submerged ceramic aerator (diffuser).
- Water quality analysis was carried out with various methods/instruments, including tests to quantify the ozone dosage. Physical and bacteriological parameters included: pH, turbidity, E. *coli*, Enterococci and F+coliphage.
- Activated sludge effluent was diluted to E. *coli* levels of 1000–2000 most probable number (MPN)/100 mL, to simulate the range of surface water pollution in Kenya.

- POU ozonation of surface water powered by a 15 W solar panel was benchmarked against chlorination (using sodium hypochlorite).

- The experience in using the technology and safety of the community was tested on 10 households for 8 weeks in western Kenya.

c) Key findings

The findings of the POU ozonation application for pathogen removal in wastewater and surface water offered plausible evidence of the pathogen degradation characteristics of the method. The main pertaining results are given in **Table 2-3.**

Table 2-3. Performance of solar-powered microplasma-generated ozone in water treatment (Dorevitch et al., 2020)

Investigation Parameter (Location)	Water quality parameter (s)	Key results/ POU ozonation removal efficiency	Remarks
Wastewater (Chicago)	- pH - Turbidity (NTU) E. coli (MPN/100 mL) - Enterococci (CCE/100 mL) - F+ coliphage (PFU/100 mL)	a) Physicochemical: LRV mean (standard deviation): - pH 7.22 (0.24) - Turbidity (NTU) 1.62 (0.89) b) Bacteriological: Effective in the removal of: E. coli at LRV mean (standard deviation) of 2.34 (0.84) at 120minutes ozonation. - Enterococci qPCR 1.16 (0.72), - F+ coliphage at 60 min ozonation as 1.54 (0.43).	.
Surface water vs Chlorination (Kenya)	E. coli (MPN/100 mL)	a) Untreated surface water (Control) E. coli LRV mean (standard deviation) at LRV-0.02 (0.13). b) POU ozonation E. coli LRV mean (standard deviation) of 1.56 (1.34) (overall), c) POU Chlorination E. coli LRV mean (standard deviation) of 3.43 (0.46).	
Household stored water (HSW) and Drinking Water (DW) (Kenya):	E. coli (MPN/100 mL)	- In 12 observations in HSW of pollution level of E. coli (100-999MPN/100mL) reduction were LRV 1.37 (0.73), 15 observations of HSW E. coli ≥ 1000 MPN/100 mL, LRV was 1.56 (0.96), 21 households for HSW E. coli >10^3, MPN/100mL, 76% had DW E. coli levels of 10^0 MPN/100mL.	
Acceptance by the community (Kenya)	Acceptability, safety and experience	- System was embraced enthusiastically, - No taste problem, no mucus membrane, no respiratory or eye irritation reported during operation reported, - Reported only the ozone odour during treatment by some participants.	
Overall system performance	WHO Framework for Household water treatment methods evaluation.	Compliant	

Note: LRV = Log Removal Value

d) Research gaps

In general, the following gaps were identified, and these assisted in developing a performing system: (i) reactor mechanical components system optimisation and fixing, notably - connection of ozone generator and ozone-out tubing, no ozone smell (absence of bubbles), system movements during treatment, (ii) reactor optimisation of ozone input conditions (air/oxygen gm/litre and treatment time), (iii) ozonation does not produce a residual, thus to minimise/control possible re-contamination, there is need to increase the half-life of ozone to protect the water in storage against new pathogen contamination during storage or any POU pipelines and (iv) groundwater with bromide can produce bromate, a possible carcinogen, calling for the mechanism of degradation of bromates once formed.

However, since in terms of drinking water quality improvement, the goal was the removal of pathogenic microorganisms, much attention was laid on (i) the reactor mechanical system configuration optimisation and (ii) ozone input parameters; and how they both influence disinfection or the bacteria inactivation efficiency.

e) Relevance to project aims and objectives

The knowledge for this paper was useful in the following aspects of the project:
- Project aim and objective 1 – design and construction of the plasma-ozonation reactor.
- Project objective 2 – optimisation of ozone input parameters (air/oxygen gm/litre and treatment time).
- Project objective 3 – testing the efficiency of the technology in surface and groundwater.
- Project objective 4 – user participation and system acceptability.

2.4.2.2 Microplasma vs Ozonation

Review paper:
Dong, S., Li, J., Kim, M.-H., Park, S.-J., Eden, J.G., Guest, J.S., Nguyen, T.H., 2017. Human health trade-offs in the disinfection of wastewater for landscape irrigation: microplasma ozonation vs. chlorination. Environ. Sci. Water Res. Technol. 3. https://doi.org/https://doi.org/10.1039/C6EW00235H

a) Review purpose and study motivation

The objective of reviewing this paper was to appreciate the performance of the plasma-ozonation against chlorine. The study contains information on the factors that affect the effectiveness of plasma-ozonation disinfection despite the fact that the paper's main focus was on wastewater (secondary effluent).

The authors conducted the study for a variety of reasons, including (i) increased wastewater reuse in the US of over 9000 million litres per day (9000 MLD) (U. S. Environmental Protection Agency, 2012), and the need for decentralised water reuse disinfection, to remove pathogens (bacteria and protozoans) with specific attention on three pathogens; Cryptosporidium *parvum* (C. *parvum*), *Giardia* and Legionella *pneumophila* (L. *pneumophila*), (ii) microplasma generators with oxygen as feedstock have resulted in higher energy efficiencies because of the combination of much smaller plasma impedance (approx. 41 kΩ) and much lower driving voltage (Kim et al., 2013b) and (iii) modular building block of microplasma ozone generators (called "chips") that produce 2 – 3 grams of ozone per hour being available on the global market, making it easier to

produce ozone at any desired rate. Although the study further evaluated the direct human health risks from pathogen exposure using the Quantitative Microbial Risk Assessment Method (QMRA) and the implications of the indirect impacts of the technology using Life Cycle Assessment (LCA), the detailed approaches and findings related to these two aspects (QMRA and LCA) are not explored and presented in this review.

b) Study methods relating to plasma-ozonation employed

The following activities were undertaken (Dong et al., 2017):

- Review of literature to determine the pathogen (C. *parv*um and *Giardia*) inactivation parameters, including the disinfection kinetics (for both ozone and chlorine) to inform the design of both chlorination and ozonation systems. Bench experiments were carried out to estimate the inactivation parameters for L. *pneumophila* by ozone. In the setup, the ozone gas was generated by a microplasma ozonator and directed into the reactor through a ceramic diffuser. Ozone flow rate was controlled by a valve (Swagelok) and monitored with a rotameter.
- Microplasma ozonation of wastewater secondary effluent benchmarked on chlorination followed by dechlorination. Chlorination is a dependable and extensively used approach for disinfecting reclaimed water. The setup of the microplasma ozonation (MPO) disinfection system consisted of MPO ozone generator, a venturi ozone injection nozzle, an ozone contact tank, and an ozone destruction unit. The top of the contact tank is where the fugitive (unreacted) ozone from the ozonated wastewater is collected before being processed by a thermal catalytic ozone destruction device.

c) Key findings and research gaps

After a critical review of the study in relation to plasma ozonation, the following outcomes were noted:
- The level of inactivation /destruction of pathogens by ozone is dependent on the ozone value (amount) and the hydraulic residence time (HRT). The ozone dosage must be greater than the wastewater effluent-specific threshold to obtain residual ozone and with increased HRT, the disinfection efficacy is enhanced/increased. The amount of ozone and HRT will then influence the system's human health impact performance for the desired pathogen destruction goal (Dong et al., 2017).
- The microplasma reactor required less power if fed with air than when fed with oxygen.

The study was centred on treating wastewater for landscape irrigation reuse, and not for drinking water purposes. A plasma reactor has been developed to remove pathogens from drinking water at the point of use (POU), though not working as microplasma.

d) Relevance to project aims and objectives

It was noted that using the right amount and length of ozone contact time yields superior outcomes (pathogen destruction). To ensure that the plasma ozonation reactor for the POU drinking water treatment performs as intended, attention was accordingly laid on the ozone generation and dosage.

2.4.2.3 Decentralised solar-powered drinking water ozonation

Review paper:

Hendrickson, C., Oremo, J., Akello, O.O., Bunde, S., Rayola, I., Akello, D., Akwiri, D., Park, S.-J., Dorevitch, S., 2020. Decentralized solar-powered drinking water ozonation in Western Kenya: an evaluation of disinfection efficacy. Gates open Res. 4, 56. https://doi.org/10.12688/gatesopenres.13138.2

a) *Study motivation and goals*

Although the paper by Hendrickson et al., 2020 was not yet published and still under peer review at the time of writing, it was included in this literature study because of the excellent scientific approaches and concepts presented.

The motivation of the study was based on the following facts: (i) meeting the UN Sustainable Development Goals (SDGs) target 6.1 towards universal and equitable access to safe and affordable drinking water by 2030, (ii) the current effective decentralised systems (membrane-based) in rural African communities, such as in Rwanda, are limited to areas with robust access to electricity and water (Huttinger et al., 2015) and (iii) development of microplasma technology – small units that achieve threefold the effectiveness of conventional dielectric barrier discharge (DBD) or corona ozone reactors (Simek and Clupek, 2002, Kim et al., 2017) and the prospect of using solely solar energy in the equatorial regions where sunlight is in plenty.

Point (iii) affirms the viability of the intended project and the appreciation of the abundant availability of renewable solar energy serves as further justification of the planned research on plasma-ozonation water treatment.

b) *Study methods relating to plasma ozonation*

A summary of the system process elements and methodological steps is given below:
- Sedimentation – Flocculation and settling (settling tank and balancing tank) for surface water from a river water source (in Kenya), before ozonation. The system was configured to disinfect rainwater with less turbidity during wet seasons.
- Ozonation - microplasma ozonation (MPO), consisting of 4 portable ozone generators, was employed (Purelife 1000, EP Purification, Champaign, IL, USA), which utilise ambient air as the feed gas at a rate of 2 litres per minute by means of an air pump. The high-frequency electric field in the microchannels aids the conversion of ambient air into ozone.
- Filtration – rapid sand filtration and activated carbon filters.
- Water quality parameters of investigation included: turbidity, total coliforms and E. *coli*. Analysis was carried out on samples before sedimentation and during ozonation at 0, 60, 120, 180 and 240 minutes. Water quality was characterised with a median and interquartile range of 25th – 75th percentiles as median (25th, 75th) percentile.
- Power supply – Initially by 240 V AC from electrical outlets, then solar only. An inverter is used to convert stored DC (from solar energy) to AC to run the water pumps and ozone generators.

c) *Key findings and research gaps*

The key results (from 9 trials) of the study by (Hendrickson et al., 2020) are summarised in **Table 2-4** below. The findings showed that the system can effectively reduce the E. *coli*, total coliforms, and turbidity and meet the WHO and Kenya standards for turbidity. However, the following gaps were identified:

- Need to benchmark the microplasma ozonation with other advanced oxidation processes (AOP) such as chlorination, a well-established water purification method, to compare the cost per volume of water treated and energy efficiency.
- Evaluating the state of the community on safe water storage, such as the use of improved vessel containers with a tap, lid narrow neck to facilitate the development of an education strategy for sustainability.
- System performance be tested with a pre-treatment bacteria concentration of 100,000/100 mL as part of the challenge test (WHO, 2018b).

Table 0-4. Impurities removal by the system (Hendrickson et al., 2020)

Process	Water quality parameter (s)	Key results	Remarks
Raw water before treatment begins	• Turbidity (NTU) • E. *coli* (MPN/100 mL) • Total coliforms • Heavy Metals (Aluminium, Manganese & Iron)	• Turbidity (NTU) - mean (SD): 322.1 (228.0), • E. *coli* - median (25th, 75th) percentile: 2,752.6 (1,554.1, 9,682.8) • Total coliforms- median (25th, 75th) percentile: 6,576.2 (2420.7, 9,682.8) • Heavy metals – compliant with Kenya standards (Aluminium 0.01 mg/L, iron 0.005 mg/L, and manganese 0.7 mg/L)	.
Sedimentation (Settling and balance tank)	• Turbidity (NTU) • E. *coli* (MPN/100 mL) • Total coliforms	a) Post flocculation • Turbidity (NTU) - mean (SD): 1.3 (1.0) • E. *coli* - median (25th, 75th) percentile: 0 (0.0, 7.3) • Total coliforms-median (25th, 75th) percentile: 50.6 (2, 58.6) b) Post-filtration • Turbidity (NTU) - mean (SD): 0.8 (0.4) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 10.7) • Total coliforms- median (25th, 75th) percentile: 48.9 (4.1, 49.7)	.
Ozonation	• Turbidity (NTU) • E. *coli* (MPN/100 mL) • Total coliforms)	At 0 minutes • Turbidity (NTU) - mean (SD): 2.3 (2.0) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 0.0) • Total coliforms- median (25th, 75th) percentile: 15.2 (7.9, 71.1) At 60 minutes • Turbidity (NTU) - mean (SD): 1.9 (1.4) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 0.0)	

Process	Water quality parameter (s)	Key results	Remarks
		• Total coliforms- median (25th, 75th) percentile: 11.9 (5.1, 125.6) At 120 minutes • Turbidity (NTU) - mean (SD): 2.2 (1.4) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 0.0) • Total coliforms- median (25th, 75th) percentile: 7.3 (0.0, 21.3) At 180 minutes • Turbidity (NTU) - mean (SD): 1.5 (1.2) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 0.0) • Total coliforms- median (25th, 75th) percentile: 4.1 (0.0, 6.2) At 240 minutes • Turbidity (NTU) - mean (SD): 2.4 (3.5) • E. *coli* - median (25th, 75th) percentile: 0.0 (0.0, 0.0) • Total coliforms- median (25th, 75th) percentile: 1.5 (0.0, 19.1)	
	• E. *coli* (MPN/100 mL) • Total coliforms)	Ave. Log Removal Values (LRV): • E. *coli* LRV mean (standard deviation) of 3.36 (0.55) • Total coliform LRV mean (standard deviation) of 3.02 (0.77)	
	• Turbidity (NTU) • E. *coli* (MPN/100 mL) • Total coliforms)	***a)*** Kenya Bureau of Standards independent testing of treated water: • E. *coli* & total coliform 0 CFU/100 mL; ***b)*** Kenya Water Resources Authority • Raw water: Turbidity >1000 NTU (WHO & Kenya <5NTU), E. *coli* & coliform bacteria: "numerous" • Treated water: Turbidity 4.5 NTU and E. *coli* coliforms with 0 CFU/100 mL (WHO & Kenya standards met)	

c) Relevance to project aims and objectives

The knowledge from this paper was useful in appraising the need for pre-treatment before ozonation for water with high turbidity values to meet the WHO performance criteria on household water treatment devices (project objective 3).

2.5 SUMMARY AND CONCLUSION ON LITERATURE REVIEW

An examination of the existing literature on point-of-use (POU) plasma-ozonation to treat water for drinking was carried out. Peer review journal articles were ascertained through known search engines and databases (Scopus, Web of Science and PubMed), complemented with other credible grey literature sources.

Four selected journal articles (Dong et al., 2017, Pooi and Ng, 2018, Dorevitch et al., 2020, Hendrickson et al., 2020) were critically assessed to obtain useful literature for studying and evaluating plasma-ozonation reactor for POU water treatment. In addition to aiding the optimising of the plasma reactor, the observed gaps therein and listed below provided; (i) the justification for new technology (the plasma-ozonation technology), (ii) the factors that aid the practical setups of the mechanical system components of the plasma reactor, and (iii) the parameters that influence the contaminant destruction efficacy by the plasma generated ozone. The literature gaps justifying the project and research were noted as follows:

a)   In the paper by Pooi and Ng, 2018, plasma ozonation was not among the compilation of the POU treatment methods in the previous decade referenced to 2008; this project aspires to realise a functional POU plasma-ozonation system.

b)   The study by Dorevitch et al., 2020 revealed the factors that affect system performance and made way for other research prospects, particularly regarding how the system may be enhanced and taking into account the opinions of a potential user community. The current study/research sought, therefore, to improve the following: (i) optimising the reactor mechanical system components and fixing, notably, the connection of the ozone generator and ozone-out tubing, the no ozone smell (absence of bubbles as reported by user community) and system movements during treatment, (ii) determining the ozone input conditions (adequate air/oxygen gm/litre and necessary treatment time) to achieve maximum efficiency in terms of pathogen inactivation by the plasma-generated ozone, (iii) increasing the half-life of ozone in water after pathogen inactivation to guard against recontamination, because ozone does not produce a residual, and (iv) determining a means of degradation of bromates once formed during oxidation of inorganic pollutants in groundwater.

c)   Dong et al., 2017 focused on treating wastewater with microplasma ozonation (MPO) for landscape irrigation reuse. Our project intended to investigate plasma-ozonation technology for the inactivation of pathogens (such as E. *coli)* in drinking water at the point of use (POU).

d)   The main goals of the study by Hendrickson et al., 2020 included: determining a solar-powered decentralised water purification system utilising ozone as a disinfectant and estimating the system's effectiveness in treating surface water, which was achieved. However, no comparison to well-established techniques was made. We intended to benchmark the (micro) plasma-ozonation with other advanced oxidation processes (AOP) such as chlorination, to compare the cost per volume of water treated and the associated energy efficiency. Also, the state of the user community was planned to be evaluated with respect to safe water storage to facilitate the development of the education strategy to ensure the sustainability of the technology once rolled out, which was not attended to by (Hendrickson et al., 2020). Finally, the system could be tested with a pre-treatment bacteria concentration of 100,000/100 mL as part of the challenge test water (WHO, 2018b) or any other

defined WHO guidelines. Further explanations and refined protocols for evaluation of household water treatment technologies (HWT) have, however, been developed as detailed in (WHO, 2019).

This initial invaluable information was continuously complemented by other literature throughout the project delivery, because literature review inevitably continues until project completion.

CHAPTER 3: SYSTEM DESIGN AND CONSTRUCTION

3.1 INTRODUCTION

The literature review paved the way for further conceptualisation of the complete system setup and assessment of possible system components. This chapter gives the designed system configuration, the system components and plasma unit/reactor details. The initial system conceptualisation, design, system components description, preliminary setup and testing are also presented in the proceeding sections of this chapter.

3.2 INITIAL SYSTEM CONCEPTUALISATION AND SETUP – (VERSION 1)

3.2.1 Description

The system was initially planned to have a compact setting, consisting of three (3) components, including the plasma-ozone generation section, power conversion unit and water disinfection tank (**Figure 3-1**). Illustration schematics are provided in Appendix A-1. In the plasma compartment, plasma discharge would be generated by a strong electric field provided by a high voltage power supply. This has been preserved. It was also thought out that an inlet gas (ambient air) would pass into the discharge region, where oxygen in the air would be ionised to produce ozone (O_3) along with some other gaseous compounds, which would be released as bubbles through a tube (ozone diffuser) into the water disinfection tank. The size of the bubbles was planned to be kept small enough to ensure a high surface area to volume ratio. Before the exit of the water disinfection tank is a filter attached to the treated water outlet tap. In the improved experiments, oxygen is used as the feed gas in order to limit the production of reactive nitrogen species products such as nitric acid (HNO_3) and nitrous acid (HNO_2) that considerably lower the pH of drinking water.

However, during process modifications, it was planned that the water would be continuously recirculated between the ozonation chamber and the plasma reactor using a peristaltic pump. Although a single-pass process operation (Vanraes et al., 2017) characterised by one-time flow of raw water through each treatment unit, would be more practical, it may not allow adequate contact time of the contaminants with the plasma-produced oxidants.

3.2.2 Energy source

Solar energy has been utilised as a power source, so that the system can be used in locations without access to conventional electricity. The power supply unit consists of a solar photovoltaic system, lithium-ion battery and an inverter, which can convert DC to AC power supply. The 220V AC output voltage from the inverter is stepped up to the required high voltage needed by the plasma unit using a transformer.

3.2.3 Preliminary system performance evaluation

The target critical pollutants are defined as contaminants with concentrations above the permissible limits by South African National Standard (SANS)/specifications for drinking water (South African National Standard, 2015) and World Health Organisation standards (WHO, 2022b). The current focus is on microbiological contaminants with prospects of implementing the technology on other source water pollutants. Concerning limits stipulated in the South African drinking water quality standard (SANS 241:2015), coliform bacteria (Total Coliforms) and *Escherichia coli* (E. *coli*) were used to characterise the bacteriological contamination of the sources before and after treatment with the plasma-ozonation system. Most standards (WHO, EC Drinking Water Standards, UK Standards and US EPA Standards) recommend no E. *coli* (faecal coliforms) in 100 ml of sample and no coliforms in at least 95% of 100 ml samples (Ratnayaka et al., 2009). SANS 2015 limits the Total Coliforms count to 10 coliform-forming units (cfu) per 100 mL and 0 cfu per 100 mL for E. *coli*, clearly specifying that cfu <1 be taken as 0. The World Health Organisation guidelines for drinking water provide microbial quality guideline values as: E. *coli* (or thermotolerant coliform bacteria) must not be detectable in any 100 mL sample (WHO, 2022b). These standards therefore formed a basis for the preliminary performance assessment of the system on the inactivation of microbial contaminants at the point-of-use (household level).
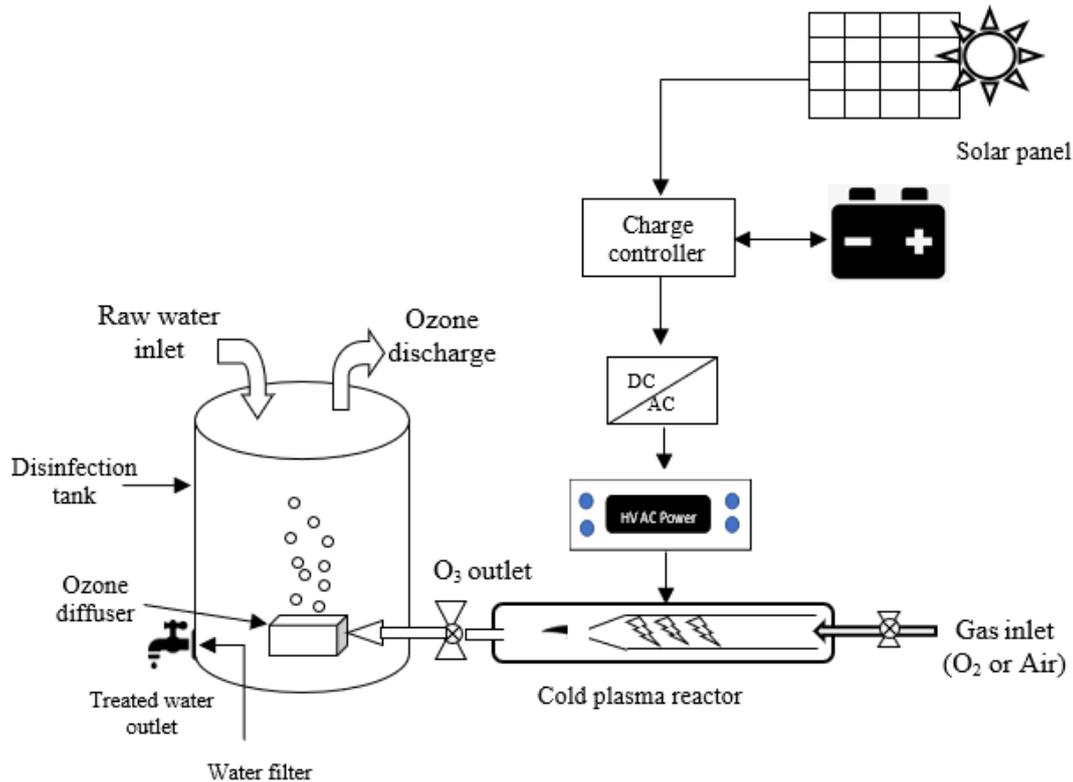
Figure 3-1. Initial Schematic Arrangement for the Plasma Water Treatment Process

3.2.3 Preliminary System Investigation and Testing

A preliminary investigation of the plasma system without the solar unit was conducted at the Plasma Research Unit in the Department of Chemical Engineering, University of Pretoria, to assess its ability to remove the critical contaminant commonly found in South African groundwater as reported in (Verlicchi and Grillini, 2020a). To achieve this, a groundwater sample was collected from a remote village in the Limpopo Province and subjected to initial screening. The results showed that E. *coli* was present in the water, and the concentration

measured was 19 MPN/100 mL. This concentration is rated as risky according to the South African drinking water standard. The presence of E. *coli* in the water also provides evidence for faecal contamination in the water, which could be the direct result of poor sanitation. Toxicity analysis has shown that the presence of E. *coli* causes diseases such as diarrhoea, urinary tract infections, respiratory illness, and pneumonia.

For the preliminary study, natural air was used in the production of ozone in situ, without any aerodynamic device. The air goes into a borosilicate glass tube of 4 cm in diameter through opened ducts. Alternating Current power with a high voltage (up to 8 kV) (and high frequency, 20 kHz) is supplied to the plasma reactor to ionise the gas between a high voltage electrode and a ground electrode at atmospheric pressure. The resultant gas mixtures, containing ozone, then directly contact raw water in a water container. The treated water was released through a tap. After just about 10 minutes, E. *coli* had been completely removed from 5 Litres of water that was treated. These preliminary results were used as process conditions for which the reactor operation was to be optimised. Considering that a minimum of 3 Litres of drinking water per person per day has been recommended in South Africa (Department of Water Affairs and Forestry, 2001), the POU technology could target about 120 Litres of water per day which should serve about 40 persons per day for the initial study period. Also, considering the treatment time for 5 Litres, we envisaged that 4 hours will be needed to treat 120 Litres of contaminated water in the present plasma configuration.

3.3 DETAILED SYSTEM DESIGN AND COMPONENTS (VERSION 2)

3.3.1 Solar Energy System

After the preliminary design, the energy estimate was then revised and updated accordingly with a proposal from GreenHouse Energy Consulting, South Africa (hereafter referred to as GreenHouse) as described in **Table 3-1**. GreenHouse carried out the detailed design, giving an estimate that includes the power needed to run the reactor, the peristaltic pump for water circulation and the oxygen concentrator to supply the oxygen feed gas to the reactor. This therefore superseded the preliminary design estimate because it required to have a solar system that matches the modern solar technologies with components from national (South African) suppliers. The solar unit components are shown in Appendix A-2. The solar system has been installed and will be implemented in the next experiments.

In simpler terms, the solar panels were the primary energy source, producing direct current (DC). This is stored in the battery for use in periods during which the energy from the panel is not adequate to meet the prevailing energy demands. The inverter converts the direct current from the solar panel (on the rooftop) into the required alternating current (AC) voltage. An important component in this design is the provision of a charge controller to prevent the battery from excessive charging, thus ensuring appropriate current regulation.

Table 3-1. Solar power system components (GreenHouse, South Africa)

SN	Component Description	Notes
1	1 x 800VA Victron 12V Phoenix Inverter	5-year Warranty
2	1 x Freedom Won 12V 100Ah Lithium Battery	5-year Warranty
3	360Wp Solar PV Array (2 x 180Wp)	12-year Warranty & 25-year performance guarantee
4	PV Framing structures (A-Frame), with earthing	10-year Warranty
5	1 x Victron Charge Controller (100/30 MPPT)	5-year Warranty
6	1 x DC Isolator	
7	AC Cabling, Switchgear, Earth Leakage & Surge Protection	
8	DC Cabling, Fusing and Connections	
9	Surface Mount DBs	
10	15U Fixed Wall Box (for equipment)	
11	Conduit & Sundry	
12	Installation Labour & GreenHouse IP	

3.3.2 High Voltage Unit

The high voltage alternating current power supply unit (HV AC PSU) converts direct current (DC) from the solar system to AC to power the reactor (R2). The reactor power input is controlled through the voltage and frequency settings (viewed on display) for the intended water treatment operation. The system was provided by Jeenel Technologies Pty, Boksburg, South Africa.

3.3.3 Oxygen Generating Unit

After further literature review complementing the earlier gap identification, new ideas towards refinements of the process configurations, system components and plasma reactor operation modes emerged. The need for superior experimental and prototype equipment to achieve the desired performance was also observed. The use of oxygen gas has been reported by several researchers to give better degradation, especially when the major degradants are reactive oxygen species (ROS), as well as energy efficiency, depending on the intended application (Vanraes et al., 2017). However, the oxygen gas is generally provided from a commercial cylinder. This approach increases the cost and is also unsustainable because the unit will not be able to run if there is a scarcity or unavailability of oxygen gas. To reduce this cost and make the unit more sustainable, an oxygen generating unit that works on the principle of pressure swing adsorption (PSA) was acquired for the subsequent supply of oxygen with purity of 93% or more, at a maximum flowrate range of 0-10 L/min. **Table 3-2** shows the oxygen generator details photographs in Appendix A-3.

Table 3-2. Oxygen Generating Unit

SN	Apparatus	Description	Purpose
1	Oxygen Concentrator (0-10 L/min)	Pressure Swing Adsorption (PSA) Oxygen Concentrator (PSA OC). Model: OX10 Wassertec Ozone Systems, Country: South Africa, Oxygen (out) flow rate: 0 – 10 L/min, Voltage & frequency rating: 230 V, 50Hz, Oxygen purity: >93%, Air pressure: 2.5 bar (Max).	Generation of oxygen gas from air to feed the plasma reactor.

3.3.4 Mass Transfer Improvement Devices

Mass transfer of plasma-produced oxygen species, specifically long-lived ozone, into solution is important because higher dissolution facilitates contaminant removal. Thus, in order to improve the dissolution of ozone, mass transfer devices were incorporated in the process design to generate microbubbles to enhance ozone dissolution. The devices are listed in **Table 3-3** (and Appendix A-4) to consist of a venturi injector and a nano bubble air disc stone.

Table 3-3. Ozone Mass Transfer Improvement Devices

SN	Apparatus	Description	Purpose
1	Venturi injector	Mazzei Venturi Injectors (USA) by Wassertec Ozone Systems, South Africa, Model: Mazzei PVDF 287 Venturi,	Improvement of ozone dissolution into water.
2	Nano bubble air disc stone	50 mm Ceramic nanobubble air disc stone (Fengkangyuan, China)	Improvement of ozone dissolution into water.

3.3.5 Plasma Reactors and Treatment Process Flow

3.3.5.1 Plasma reactor R1 (30 mm x 300 mm x 2.3 mm) and system configuration

In order to study the process optimisation and reactor parameters adequately, two DBD reactors were used to investigate the plasma-ozonation (PO) applications in water purification. The study of the effect of experimental parameters towards the optimisation of the ozone production, a smaller DBD plasma reactor (R1) consisting of a borosilicate glass tube with dimensions 30 mm x 300 mm x 2.3 mm was used (**Figure 3-1 Left**). R1 was designed to only produce ozone gas for treating water and not to house water during treatment. The system schematic involving R1 is presented in **Figure 3-2**.

R1
Dimensions: 30 mm x 300 mm x 2.3 mm

R2
Dimensions: 40 mm x 300 mm x 2.3 mm

Figure 3-1. Reactors R1 and Reactor R2 used to conduct all experiments.

Figure 3-2. Schematic diagram of the experimental setup with 30 mm x 300 mm x 2.3 mm reactor tube (R1).

3.3.5.2 Plasma reactor R2 (40 mm x 300 mm x 2.3 mm) and system configuration

The second DBD plasma reactor R2 consists of 40 mm x 300 mm x 2.3 mm borosilicate glass tube, a stainless-steel high voltage electrode, with an electrically conducting 5 mm diameter copper tape wrapped around the glass tube (material same as for R1) as shown in **Figure 3-1 Right**. The reactor R2 was designed to produce ozone and to allow water circulation within the plasma region to facilitate contact of water with the plasma species so as to remove the contaminants to make the water suitable for drinking.

The connection of R2 in the laboratory system process is shown in **Figure 3-3** and the schematic in **Figure 3-4**. The process consists of an HV AC power source (connected to solar power system), a compressed air filtering system, an oxygen concentrator, the plasma reactor, a peristaltic pump, ozonation chamber and a network of tubings (OD 6 mm – 10 mm). Dry compressed air at a pressure of 1 bar is passed through a 40-micron filter followed by a 0.01 micron coalescing filter to the oxygen generator (OX 10, range 0-10 L/min) via OD 10 mm tubing. The compressed air is distributed alternatively to the two molecular sieve columns by means of a rotary valve and oxygen production occurs through the pressure swing adsorption (PSA) principle. In the PSA mechanism, as the molecular columns charge, nitrogen and moisture are selectively adsorbed on the sieves, allowing oxygen to pass through the column top (Wassertec Ozone Systems, 2023).

The process operation mode depends on the intended purpose of the experiment and is controlled by valves V1, V2 and V3. When valves V1 and V3 are closed, the reactor works in circulating (continuous flow) mode whereby the water under treatment is circulated between the ozonation and reactor chamber. When V2 is closed (V1 and V3 open), the produced ozone is micro-bubbled through the venturi injector to the ozonation chamber where it is treated by reactive aqueous ozone together with its secondary products. The reactor is driven on oxygen gas from PSA oxygen concentrator (Wassertec Ozone Systems, South Africa) and water circulation by a peristaltic pump (Integra, Dose It, Switzerland).

Figure 3-3. Laboratory set up with reactor R2 and other system components.
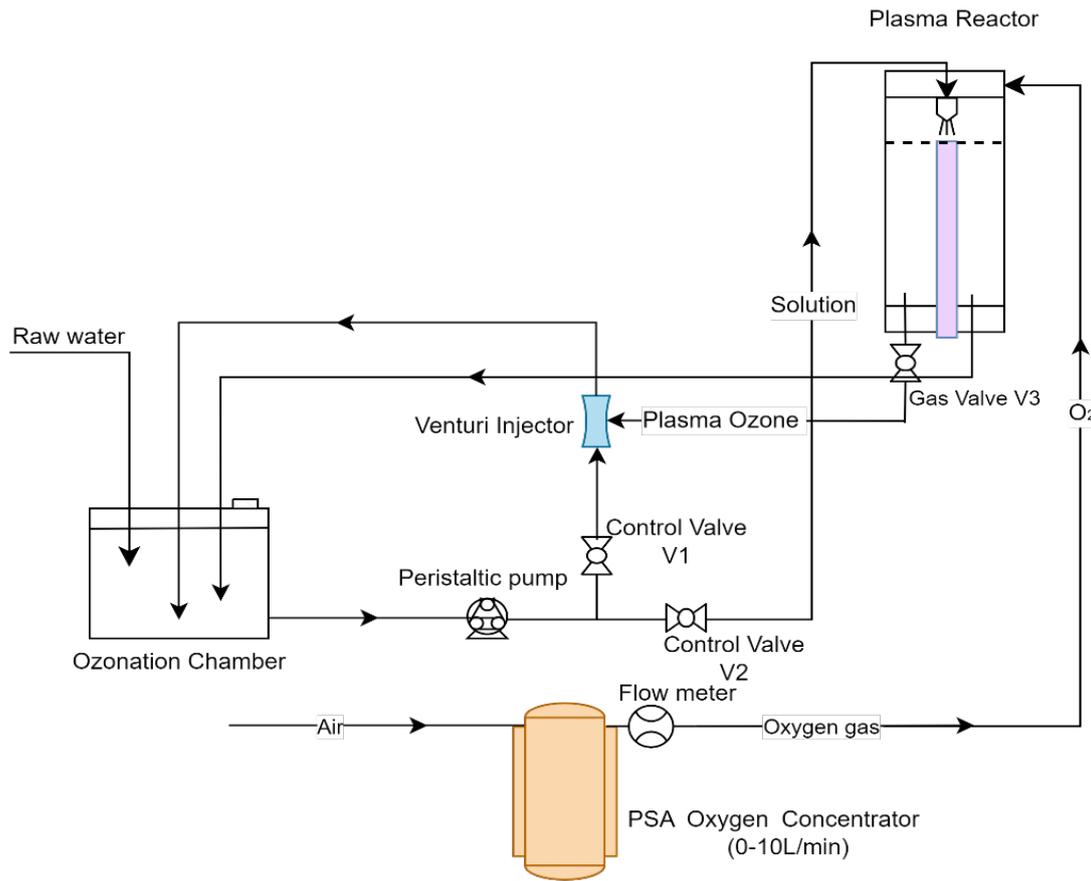
Figure 3-4. Experimental schematic utilising 40 mm x 300 mm x 2.3 mm reactor tube (R2).

3.4 SUMMARY OF REACTOR DEVICES, PROCESS COMPONENTS AND OPERATION MODES

3.4.1 Reactor Devices and Components

The summary of the plasma-ozonation unit and process components is given in **Table 3-4,** where only the major components have been listed.

Table 3-4. Plasma-ozonation unit components

SN	Process Component	Description	Notes
1	Reactor Device 1 (R1)	30 mm x 300 mm x 2.3 mm borosilicate glass tube, stainless-steel high voltage electrode and electrically conducting 5 mm diameter copper tape wrapped around the glass tube.	University of Pretoria Mechanical Workshop & Jeenel Technologies Pty, Boksburg, South Africa.
2	Reactor Device 1 (R2)	40 mm x 300 mm x 2.3 mm borosilicate glass tube, stainless-steel high voltage electrode and electrically conducting 5 mm diameter copper tape wrapped around the glass tube.	University of Pretoria Mechanical Workshop & Jeenel Technologies Pty, Boksburg, South Africa.
3	Air purification	40-micron filter,	Festo, South Africa
		0.01-Micron filter	Parker, England by Compressed Air Driers & Filters, South Africa
4	Oxygen Generator	Pressure Swing Adsorption Oxygen Concentrator (PSA OC), 0-10 L/min, 93% Purity	Wassertec Ozone Systems, South Africa
5	Solar Energy Supply	Solar Power Unit	Greenhouse, South Africa
6	High voltage (AC) power source	High voltage AC power supply unit (HV AC PSU)	Jeenel Technologies Pty, Boksburg, South Africa.

SN	Process Component	Description	Notes
7	High voltage pulsed DC power source	High voltage pulsed DC power supply unit (HV PDC PSU)	Jeenel Technologies Pty, Boksburg, South Africa).
8	Pumping Unit	Peristaltic Pump, Dose IT	INTEGRA, Biosciences Switzerland.
9	Ozone mass transfer devices	Model: Mazzei PVDF 287 Venturi,	Mazzei Venturi Injectors (USA) by Wassertec Ozone Systems, South Africa,
		50 mm Ceramic nanobubble air disc stone	Fengkangyuan, China
10	Treatment Vessels	1000mL and 2000 mL Flasks,	Germany by Glassworld, South Africa
11	Connection Tubings	Various	Non-reactive plastic materials/resistant to chemical attacks.

3.4.2 Reactor Operation Modes and Process Flow

The DBD plasma reactor R2 (main) has been configured and engineered to operate in a range of modes, ideated based on literature (Vanraes et al., 2017) but mainly to fit the primary function as plasma-ozonation. Controlled by simple valves, R2 can perform a range of processes depending on intended objective and level of contamination detected as outlined below:

a) Ozonation alone – where the produced ozone gas (plasma oxygen species) is diffused into contaminated water using a venturi injector or nanobubble disk stone (mass transfer improvement devices). This is batch mode operation, where long-lived ozone destroys the pathogens and other contaminants within a disinfection tank.

b) Plasma alone – continuous flow/recirculating mode – where the full spectrum of the plasma interacts with the water pollutants within the plasma region. The recirculation for a defined time ensures continued contact of contaminants with plasma and effective treatment.

c) Plasma-ozonation – where ozonation is carried out first (as described) and then plasma continuous flow/recirculation is done to achieve the synergistic treatment effect from the two processes.

d) Plasma alone – single pass – where the water passes through the plasma reactor once. This mode's challenge is on the limited residence time in the reactor, translating into less effective treatment, even though it's more practical and energy and time-saving.

CHAPTER 4: USER PARTICIPATION EVALUATION

4.1 INTRODUCTION

In the development of household water treatment (HWT) technologies or point-of-use methods normally employed to provide additional protection of public health by treating contaminated water or providing additional treatment where it is inadequate, it is important to seek views of the prospective user communities on the planned technologies.

The plasma device was developed and has been used to treat surface water (and groundwater) for drinking purposes during preliminary tests. Progressive improvements have been made on the device for better performance. Concerning this, the device was further tested on a highly contaminated surface stream for which the results were very promising as described in section 5 (or earlier in Progress Report 4). The device, together with its components, has been installed in a movable housing unit (container) with the characteristic of being lifted by a crane and transported to the community for demonstration purposes.

Thus, under this objective (No.5) that is part of the general project aims, a community laden with water contamination problems was selected as a prospective area for possible testing of the point-of-use (POU) plasma device. The Hammanskraal community in the City of Tshwane (CoT) was considered suitable for such technology testing. The specific tasks carried out, the methods applied, and outcomes are described in the proceeding sections of this manuscript.

4.1.1 Objectives of User Participation

With such a technology to be implemented at community level, it is best practice to collect and analyse user social perspectives towards the technology's application in drinking water treatment. The community engagements were carried out to obtain community opinions about the POU technology in the Hammanskraal area, hereafter described as "Community". We considered and defined the Hammanskraal community to be: "residents of Hammanskraal in the City of Tshwane (CoT) utilising water from a defined source such as municipal water supply or any other alternative water source for drinking purposes".

Therefore, the purpose of the study was to bring awareness to communities with Hammanskraal as a case study, about a plasma based POU water purification technology that can run on renewable energy. Also, perspectives of focus groups within the community were sought on their openness to such technology from a design and useability viewpoint.

The main goals are hereby described as:
a) To inform and raise awareness in the community of possible effects of using untreated water and introduction of plasma technology water treatment as a new technology being researched at the University of Pretoria.

b) To obtain feedback/attitude, preferences, acceptability, views about the proposed technology and community's openness to embrace it.

c) To collect water samples from the water source in the wet and dry seasons for analysis for research purposes only.

4.2 METHODOLOGY

4.2.1 Selected community

It is appreciable that South Africa is one of the countries with water-supply challenges (Sharma et al., 2023). The country is semi-arid, and like other developing African countries, rapid urbanisation and industrialisation have led to an increased release of contaminants in water, which enters lakes and rivers (Constantine, 2014). For example, recent reports from the Department of Water and Sanitation reveal inadequate wastewater treatment, leading to about 46% of South Africa's water not being safe for drinking and requiring additional treatment before use (Jacobs, 2024).

Hammanskraal is located in the City of Tshwane (CoT) and the entire community is supplied by municipal water supply. There has been evidence of unsafe water in Hammanskraal, as affirmed by the outbreak of waterborne disease (Malan, 2023). The possible cause of contamination has likely attributions such as discharge of untreated sewage into the Apies River that flows into the Leeukraal Dam, where the raw water for the serving water treatment plant is drawn (McCain, 2024).

In addition, the community was nearer to the research station (University of Pretoria), about 47.5 km (42 minutes' drive), implying that several visits could be made to interact with the community more often and, where necessary, to collect water samples for further research investigation. Also, several ethical clearances were made as required, including CoT acceptance to use Hammanskraal as a case study for the research in plasma technology application in drinking water treatment.

4.2.2 Preliminary Operation Planning

There was initial planning before field activities were embarked on. The planning aspects included the following (Peter van Eeuwijk, n.d.):

a) Determination of suitable procedures and informed consent forms.
b) Acquiring official approvals from the ethical committee of the University of Pretoria.
c) Obtaining approval from the City of Tshwane (CoT) where the case study community (Hammanskraal) is located.
d) Obtaining information from the contact person (the Councillor) on meeting location and agreeing on the meeting date and time.
e) Preparation of meeting materials including informed consent forms, approvals, questionnaires, audio recording device and spare batteries, a laptop and notebooks.
f) Preparation of transport/securing car from the University and ensuring it is fuelled.

4.2.3 Ethical Clearance

The ethical clearance was sought from the University of Pretoria, where the project was carried out and was consequently granted. The clearance ensured that the participants were protected and that informed consent was sought before participants got involved. In addition, the clearance ensured that the institutional and legal standards of the University of Pretoria were complied with.

4.2.4 Data Collection Methods

There are several types of community engagement processes depending on the information desired and the objectives of the engagement. Sometimes they are (i) initiatives that benefit the community and (ii) undertakings to gather information from the community (Angela Dean et al., 2016). The goals of the engagement in this case were (i) to raise awareness of the plasma-ozonation technology and (ii) to determine openness to the technology. The following methods were employed to achieve both objectives of enlightening the community and gathering useful information in the context of the research agenda of plasma-ozonation as a POU technology.

  a) **Focus Group Discussion (FGD)**

With respect to this, a natural group of 14 community members was recruited through the Local Hammanskraal Leadership headed by the Councillor and the interaction was carried out in September 2024 (as per planned period July – November 2024). The focus group discussion (FGD) was carried out while observing the commonly recommended guidelines for conducting an FGD, acquisition of information and analysis of the qualitative data (Peter van Eeuwijk, n.d.). One FGD was held with a group of mature Hammanskraal community members as physically observed during the discussion at the Councillor's area office.

The information was captured through handwritten notes and voice recordings with the consent of the participants and analysed qualitatively. Before the start of the exercise, each of the community members signed, at their will and liberty, an informed consent. The facilitators (Researcher and Supervisor) delivered basic information about the project including a video of the first project phase (Academy, 2023) (https://sdgacademylibrary.mediaspace.kaltura.com/media/Project+Tujenge+Siemens+Gamesa/1_qfmdvca3). This enlightened some of the enthusiastic community members who were very pleased with the research and envisaged solutions to their problems in the future.

  The main elements of the discussion were the following:
  (i) Fostering knowledge and information about household water treatment (HWT) or point of use (POU) treatment importance for household wellbeing, and prevention and control of disease spread. Although the dangers of taking contaminated water seemed to be well-known to the community, further efforts were made to inform the community about water-related diseases.
  (ii) Informing the community about the plasma technology application in water treatment and the research being carried out with prospects of having a community model (system housed in a movable container) occupying space of 3 m (Length) x 2 m (Width) and 2.4 m (Height).

(iii) Informing community members about the value of their responses in such a research development, the first of its kind in South Africa, and an appreciation of how far-reaching such a home (SA) - developed technology will be in the future.

(iv) Identification based on the discussions, any possible improvements to make on the proposed technology to fit the community's interests.

(v) Guiding the community members on the written informed consent and how to fill out the questionnaire to gather responses.

b) Questionnaire

The general objective of administering the questionnaire was to assess the application of plasma-ozonation technology in drinking water treatment with the case study as Hammanskraal, City of Tshwane, South Africa. The specific task was to obtain responses on specific questions designed to acquire information on (i) the community's acceptability of the plasma-ozonation technology as a POU or HWT technology by allowing initial testing and to use the technology, and (ii) the community's openness to using the technology for water purification. The other fundamental question was the willingness to pay a small amount of money to service small broken components during functionality of the system or to pay for operation and maintenance (O&M). The responses to all the questions, including the ones above, were analysed both qualitatively and using simple MS Excel tools to draw conclusions that are in line with the objectives of community engagements.

4.2.5 Data Analysis and Interpretation

a) Focus Group Discussions and Interactions

The information gathered through the FGD was analysed qualitatively and the following has been derived. The natural group participants' attitudes, knowledge and experiences within the locality related to HWT and opinions were recorded (Peter van Eeuwijk, n.d.). A critical analysis of the discussion resulted in the following inferred information concerning the elements listed in discussion guide items in section 4.2.3 (a).

(i) Knowledge of HWT/POU and Awareness of Water-related Diseases

With respect to this, the community was very aware of dangers associated with taking unsafe water and seemed angry in the beginning of the meeting, resisting responses due to the fact that we had not gone with an immediate complete solution of stopping the contamination in the tap water that they had abandoned since the outbreak of cholera in May 2023. After a detailed explanation of the stage of the research at which we were, the members calmed down and discussions proceeded. Obviously, the community was already aware of the dangers of taking contaminated water.

(ii) Discussion on plasma technology application as HWT/POU

They appreciated the planned technology and mainly liked the small space of 3 m (L) x 2 m (W) x 2.4 m(H) that the community unit would take. One member was keen on having a module in her house and one fixed on the tap such that contaminants are removed immediately after water flows out of the tap. This was a great

observation calling for a new idea (for the future) of having a small, powerful solar panel and other necessary system improvements to achieve a small tap module of the plasma reactor device.

During the time of the community engagement water was being supplied through mobile water tanks in Hammanskraal at regular intervals (thanks to RSA Government), which they just take because its clean water. One member reported that she just boils the tap water and has continued to use it at the times its flowing in taps.

(iii) Clean water provision options and proposed improvements on the plasma technology

The team was very keen on the having two models, one for the community and one for the individual household. They wished not to buy the treatment units but to be provided by the Municipality freely if its enrolled out as a functional technology. Also, most members echoed their wish to have clean water flowing in the taps again even with the development of this new HWT/POU plasma technology.

(iv) Written informed consent and Questionnaire

The importance and relevance of the informed consent form were explained to the members. Assistance was offered by one of the community members working in the Councillor's office as an interpreter (to local language) and after everyone was convinced and had understood the purpose of the consent form, they agreed to sign at liberty and free will. They were then guided on how to fill in the questionnaire (still with the assistance of an interpreter for some members). The questionnaire generally focused on plasma technology and the community's perspectives, which they candidly filled. Those who could not were assisted by their colleagues.

b) Questionnaire Responses

The responses from the questionnaires were analysed and the following useful information was derived:

(i) **Questions 1 and 2:** Whether additional treatment is carried out at household level (Qn 1) and the methods (processes) employed (Qn 2):

Qn 1 sought to establish if any HWT/POU method is carried out to achieve further improved quality of drinking water in the community, and Qn 2 sought to ascertain the actual processes being utilised. In response, only 5 out of 14 (36%) community members in the FGD indicated that they provide additional treatment. Only 2 out of the 5 utilise boiling while the remaining 3 did not specify which other processes they employ. Thus, overall, of the 14 members, only 2 boil their water (14%). This preliminary information explains why the community was cholera-laden in May 2023. Thus, a modern HWT technology was observed as required. Also, the WRC financing of the research is a good development track for determining solutions for improving the quality of life and well-being of the South African people by providing clean water.

(ii) **Question 3:** Whether the community has alternative sources of water other than Municipal supply.

This question objectively sought to establish if there are alternative sources of water in the community. This is fundamental for understanding the real water matrices that the plasma device will treat. This is also of great significance because the reactor, in addition to the removal of microbiological contaminants as a primary target

to control disease, is designed to remove recalcitrant organic compounds which the treatment plant unit processes cannot degrade.

The community currently only uses Municipal water supply from the designated treatment plant as per the response of all 14 members (100%). This response is very vital and responds to the Researcher's need to upscale and improve the throughput of the plasma device technology and to develop the technology up to the treatment plant. This is another practical research problem that can be explored by either retrofitting the existing plants or building new plasma-based unit processes for large community water supplies, but all seems farfetched for now. Some knowledge-building information on retrofitting of existing plants has been presented by (Naicker et al., 2023).

(iii) **Question 4 and 5:** Whether water from alternative sources is treated (Qn 4) and methods employed (Qn 5).

Since in Qn 3 all members indicated that all their drinking water needs are based on the Municipal water supply, no significant conclusions can be drawn from the responses to these questions. However, this further confirms the need to do more research to improve the unit processes at treatment plant scale.

(iv) **Questions 6 and 7**: Whether community was aware of plasma or plasma-ozonation as a possible HWT/POU technology (Qn 6) and whether it has ever been tested in Hammanskraal (Qn 7).

The purpose of question 6 was to determine whether the community has ever heard of or has knowledge of plasma technology's possible application in HWT. In response, 12 out of 14 members (86%) have never heard of and were not aware of plasma technology as a possible HWT/POU technology. Only 2 members (14%) noted that they had heard of the term plasma in the context of water treatment. The feedback towards Qn 7 revealed that the plasma or plasma-ozonation technology has never been tested in Hammanskraal as a POU technology. The responses confirm that plasma water research is novel and new in South Africa, and is worthy of further exploration.

(v) **Question 8:** Willingness to test and use the solar-powered plasma technology on drinking water treatment.

The objective of this question (8) was to establish whether the community is willing (allowing the investigators) to test the plasma-ozonation as HWT/POU technology for further cleaning drinking water in their community. The community agreed to test and use the technology in their area as evidenced by the 100% acceptance (i.e., all 14 members). This response gives opportunity to the Researcher and other stakeholders for further community engagements on the technology and acquisition of more information towards solving the community's clean water supply challenge.

(vi) **Question 9:** Willingness to pay for operation and maintenance (O&M) to service minor system breakdowns.

In common practice globally, the initial capital investment of most water schemes is by the responsible government or local authority. Accordingly, the scheme's water users are always required to pay a relatively small service fee to carry out operation and maintenance (O & M) of the system's sustainability. In the wish to check compliance with this common best practice, Qn 9 was presented to the community. In respect of sustainability and being able to service (repair and replace) broken system components, 9 of 14 members (64%) marked they are willing to pay a small fee for O & M, while 5 of the 14 (36%) were not willing to pay. This response gives a snapshot of a real-life installation and operations scenario during the new system's operational lifetime. This answer is consistent with the explanation during the FG discussion, where some members remarked they are not able to pay due to a number of reasons, among them having no employment. This implies community sensitisation will be required to convince the 36% to appreciate the need to contribute to the scheme's sustainability. However, if more than 50% of the members are willing to pay for O & M, then we can firmly believe that the majority are willing to pay for the system's O & M.

(vii) **Question 10:** Openness to using solar-powered plasma technology for drinking water treatment.

This question aimed at establishing the attitude of ready accessibility or receptiveness of the technology. This aspect is very principal to the system's functionality and to serving of its intended purpose. What happens sometimes (though rarely) in water supply, but mainly in other community infrastructures (such as markets, community sanitary units etc) is, however well engineered, aesthetic or strategically located etc, the unit may be, the community may reject it and prefer old conservative ways or dilapidated structures. Such precedence echoed the need to know whether the Hammanskraal community (as a case study) is open to using solar-powered plasma water treatment technology. In their positive response, all 14 members (100%) were open to using the green energy-powered POU water treatment technology.

(viii) **Question 11:** Willingness to embrace any other household water treatment technology for biological contamination control.

The objective of this question was to find out whether the community can take on any other HWT/POU technology other than the plasma-based one, since all such technologies are intended to serve similar purposes. The all-positive response to this question explained the dire need for HWT/POU for such a clean water supply-challenged community. All the members (100%) were willing to embrace any other technology as long as it could solve the problem.

This shows a high potential for opportunity to develop and implement an HWT/POU device to solve a community's problem, implying that plasma-ozonation has a chance in such communities.

(ix) **Question 12:** Knowledge of any other new/modern HWT/POU technology one would wish to be introduced to the community.

This question explored the diversity of the HWT/POU technologies that can feasibly be introduced to the community other than the plasma-based one. The Researcher wished to find another modern but simple technology that could be compared to plasma. However, 13 out 14 (about 93%) members reported that they

have not heard of any other modern/new technology for HWT/POU. Only one (1) member noted they heard of another technology but did not specify it as the question desired. This response shows that plasma-ozonation is timely and if the technology rolls out, it will be fully embraced in the Hammanskraal area, City of Tshwane and throughout South Africa.

Summary of Questionnaire responses.

In order to have simplicity and clarity, the questions and responses have been summarised in **Table 4-1**.

Table 0-1. Summary of responses from questionnaire

Qn No.	Abridged questions derived from questionnaire (Appendix 3)	Summarised Responses: 14 Participants (100%)
Qn1	Whether additional treatment is carried out on Municipal water supply before household use.	• No additional treatment: 64% • Additional Treatment: 36%
Qn2	Method of additional treatment of Municipal water (if any).	• None: 64% • Boiling (21%), • Other methods (unspecified): 14%
Qn3	Secondary (alternative) sources of water.	No alternative source
Qn4	Water treatment from alternative sources.	No treatment for alternative sources since they do not exist.
Qn5	Methods for treating water from (alternative) sources.	No methods for alternative sources since they do not exist.
Qn6	Whether aware of plasma or plasma-ozonation.	• Not aware of plasma: 86% • Aware of plasma existence: 14%
Qn7	Seen or heard of plasma-ozonation technology being tested in Hammanskraal in SA.	Plasma-ozonation has never been tested in Hammanskraal in SA.
Qn8	Willingness to test and use the solar-powered plasma technology on drinking water treatment.	Community is willing to test the plasma technology for HWT/POU.
Qn9	Willingness to pay for operation and maintenance (O&M) to service minor system breakdowns	• Willing to pay for O&M: 64% • Not willing to pay for O&M: 36%
Qn10	Openness to using the solar-powered plasma technology on drinking water treatment.	All community members (100%) were open to utilising the plasma technology.
Qn11	Willingness to embrace any other household water treatment technology for biological contamination control.	All community members (100%) were willing to embrace any other technology to solve the unclean water problem.
Qn12	Knowledge of any other household water treatment technology one would wish to introduce to the community.	• No other HWT technology is known: 93% • Another HWT is known (but they did not specify what it is): 7%

4.3 ACCEPTABILITY, DESIGN AND SYSTEM USEABILITY

a) Is the technology acceptable to the community?

Based on the analysis of the responses recorded during the FG discussions and the questionnaires, plasma or plasma-ozonation technology as a POU/HWT is acceptable to the community. This was confirmed by the 100% affirmative response to the willingness to embrace the technology and their being open to using it, as determined from Hammanskraal, City of Tshwane, SA, as a case study.

b) Which improvements should be made to fit for use in the future?

What was inferred concerning this aspect was to consider having different modules of the device. Community members implored the Researcher to have two main installations to include:

- Community supply – in a container/housing unit, 3 m (L) x 2 m (W) x 2.4 m (H), and occupying a small space.
- Household module – which can be fixed on the individual household tap.

4.4 CONCLUSION ON USER PARTICIPATION

This chapter mainly focused on evaluating user participation in terms of technology acceptability, design and usability of the system. The major activity involved mainly community engagements and with two salient features as (i) raising awareness of possible effects of untreated water and introduction of plasma/plasma-ozonation technology as a point of use (POU)/Household water treatment (HWT) technology and (ii) evaluating user acceptability, design and useability or community's openness to embracing the technology. To achieve these, Hammanskraal, in City of Tshwane (called "the community") was selected as a case study due to its current state of being encumbered with a contaminated drinking water problem. The community was visited after obtaining relevant City authority's approvals and relevant ethical clearances. The interaction methods included focus group discussions (FGDs) and questionnaire transmission to and response from the community. The FGD consisted of 14 members who aired out their views freely after signing a written informed consent to participate. The most valuable information of the FGD is outlined below:

a) *Interactive discussions*
(i) Plasma technology application as HWT/POU

The community appreciated the planned technology and mainly liked the small space of 3m (L) x 2m (W) x 2.4 m (H) that the housing unit would occupy for the community water treatment unit. They, however, wished to have a smaller module for the household with the reactor fixed on the tap such that contaminants are removed immediately as water flows out of the tap through the reactor and then to the collection system. This was a great observation, calling for a new idea of having a small, powerful solar panel and other necessary system improvements to achieve a small plasma reactor device as a tap module. But this seems, at this project stage, to be quite a significant task that can be undertaken in future projects.

(ii) Clean water provision options and proposed improvements on the plasma technology

The team was very keen on the having two models, one for the community and one for the individual household. They wished not to buy the treatment units but to be provided by the Municipality freely if its enrolled out as a functional technology.

b) *Questionnaire administration*

From the questionnaire the main outcomes included:

(i) Awareness of plasma or plasma-ozonation as a possible HWT/POU technology.

In response 12 out of 14 members (86%) have never heard of and are not aware of the plasma technology as a possible POU technology. Only 2 members (14%) noted that they had heard of the term plasma in the context of water treatment. The feedback towards Qn 7 revealed that the plasma or plasma-ozonation technology has never been tested in Hammanskraal as a POU or HWT technology.

(ii) Willingness to test and use the solar-powered plasma technology,

The community agreed to test and use the technology in their area as evidenced in the 100% acceptance (i.e., all 14 members). This response gives opportunity to the Researcher and other stakeholders for further community engagements on the technology and acquisition of more information towards solving the clean water supply to the community.

(iii) Willingness to pay for operation and maintenance (O & M),

In respect of sustainability and being able to service (repair and replace) broken system components, 9 of 14 members (64%) marked they are willing to pay a small service fee, while 5 of the 14 (36%) were not willing to pay for operation and maintenance (O & M).

(iv) Openness to using the solar-powered plasma technology on drinking water treatment.

In their positive response, all 14 members (100%) were open to using the green energy-powered POU water treatment technology.

(v) Willingness to embrace any other HWT technology for biological contamination control.

All the members (100%) were willing to embrace any other technology as long as it can solve the problem. This shows a high potential for opportunity to develop and implement an HWT/POU device to solve a community contaminated water problem, implying the plasma-ozonation has a chance in such communities.

c)   Acceptability, design and useability

Based on the analysis of the responses recorded during the FG discussions and the questionnaires, plasma or plasma-ozonation technology is acceptable to the community as determined from Hammanskraal, City of Tshwane, SA, as a case study. With respect to design, the community members implored the Researcher to have two main installations to include: (i) Community supply – in a container/housing unit, 3 m (L) x 2 m (W) x 2.4 m (H)and (ii) Household tap module – which can be fixed on the tap for the individual household.

CHAPTER 5: SYSTEM PERFORMANCE EVALUATION

5.1 INTRODUCTION

This section focuses on evaluation of the plasma-ozonation reactor/device and system process in relation to the project-specific goals of (i) assessing the effect of reactor parameters (ozone dosage and oxygen flow rate), treatment time and disinfection of contaminants and (ii) evaluation of efficacy of point-of-use solar-powered cold plasma-ozonation technology on real water based on the WHO criteria and benchmarking with well-established methods. Also, the earlier studies presented in progress reports (PR 3 and PR4) were complemented with (i) improving the surface water treatment by R2 and (ii) benchmarking the results with other drinking water treatment methods.

5.1.1 Basis on Literature Review

In order to study and adequately evaluate the reactor device, an additional literature review was carried out, but with much attention on process configuration, operation modes and reactor optimisation parameters. The following literature highlighted significant features that guided laboratory-scale experiments and the performance of the system prototype. This information guided a number of activities that were set out as described in the project objectives, notably the investigation of the reactor influencing parameters of plasma-ozonation system efficiency and efficacy.

The performance of the plasma+ozonation (PO) treatment process has been investigated by (Magureanu et al., 2016). The researchers explain with experimental evidence that, in their investigation to comprehend the removal of organic compounds from water by plasma, the plasma treatment-ozonation process resulted in higher success. The investigators also noted that, with better mass-transfer of the ozone generated in the plasma+ozonation setup, the system performance with respect to breakdown of contaminants was six times better. The synergetic effect of plasma and ozonation was commendably experienced, with other plasma-generated species mainly the hydroxyl radicals (•OH), having a vital role in the breakdown of the organic contaminants.

In the study by (Vanraes et al., 2017) to remove micropollutants in wastewater, a process flow in which plasma from dielectric barrier discharge (DBD) was combined with adsorption and ozonation was developed. The authors gave credible insights on the best mode of reactor configuration with respect to energy efficiency. A reactor where the influent water passes through the contaminant degradation chambers once, with ozonation first (ozone generated by plasma reactor) and then plasma treatment, was found to be more energy efficient and with improved degradation. (Vanraes et al., 2017) further comment and argue that such a single-pass mode reactor may be more practical and feasible for purification of larger volumes of water in shorter time scales. These research outcomes provide an opportunity for several experimental investigation scenarios to achieve highly performing PO system processes.

The goal of (Wardenier et al., 2019) was to compare the efficiency of common advanced oxidation techniques (AOTs) including Ultraviolet (UV) radiation, hydrogen peroxide (H_2O_2) and Ozone (O_3) with a more recent plasma-ozonation (PO) process. The researchers clarified that the destruction kinetics of PO resulted in faster complete elimination of the contaminant (i.e., better performance) compared to the other mentioned AOPs. The PO technique however, resulted in intermediate energy use efficiency with reference to the other AOPs. However, PO resulted in more than 95% degradation efficiency with complete removal for specific micropollutants.

The information described aided the process flow design improvements that facilitated different operation models to achieve notably, the synergistic treatment effect. However, the research by (Magureanu et al., 2016, Vanraes et al., 2017, Wardenier et al., 2019) concentrated on micropollutants and organic compounds, however, our goal is to implement the coupled PO technique and reactor system to successfully remove microorganisms from surface water sources.

5.1.2 Pasma Reactors and Modes for Performance Evaluation

In order to study the process optimisation and reactor parameters adequately, the two DBD reactors earlier described were used to investigate the PO applications in water purification. Reactor, R1 (30 mm x 300 mm x 2.3 mm borosilicate glass tube) was used to study the effect of experimental parameters toward the optimisation of the ozone production while reactor, R2 (40 mm x 300 mm x 2.3 mm borosilicate glass tube) was used to investigate surface water treatment for device evaluation in terms of efficiency and efficacy. The detailed description of reactors was given in section 3, as illustrated in **Figure 3-1.**

5.2 EFFECT OF EXPERIMENT CONDITIONS ON REACTOR EFFICIENCY AND EFFICACY

5.2.1 Influencing Experimental Parameters

The majority of the researchers have reported that, a) input power (energy source), b) initial concentration of the contaminant, c) feed gas type (and flow rate), d) reactor design/configuration, e) physical and chemical characteristics of water (solution pH and conductivity) and f) nature of pollutant, have significant influence on plasma reactor treatment operation and performance (Zeghioud et al., 2020, Magureanu et al., 2021, Aggelopoulos, 2022). For a model pollutant such as a microorganism (or for microbes), (Murugesan et al., 2020b) further remarked that other internal variables, such as composition of the microbial cell wall, significantly affect the reactions, including the mechanisms and kinetics. The reactor efficiency and efficacy with respect to contaminant destruction and energy consumption are utilised to characterise and explain the reactor performance on water purification.

The design of experiments (DOEs) technique is normally used in designing studies and leads to robust investigations. However, the DOE, based on several variables, results in a lot of experimental runs and makes the model equation very complex. For example, for five (5) factors, three (3) levels using the Central Composite Design (CCD), 54 experimental runs are required. Therefore, in order to limit this, the first step is design

screening to identify the key factors that should be used in the DoE. Thus, based on the outcome of the design screening, the applied voltage, repetitive frequency and gas flow rate were found to have the most influence on the production of ozone (O_3).

5.2.1.1 Effect of plasma energy

The energy input into the plasma reactor is a major influence on the degradation process as reported by (Magureanu et al., 2021). Generally, most power supply units designed for the generation of plasma either have voltage or current variation. Therefore, the input power is adjusted by varying the voltage (kV) of the plasma power source. It is expected that every change in applied voltage will affect the production of chemical oxidants such as ozone and consequently the degradation of contaminants. However, this strongly depends on the power supply unit utilised and the type of discharge being generated. For example, the effect could be linked to the applied voltage and operating current only if gliding arc or glow discharge is being generated, or it could be the applied voltage and the repetition frequency if a dielectric barrier discharge (DBD) is considered. This is because a DBD cannot be generated by a conventional direct current and hence, an alternating current power supply and a high voltage pulsed direct current are used. From our design screening, it was found that the applied voltage and repetition frequency have a stronger effect on the energy than other parameters. Therefore, the voltage effect has been examined from the range at which a breakdown voltage can be achieved based on the reactor geometry, to its maximum for the discharge to be sustained in order to get an optimum voltage in relation to ozone production, and potentially extend to a real water source.

5.2.1.2 Effect of gas flow rate

The influence of the gas flow rate is very crucial in the process as it can alter the energy required by the system (Back et al., 2018). Therefore, to realize an optimum ozone dosage, the gas inlet system is controlled, and a flow meter is normally used to measure the amount of oxygen flowing into the reactor. The produced ozone is considered with regards to the flow rate of the feed gas (oxygen), which can be controlled periodically to achieve significant contaminant degradation without producing residual ozone. As previously mentioned, pure oxygen gas was used instead of synthetic air in order to eliminate the formation of nitrates, which can potentially reduce the pH of the water. The laboratory assessment has used oxygen from a cylinder as the inlet gas. A similar experiment was run on the new setup incorporating an oxygen generator in order to verify the reproducibility of the results and smoothly transition from the use of commercial oxygen cylinders to a more sustainable approach. The ozone was assessed in aqueous phase using the standard analytical options in the Lovibond® SpectroDirect. This is a modern single-beam spectrophotometer that is specifically designed for water testing.

5.2.2 Plasma Ozone Production and Process Optimisation

5.2.2.1 Plasma Reactor and Process Configuration

Based on the design screening, a number of experimental trials and tests were initially conducted to determine the plasma (produced) ozone dosage required to treat water. In such preliminary work, the observations on system behaviour with respect to varied input conditions of voltage and oxygen gas flow defined a framework

for further experiments on plasma ozone production, quantification and chemistry under such conditions. The results from such preliminary studies have not been reported, but as noted, taken as a framework for the in-depth study, in an attempt to develop a predictive model for the optimal ozone dosage for the treatment of contaminated water with no residual ozone in a cold plasma-ozonation system.

After the preliminary ozone optimisation was performed, two different sets of experiments were conducted in an attempt to determine the effect of ozone on the treatment of Total Organic Carbon (TOC), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) in water. The experiments included COD/TOC and COD/TSS experimental investigations because, as per the different literature, these three (TOC, COD and TSS) were identified as the starting major parameters to determine the ozone dosage needed to treat water (Janex et al., 2000, Paraskeva and Graham, 2002).

Oxygen gas was used instead of air for all experiments because air plasma produces nitrogen oxides, causing the sample's water pH to decrease when reactive nitrogen species products such as nitric acid (HNO_3) and nitrous acid (HNO_2) are formed. In addition, using pure oxygen as a feed gas in plasma, a lot more ozone is synthesized with less energy consumption than in air plasma where energy is shared with nitrogen reactions (Kim et al., 2013). Our study is pH dependent, thus, it was a better fit to use an oxygen gas cylinder, which was then replaced with an air-to-oxygen concentrator that is operated on the principle of a pressure swing adsorption (PSA) to reduce the overall cost of the experiments. Also, there were some modifications to the reactor dimensions earlier submitted. It should be noted that such (minor) modifications to the reactor dimensions are sometimes necessary to obtain credible results and to define an efficient DBD reactor system for the conceptualised POU system. Along that line of action, a second copper tape was also added vertically to the back of the reactor to increase the amount of discharge produced before the final optimisation experiments were performed. The process setup and reactor type are shown in **Figures 3-2** and **5-1,** respectively.
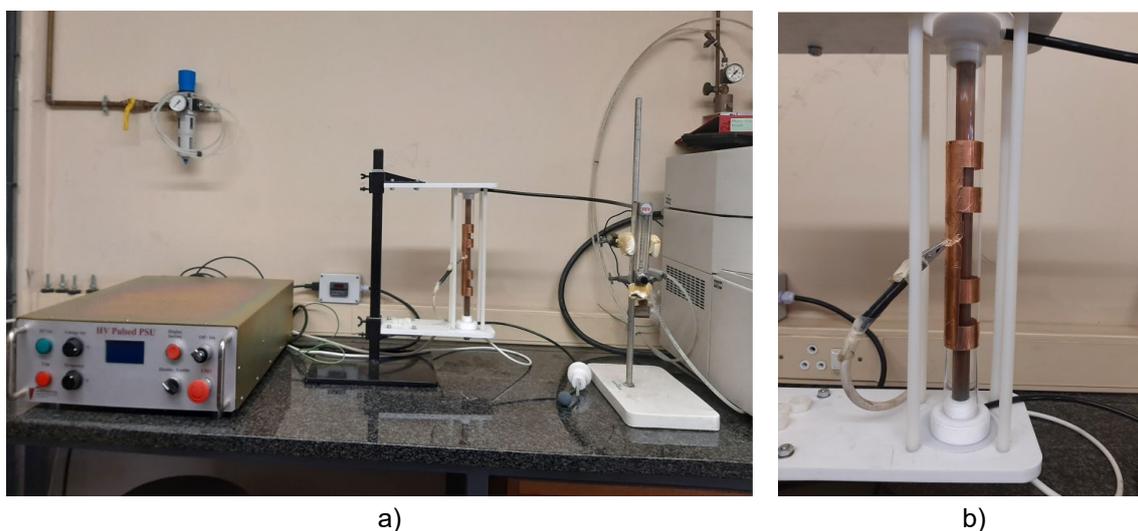
a)   b)
Figure 5-1: Reactor set up used for all experiments - (a) and Reactor tube - (b).

5.2.3 Experimental Investigations and Procedures

5.2.3.1 Materials and Methods

The overall goal of this experimental work was to determine the maximum optimal ozone (O_3) in aqueous solution that could generated by the modified DBD reactor and fully utilised without leaving behind residual ozone. The oxygen feed gas from a cylinder (under controlled pressure) was regulated by a rotameter (O_2 flow meter). The input voltage and frequency were determined by a high voltage pulsed direct current (HV Pulsed) power supply unit (PSU). The ozone concentration was monitored from a solution Bottle (1 Litre capacity) of deionised (DI) water, and the amount of ozone produced is quantified by SpectroDirect Spectrophotometer and method 300 for ozone without chlorine (Lovibond, 2017).

The activities undertaken therefore consisted of (i) calibration of the O_2 flow meter (rotameter) (ii) Ozone quantification and (iii) preliminary reactor optimisation. The detailed discussion of the experimental techniques, the results obtained, and their interpretation is given in the following sections.

5.2.3.2 Rotameter Calibration

The Rotameter (O_2 flow meter) was calibrated to determine the oxygen flow rate at five different settings ranging from 10 – 50. All the experiments were performed for 10 seconds (s) with the pressure regulator set to 100 kPa. During this experiment the independent variable was the rotameter setting and the dependent variable was oxygen flow rate which is calculated by taking the difference in volume divided by the reaction time (10 s). For the calibration, a 1 Litre measuring/graduate cylinder was filled with tap water and inverted, initial volume was noted. After setting up the correct reaction conditions and accurately setting the flow rate (Rotameter setting) the outlet tube was placed in the cylinder for the desired reaction time. The tube was then removed, and the gas flow turned off upon which the final volume of the water was noted. This experimental procedure was repeated at least 3 times per rotameter setting and then the same procedure was performed for the other flow rates.

$$Flow\ Rate = \frac{Final\ Volume\ (L) - Initial\ Volume\ (L)}{Time\ (min)} \tag{5}$$

5.2.3.3 Ozone quantification

The concentration of ozone (O_3) in the gas phase, exiting the reactor, was determined by the well-established iodometric titration method (Rakness et al., 1996). This method was used with the exception that there was no pressure correction performed and therefore, no pressure-related volume correction was performed. During the quantification, 400 mL of potassium iodide (KI) was ozonated and then spilt into two 200 mL samples for titration performed by two independent people each time as described in the method. This procedure was repeated 3 times, therefore allowing for 3 ozonation runs and 6 titrations in total to increase accuracy of the quantification experiment. The reason for splitting the volume in two and allowing independent analysts to titrate the sample is due to the high human error that can come in when doing titrations, as it depends on your colour observation as well as parallax errors when reading burette values. This experiment allowed for good and reliable data for the determination of the concentration of ozone in the gas phase.

5.2.3.4   Preliminary Reactor Optimisation

To optimise for the reactor conditions, deionized (DI) water was used and the water volume, temperature, run time and regulator pressure were kept constant at 500 mL, $\pm25℃$, 10 minutes and 100 kPa respectively. The independent variables were flow rate (rotameter setting), applied voltage, frequency, and tube lengths (Figure 5-1) while ozone concentration was the dependent variable, measured using the Hanna Instruments HI 38054 Ozone Test kit (Hanna Instruments, 2009). The independent variables were changed using the One-Factor-At-A-Time (OFAT) approach to see the effect on ozone concentration. First, all other variables were also kept constant while the applied voltage was changed. This was then followed by the operating frequency, which was changed to a new value and kept constant while the applied voltage was adjusted. Then tube lengths were changed and kept constant at the new value while the applied voltage was adjusted. Finally, oxygen flowrate was changed and kept constant at the new value while the applied voltage was adjusted.

Response Surface Design- Box Behnken Ozone Optimisation

The JMP® statistical software, that empowers users to explore and analyse data visually, solve critical problems and provide the necessary insights to make stronger data-driven decisions, was used for the design of experiment. In order to understand the interactions between the different variables, a well-known experimental design for response surface methodology (RSM), namely the Box–Behnken design (BBD) with 3 factors, each with 3 levels and one response (ozone concentration) was employed. The 3 factors were flow rate, applied voltage, and frequency as these where the variable identified to have the greatest influence on ozone concentration in the system. The experiments were randomized with the number of centre points selected to be 3 and replicate 1 during the experimental design. This gave a total of 30 randomized runs, however only 19 experiments were run at the end, the repeats that seemed most likely to give the highest ozone concentration based on theoretical knowledge and background was selected from the list while the rest were discarded. The ozone concentration in water for all the experiments about ozone optimisation was measured using a SpectroDirect spectrophotometer and method 300 for ozone in the absence of chlorine (Lovibond, 2017). For all experiments, 500 mL of deionised water (DI) was used. The three-experiments carried out to finally optimise the results generated by the JMP® software are described below:

a) First, the validity of the preliminary work was tested by replicating the same experimental conditions using 500 mL DI water at a flow rate of 1.27 L/min, applied voltage of 19.0 kV and frequency of 2.00 kHz.

b) The maximum factor parameter for the gas flow rate and the applied voltage was then tested against all operating frequencies to understand whether the system can operate (withstand) these conditions for maximum run time of 20 minutes. The sample volume was kept constant at 500 mL.

c) All the runs generated by the JMP® software program were performed based on the levels determined by the above to experiments. Experiments were performed in the exact same randomized order as generated by the program. Due to the fact that the ozone concentration was higher than the range of the instrument 0.02 - 1.0 mg/L ozone, all the runs were diluted on a x 2 dilution factor for ozone concentration using 5 mL of the ozonated sample and 5 mL of normal DI water. Dilutions were to be carried out even if the ozone concentration seemed to be low for that specific sample to ensure that great precision and accuracy is obtained.

5.2.4 Experimental Results and Discussions

5.2.4.1   Rotameter Calibration

The Rotameter (oxygen flow regulator) used in the experiment was calibrated to determine the oxygen flow rate delivered to the plasma reactor. Initially, during preliminary works investigations, a commercial ozone unit using air was tested but very low ozone concentrations were obtained. Oxygen gas was therefore opted for used in the reactor set up instead of air. The selected range for calibration of the independent variables was preferred because it provided data points below and above the optimal oxygen flow rate that was found in non-dissimilar setups as well as for the oxygen concentrator which will be implemented later for ozone generation to decrease the cost of using a gas cylinder (Vaduganathan et al., 2012, Boonduang et al., 2012, Qasim et al., 2022). The calibration results are presented in **Table 5-1** and **Figure 5-2.**

Table 5-1. Summary of results from rotameter calibration

Rotameter Setting	Ave. Flow Rate (L/min)	Std. dev.	% Error	Ave. + std. Dev
10	**0.64**	0.0173	2.7%	0.66
20	**0.92**	0.0346	3.8%	0.95
30	**1.27**	0.0502	4.0%	1.32
40	**1.64**	0.0346	2.1%	1.67
50	**1.87**	0.1154	6.2%	1.99
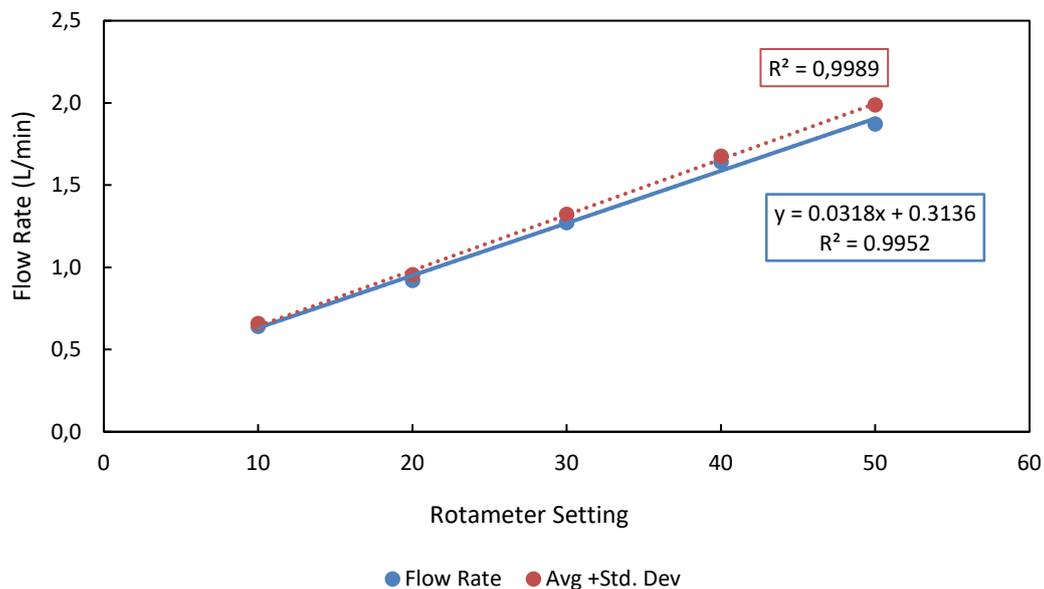
Figure 5-2. Relationship between flow rate and rotameter settings at 100 kPa.

The calibration experiments showed a linear relationship with a good correlation coefficient between flow rate and rotameter settings (R^2 = 0.9989), meaning that it is possible to interpolate the graph to predict the flow rate if different flow rates at those rotameters are to be determined. The standard deviation was also low throughout all experiments but would increase slightly with flow rate.

5.2.4.2 Ozone quantification

From the iodometric titration method the average concentration of ozone in the gas exciting the reactor was found to be 2.6 mg/L (σ = 0.32, % error = 12.11) for 5 of the 200 mL titrations described in the experimental procedure. During the experiment the first titration was overshot and because the volume used could not be determined with confidence, the data was excluded. The rest of the experiments delivered consistent results even though human error in the titration was an initial concern. Further variation in the result were attributed to the difficulty in simultaneously setting the pressure regulator and the rotameter accurately, since these variables influence one another and had to be set using analog knobs. This challenge was eliminated with the availability of the oxygen concentrator because it has a calibrated flow meter installed and therefore, human error is minimised.

5.2.4.3 Preliminary Reactor Optimisation

The ozone concentration was optimised by changing one independent variable-at-a-time (OVAT) (frequency, voltage, flow rate and tube length) to evaluate their influence on the dependent variable (ozone concentration). The run time was kept constant most of the time (at 10 minutes) and only reduced to 5 minutes after the maximum ozone concentration was obtained, under the same optimal conditions to assess how quickly ozone is produced in the system. It was then noticed that the ozone concentration in the water at 5 and 10 minutes of ozonation is roughly the same. However, longer run times might be needed to effectively disinfect wastewater but must be tested during later investigation phases of the project. The preliminary plasma reactor operating parameters for optimal ozone dosage is presented in Table 5-2.

Table 5-2. Summary of preliminary optimal reactor conditions.

SN	Variable	Value
1	Flow Rate	1.27 L/min
2	Applied Voltage	19 kV
3	Frequency	2 kHz
4	Run time	10 min
5	Regulator Pressure	100 kPa
6	Tube Lengths	0.5 m

	1.2	**MG/L**
Ozone Concentration		

5.2.4.4 Response Surface Design - Box Behnken Ozone Optimisation

After the ozone concentration was determined in the preliminary experiments by changing only one- factor-at-a-time (OFAT) the results were validated by carrying out a parametric scan, also known as a factorial design experiment, to reoptimise for ozone concentration in water. JMP® statistical software was used to design a Response Surface Methodology Box-Behnken experiment with 3 factors, each with 3 levels and ozone concentration as the response. As described in the experimental procedure, only certain runs from the design were replicated. The replicates were selected based on previous experimental observation and knowledge that high voltage is needed to generate discharge and therefore high ozone. High frequencies again generate

heat which is unfavourable conditions for ozone as ozone decay increases with increasing temperatures. Higher flow rates also imply more oxygen is delivered to the system, so more ozone should be generated if the system is working efficiently. Three sets of replicates were selected with the fourth replica beginning, the centre point being level 0 for each factor.

For part (a) explained in the experimental procedure the parameters (flow rate = 1.27 L/min, applied voltage = 19.0 kV and frequency = 2.00 kHz) used to get the highest ozone concentration during preliminary experiments could however not be replicated as no discharge formed at 19 kV, thus the instrument setting was adjusted to 20 kV. The ozone concentration was then measured for 20 minutes at 4 different time intervals as presented in Table 5-3.

Table 5-3. Data for testing the preliminary ozonation optimisation results validity using parameter; flow rate= 1.27 L/min, applied voltage = 20.0 kV and frequency = 2.00 kHz.

Time (min)	Ozone Conc. (mg/L)	Dilution factor	Actual Ozone Conc. (mg/L)	Volume used to measure ozone (mL)
	Over Range	N/A	N/A	10
5	0.71	2	1.42	8
10	0.72	2	1.44	8
15	0.95	2	1.90	8
20	0.36	5	1.80	10
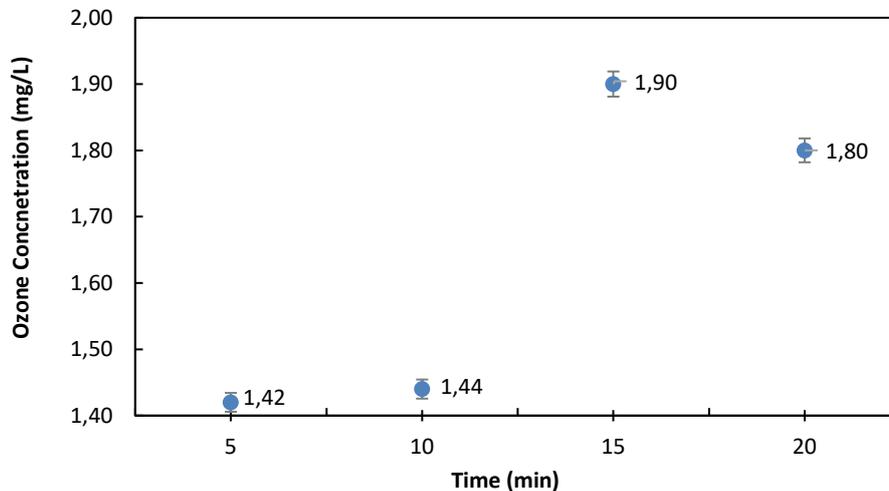
Figure 5-3. Validation of preliminary ozonation optimisation results and Determination of run times

After 5 minutes of ozonating a DI (deionised) water sample, the concentration of ozone measured on the Lovibond SpectroDirect UV-VIS was measured over-ranged. This sample was kept and, after the 20 minutes total run time, was diluted with a x2 dilution factor to obtain the result of 1.42 mg/L of ozone. After observing that the concentration is out of the detection limit of the SpectroDirect, the dilution factor for all subsequent measurements was used as seen necessary. For the x2 dilution, 4.0 mL sample and DI water were used respectively giving a total volume of 8 mL, which exactly reached the 10 mL mark on the test vials. However, for the x5 dilution factor, 2 mL sample and 8 mL DI water were used giving a total volume of 10 mL, which

might have a slight influence on the final concentration reading obtained. The concentration after 20 min of treatment was 1.8 mg/L, and lower than at 15 min of treatment, which is 1.90 mg/L, but this can however be because a larger volume of sample was used. For all future ozone concentration measurements, the final volumes will be kept constant at 10 mL as instructed in the Lovibond SpectroDirect UV-VIS manual.

The ozone concentrations obtained from this experiment was slightly higher at 10 min of treatment time (1.44 mg/L) compared to the maximum of 1.30 mg/L obtained during the preliminary experiments, which is expected as a higher voltage is used. When increasing the reaction time from 10 – 15 min, the ozone transferred from the gas phase into the water also increased from 55% to 73%. The experiments were carried out at $\pm15.5℃$ compared to 25℃ because ozone solubility and half-life increase as temperature decrease, which might have played a role in the slight increase in the ozone concentration (Galdeano et al., 2018, Kim et al., 2023).

After testing the preliminary experimental optimum conditions, and obtaining different results, new levels were identified for the factorial design shown in **Table 5-4** below. The maximum factor parameter for flow rate and applied voltages was then tested against all frequencies to check whether the system could withstand these conditions for a maximum run time of 20 minutes because a longer run time gives higher ozone concentration based on the previous experiments' results. The results for testing the capacity of the plasma reactor under established optimal conditions are given in **Table 5-5.**

The main purpose of this experiment was to ensure the setup can endure all reaction conditions for the upcoming runs as designed by the JMP software which was proven to be successful. It also confirms the prediction that with higher frequency, lower concentrations of ozone will be generated.

Table 5-4. Factorial design factors and levels

Levels	Factors		
	Flow Rate (L/min)	Applied Voltage (kV)	Frequency (kHz)
-1	1.27	20	2
0	1.64	21	3
1	1.87	22	4

Table 5-5. Results for testing capacity of the plasma reactor set-up

SN	Flow Rate (L/min)	Applied Voltage (kV)	Frequency (kHz)	Ozone Conc. x2 dilution (mg/L)	Ozone Conc. (mg/L)	Temp. Before (°C)	Temp. After (°C)
1	1.87	22	4	0.09	**0.18**	20.5	18.5
2	1.87	22	3	0.39	**0.78**	19.5	18.0
3	1.87	22	2	0.61	**1.22**	20.0	18.0

Table 5-6. Response surface design - Box Behnken experimental runs and results

JMP	Flow	kV	Freq.	Ozone Conc. x2 dilution (mg/L)	Ozone Conc. (mg/L)	Temp Before (°C)	Temp After (°C)
(+0-)	50	21	2	0.41	**0.82**	20.00	18.50
0	40	21	3	0.18	**0.36**	20.50	18.75
(-0-)	30	21	2	0.44	**0.88**	20.50	18.50
(-0+)	30	21	4	0.08	**0.16**	20.50	19.00
0	40	21	3	0.26	**0.52**	20.50	18.50

JMP	Flow	kV	Freq.	Ozone Conc. x2 dilution (mg/L)	Ozone Conc. (mg/L)	Temp Before (°C)	Temp After (°C)
(0-+)	40	20	4	0.06	**0.12**	20.50	18.50
(+-0)	50	20	3	0.21	**0.42**	20.00	18.00
(+0+)	50	21	4	0.05	**0.10**	21.00	19.00
(++0)	50	22	3	0.19	**0.38**	21.00	19.00
0	40	21	3	0.22	**0.44**	21.00	19.00
(0+-)	40	22	2	0.44	**0.88**	21.00	19.50
(--0)	30	20	3	0.11	**0.22**	21.00	19.50
(-+0)	30	22	3	0.14	**0.28**	21.00	19.50
(0--)	40	20	2	0.52	**1.04**	21.00	19.50
(0++)	40	22	4	0.05	**0.10**	21.00	19.25
(++0)	50	22	3	0.13	**0.26**	20.75	19.00
(+0-)	50	21	2	0.47	**0.94**	20.50	19.00
(0+-)	40	22	2	0.62	**1.24**	21.00	19.00
0	40	21	3	0.22	**0.44**	21.00	19.25

During the 20 min ozonation time of the DI water, temperature decreased on average by $\pm1.75℃$. From the data obtained, surface plots were used to determine the optimal ozone production by the plasma reactor. For the surface plot, the last run from **Table 5-5** was included (with flow rate = 1.87 L/min, Voltage = 22 kV and Frequency = 2 kHz) because this combination of levels was not part of the runs generated by the JMP design. This also delivered a high ozone concentration.

From the analysis of variance (ANOVA) and observed on the response surfaces, it seems that frequency has the only statistical value on the ozone concentration. In both **Figures 5-4** (a) and (b), the highest ozone concentration is obtained when the frequency is at the lowest level (-1), where neither flow (flow rate) nor kV (voltage) has an influence on the ozone concentration. However, in Figure 5-4 (c), where flow rate and voltage are used to create the response surface, the best conditions were obtained for the flow rate at level 0 and voltage at level 1. However, the voltage is very similar for this response surface.

Using **Table 5-4** in conjunction with the response surfaces generated, it can therefore be concluded that the optimal conditions for ozone production will be at a flow rate = 1.64 L/min, voltage = 22 kV and Frequency = 2 kHz for samples at 20°C

(a)

(b)
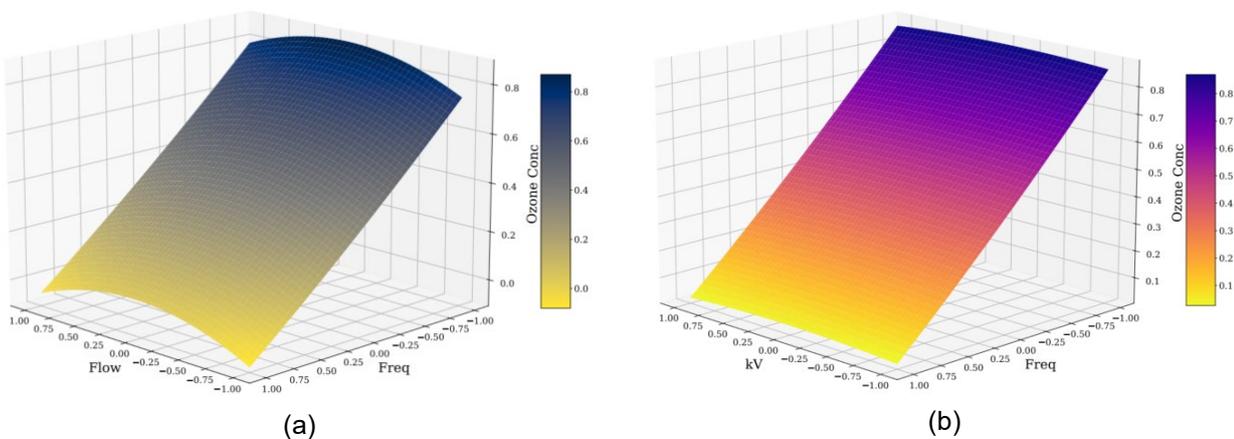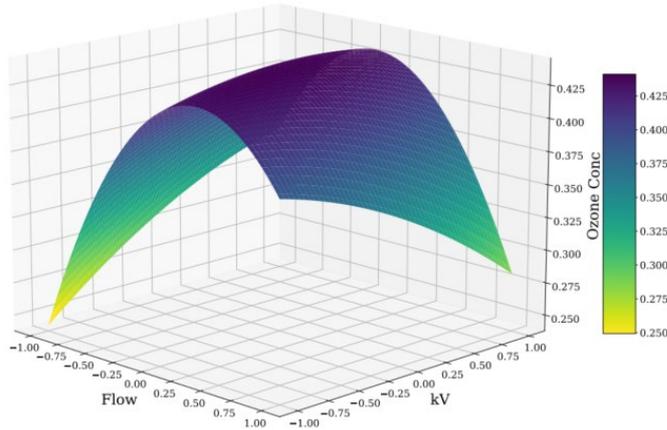
(C)

Figure 5-4. Surface plot to determine optimal ozone production by the plasma reactor (a) Flow rate vs Frequency, (b) Voltage vs. Frequency and (c) Flow rate vs Voltage.
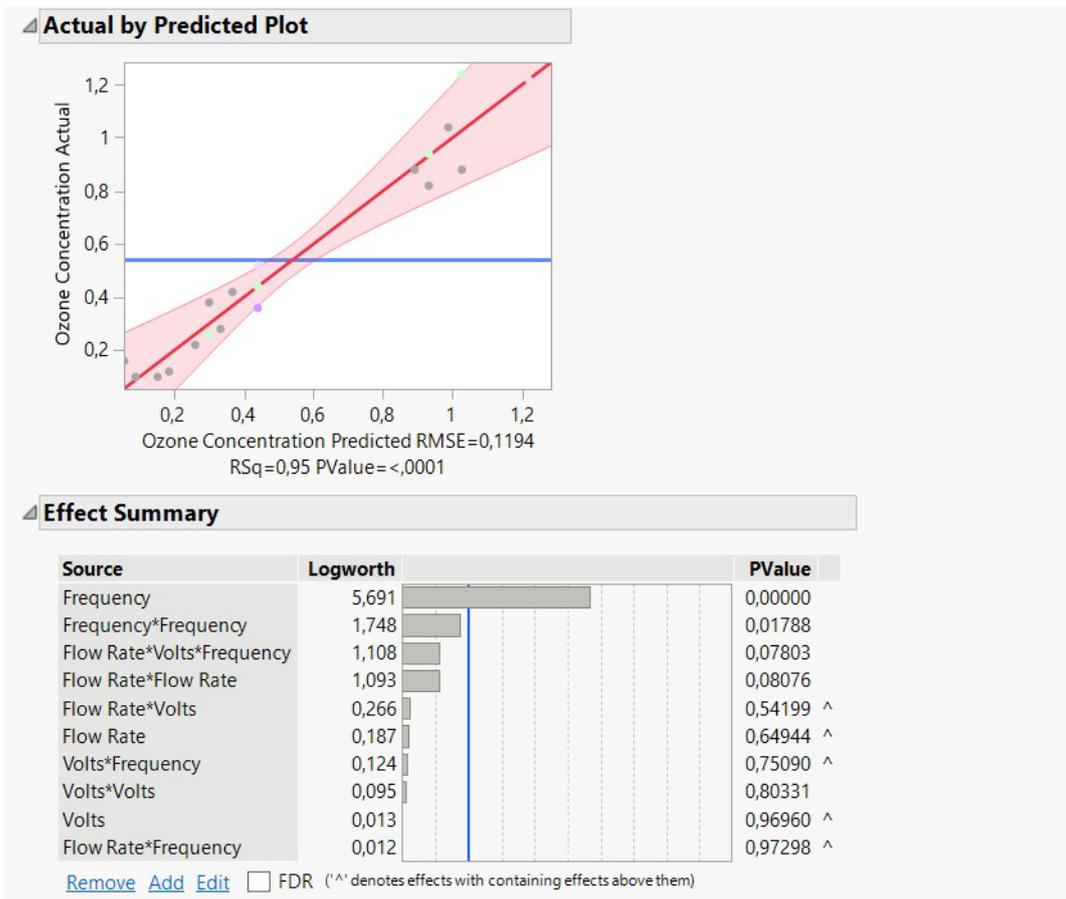
Figure 5-5. Plot of the experimental versus predicted responses for the ozone concentration.

5.2.5 Conclusions on the Effect of Experimental Conditions

The study of ozone in plasma-ozonation water contaminant removal method was premised on the evidence that under lower temperatures, aqueous ozone has a longer lifetime of up to 20 - 30 minutes at 20°C (Tomiyasu et al., 1985), compared to other plasma-generated chemical oxidants with lifespans of the orders of nano-, micro- and milliseconds. This study utilised a smaller reactor R1 (30 mm x 300 mm x 2.3 mm tube). The gas flow rate (in L/min), voltage (in kV) and Frequency (in kHz) were consistently used as the three main

independent variables influencing ozone concentration under the described experimental conditions. Deionised (DI) water was utilised to study the aqueous ozone concentration, for which the ozone produced in gaseous plasma phase was diffused it (DI water).

The activities included (i) calibration of the Rotameter (oxygen flow regulator), (ii) plasma ozone quantification, and (iii) establishing optimal reactor operating conditions for optimal ozone production. The calibration of the rotameter (to regulate oxygen flow) showed a linear relationship with a good correlation coefficient between flow rate and Rotameter settings (of $R^2 = 0.9989$). This implied that with given Rotameter settings (including the range 10 – 50), it is possible to predict the oxygen flow rate. The plasma-generated aqueous ozone was quantified using the iodometric titration method. The gas flow rate (in L/min), voltage (in kV) and Frequency (in kHz) were consistently used as the three main independent variables influencing ozone concentration under the defined experimental conditions. The JMP statistical software was used to design a Response Surface – Box-Behnken experiment with 3 factors, each with 3 levels and ozone concentration as the response. From the investigations, it is concluded that the optimal conditions for ozone production will be at a flow rate = 1.64 L/min, voltage = 22 kV and Frequency = 2 kHz for samples at 20 ℃. Based on the evaluation of the results, it can be concluded that only frequency is of statistical significance based on the response surfaces. This was not expected, because generally, a higher voltage would lead to more ozone generation because of the associated higher plasma discharge. The results also depict how important the role temperature plays in the generation/solubility and half-life of ozone. This is because with higher frequencies, more heat is generated, and dissociation of ozone becomes faster.

These experimental results gave valuable ideas for further investigations using the same reactor type. Testing of the determined conditions was made on real surface water. The study on how the optimal conditions perform in treating real water samples to comply with WHO standards and SANS 241 were carried out, including the reduction of TOC, COD, and TSS in such real water samples by plasma ozone. However, the target pollutants are the microbiological contaminants (faecal coliforms and *E. coli*) and the system performance evaluation was primarily based on these microbiological contaminants.

5.3 EFFICIENCY/EFFICACY OF TREATMENT TECHNOLOGY – WHO CRITERIA AND SANS 241

5.3.1 Plasma Reactions

The gas type was observed earlier to be among the reactor-influencing conditions because it affects the nature and number of active oxidants (active and reactive species) generated by a plasma system. The energetic electrons due to the electric field will dissociate the feed gas, depending on the action phase, into a wide group of species with varying chemistry that can be treated, and also influence the water quality characteristics. Air consists of nitrogen (78%), oxygen (21%), other gases (1%) and water vapour, by volume, implying that the air plasma region will consist essentially of the reactive nitrogen species (RNS), reactive oxygen species (ROS) and other plasma agents such as UV light as shown in Figure 5-6 (Takamatsu et al., 2014, Iya-Sou et al., 2021). In air plasma, the presence of NO_X (nitric oxides) leads to RNS such as HNO_3 (nitric acid), which lowers the pH of water. This makes the plasma feed gas a fundamental aspect in plasma water treatment. In our

design, this has been overcome by producing oxygen from the PSA O_2 generator, which eliminates the NO_X species. Oxygen plasma in gas and aqueous phase will produce ROS consisting of O_3, H_2O_2 (molecules), O^+, O^-, H^- (ions) and $\cdot OH$, $\cdot O$, $\cdot H$, $\cdot OH$, $HO_3\cdot$ (radicals) and $O_2^{-\cdot}$, $O_3^{-\cdot}$ (radical ions).
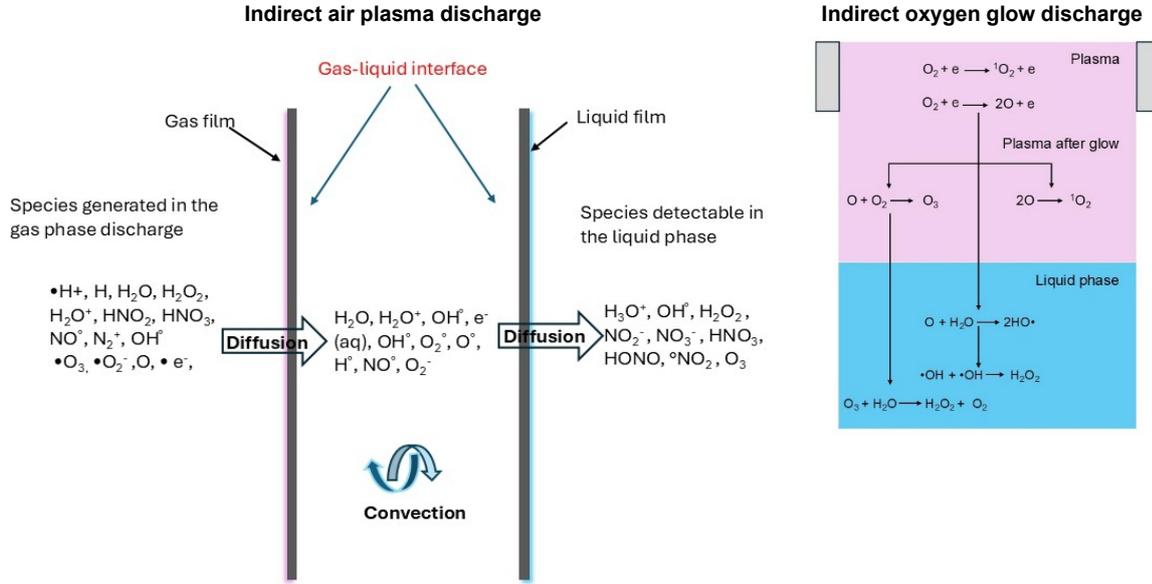
Figure 5-6. Schematic showing most of the reactive nitrogen and oxygen species generated in indirect air and oxygen plasma discharges (Adapted from: (Takamatsu et al., 2014, Iya-Sou et al., 2021))

5.3.1.1 Oxygen Plasma Reactions

In oxygen plasma gas phase kinetics, the electron impact dissociation of molecular oxygen (O_2) generates ground state atom O (^{3}P), ions (O^-, O^+ and O_2^+), and O* (metastable O^1D) (El-Aragi, 2009) and physical phenomenon such as shock waves and UV photons. Ozone is formed in two stages as described by equations 1 to 4, where the inelastic electron impact dissociation of molecular oxygen generates oxygen free radicals, which progressively react to produce ozone (O_3) (Benstaali et al., 1998, Nijdam et al., 2012, Merouani et al., 2015). Ozone (O_3) is a long-lived species compared to lifespans of other oxygen-free radicals of orders of microseconds.

$$e + O_2 \rightarrow O^+ + O + 2e^- \tag{1}$$

$$e + O_2 \rightarrow O + O + e \tag{2}$$

$$e + O_2 \rightarrow O^- + O \tag{3}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{4}$$

where M is an arbitrary third-body collider (O_2 or N_2 in case of air plasma).

In aqueous phase, a number of reactions occur in the plasma region depending on the reactor operating conditions. The possible O_2 plasma aqueous phase reactions are given in equations 5 – 23 (Takamatsu et al., 2014, Cui et al., 2018, Murugesan et al., 2020b, Zeghioud et al., 2020) producing reactive oxygen species (ROS) used to treat water in addition to UV photons and shock waves.

The reactive ROS generated in the medium such as hydrogen peroxide (H_2O_2), ozone (O_3) and hydroxyl radical (•OH). The others from oxygen plasma are singlet oxygen ($^1O_2$), superoxide ion ($O_2^{•-}$), peroxyl radical (ROO•) and hydroperoxyl ($HO_2^•$). The presence of nitrates (NO_3^-), nitrites (NO_2^-) and other inorganic ions in the water under treatment can also initiate other reactions, some contributing to the breakdown of pollutants but may also change the water's chemical characteristics.

$$e^{-*} + H_2O \rightarrow H^• + HO^• + e^- \tag{5}$$
$$e^{-*} + H_2O \rightarrow H_2O^+ + 2e^- \tag{6}$$
$$H_2O + H_2O^+ \rightarrow H_3O^+ + HO^• \tag{7}$$
$$e^{-*} + H_2O \rightarrow H_2O^* + e^- \tag{8}$$
$$H_2O + H_2O^* \rightarrow H_2O + HO^• + H^• \tag{9}$$
$$H_2O + H_2O^* \rightarrow H_2O + O^• + H_2 \tag{10}$$
$$H_2O + H_2O^* \rightarrow H_2O + O^• + 2H^• \tag{11}$$
$$O^• + H_2O \rightarrow 2HO^• \tag{12}$$
$$O^• + O_2 \rightarrow O_3 \tag{13}$$
$$HO^{•-} + O_3 \rightarrow H_2O^• + O_2^- \tag{14}$$
$$O_2^- + H^+ + O_3 \rightarrow HO_3^• + O_2 \tag{15}$$
$$HO_3^• \rightarrow HO^• + O_2 \tag{16}$$
$$HO^• + HO^• \rightarrow H_2O_2 \tag{17}$$
$$2 H_2O \rightarrow H_2O_2 + H_2 \tag{18}$$
$$e_{aq}^- + H_2O_2 \rightarrow HO^• + HO^{•-} \tag{19}$$
$$H_2O_2 + H^• \rightarrow H_2O + HO^• \tag{20}$$
$$H_2O_2 + O_3 \rightarrow H_2O^• + O_2 + HO^• \tag{21}$$
$$H_2O_2 + hv \rightarrow HO^• + HO^• \tag{22}$$
$$H_2O + hv \rightarrow H^• + HO^• \tag{23}$$
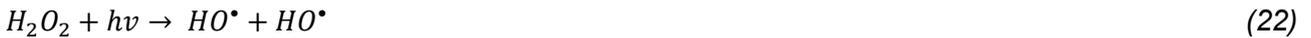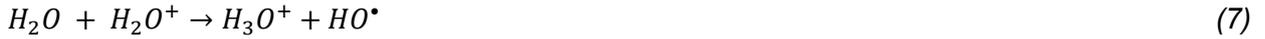
Energetic electron state.

5.3.2 Reactor Conditions and Water Treatment Experiments

In the previous section, during the DOE to determine the optimal parameters for ozone production, the design screening resulted in the most influential parameters as the applied voltage, repetitive frequency and gas flow rate. These guided the choice of conditions for surface water treatment to test the efficiency/efficacy of treatment technology and to evaluate it based on WHO performance criteria and SANS 241. However, because reactor R1 was not designed to accommodate water flow inside the tubing, R2 (40 mm x 300 mm x 2.3 mm glass tube) was utilised because it's able to allow ozone production, batch mode operation and continuous liquid flow. Even then, being two investigators, each needed a reactor in order to complete the research tasks in time to achieve the project objectives.

It should also be noted that plasma reactors may be influenced by not only the mentioned parameters but also laboratory physical environment, such as movement of connections and pipe tubings. Thus, it was sometimes necessary to determine new parameters for surface water treatment using the second reactor (R2).

The following investigations on treatment of surface water have been carried out:

a) Treatment of surface water from a nearby stream (**LC De Villiers**, Sports Centre) hereafter described and code named as **LC De Villiers Stream**. Sampling and treatment were carried out two times, and the results have been compared;

b) Water quality analysis and plasma-ozonation of water treatment plant (WTP) final drinking water from the storage reservoir destined to the community distribution network, hereafter described with acronym **WTP**;

c) Water quality analysis and plasma-ozonation treatment of community tap water (TAP), randomly selected in a certain community and hereafter described with the acronym **TAP**.

d) Water quality analysis, plasma-ozonation and other methods of treatment of surface water (**Mutshedzi River**) and groundwater (**Manyii and Mamvuka springs**) located in Limpopo province.

5.3.2.1 LC De Villiers Stream Surface Water Treatment

a) Initial water treatment experiments for LC De Villiers stream

(i) Reactor conditions for LC De Villiers stream water treatment

It should also be noted that plasma reactors may be influenced by not only the mentioned parameters but also the laboratory physical environment such as movement of connections and pipe tubings. Thus, it was necessary to determine new parameters (**Table 5-7**) for surface water treatment using the second reactor (R2), consisting of a coaxial 40 mm x 300 mm x 2.3 mm borosilicate glass tube, a high voltage electrode as a spiked steel rod and copper tape around the glass tube. In this case, the reactor (R2) was powered by an HV-pulsed DC power supply unit (HV Pulsed DC PSU), the same PSU utilised by R1.

Table 0-7. Reactor operating conditions for surface water treatment

Experimental condition	Parameter Value (Unit)
Solution volume	1100 mL
Oxygen gas flow rate	8 L/min
Water flow rate	400 mL/min
Applied voltage	16 kV
Frequency	2.0 kHz
Plasma discharge time	30 minutes
Water Treatment time	30 minutes
Reactor mode	Continuous flow-recirculating mode

The oxygen was synthesised by the PSA OC (Wassertec Ozone Systems, South Africa). The air was supplied by a compressor at a pressure of 1 bar and purified by two filters, 40 microns (Festo, South Africa) followed by a 0.01-micron coalescing filter (Parker, England by Compressed Air Driers and Filters, South Africa) to remove any oil particles and moisture. The input voltage and frequency were determined by an HV-Pulsed DC PSU (Jeenel Technologies Services Ltd Pty, Boksburg, South Africa). These experiments were carried out using power from electrical sockets because by then, solar power had not been installed due to challenges faced by GreenHouse Solar Energy, South Africa, the procured supplier with regards to the housing container for the solar system and the plasma-reactor units as well as accessories.

(ii)   LC De Villiers water sampling

The selected surface water source for this further preliminary testing and investigation was obtained from the University of Pretoria, LC De Villiers Sports Centre stream (Figure 3-1) at the Waybridge on the downstream side at approximately Latitude: -25.747°, Longitude: 28.248°. The natural stream feeds a small storage dam. The source was selected because it is the closest to the Chemical Engineering Laboratory of the University of Pretoria to test the system performance notably the PSA OC and the modified plasma reactor (R2). Therefore, 10 litres were collected from the stream, of which 2.5 litres were delivered to the independent analytical laboratory for testing together with 1 Litre of the treated water sample. The balance of 6.5 litres was stored in the UP Laboratory cold room at 4°C for use in additional experiments.

| (a) | (b) |

Figure 5-7. LC De Villiers Sports Centre Stream (a) – Upstream and (b) – Downstream at Sampling Point

(iii)   Water treatment experiment

The water flowing at a rate of 400 mL/min was continuously recirculated by a peristaltic pump between the water chamber and the plasma reactor region containing chemical oxidants, including radicals, molecules, ions and additional physical phenomena such as shock waves. The oxygen at a flow rate of 8 L/min from the PSA OC is introduced together with water into the reactor gap. This flow rate was selected because of the ability to produce a prominent discharge (**Figure 3-2a**) for the HV Pulsed DC PSU employed for the experiment. The oxygen/water mixture is dissociated by energetic electrons within the plasma region, generating a wide group of reactive oxygen species as shown in Equations 1 to 23.

The reactor operated in continuous flow mode - whereby the water under treatment is passed through the plasma region, with continuous recirculation for 30 minutes by means of a peristaltic pump. The water was introduced into the plasma region by means of a micro-mist spray nozzle (Hydroponic, South Africa) (**Figure 5-8 b**). After 30 minutes of treatment, the surface water sample was transferred to a clean, sanitised dry container and taken together with the untreated (raw water) sample to an independent laboratory (Waterlab (Pty) Ltd, South Africa) for analytical testing.

a)

b)
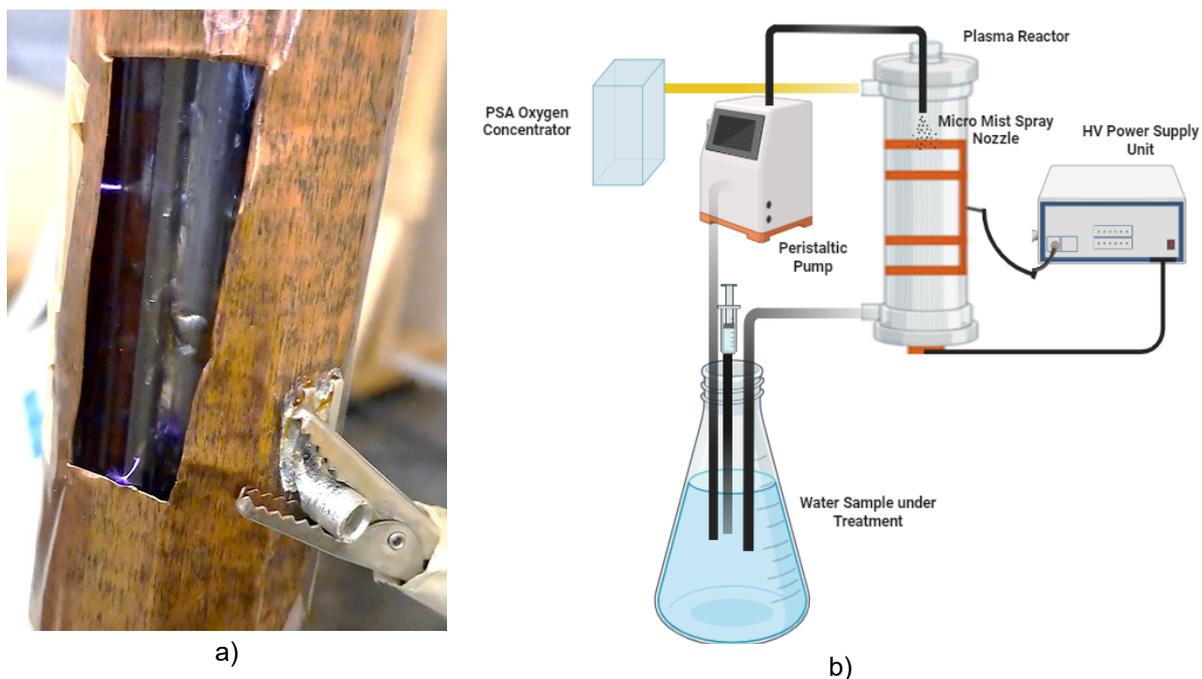
Figure 5-8. Reactor set-up for water treatment experiment – a) plasma discharge and b) storage for the water–circulating process.

(iv)   Initial Performance of plasma technology based on WHO and SANS 241 criteria

Among the project objectives included performance evaluation of the plasma technology on real surface water against the WHO guidelines and SANS 241 (under deliverable 4). **Table 5-8** shows the analysis of raw water and treated sample of LC De Villiers Sports Centre stream for selected parameters as a preliminary investigation. The detailed results as obtained from the analytical laboratory (Waterlab (Pty) Ltd) are given in Appendix B-1. This experiment was considered to be one of the initial checks of the system performance where only selected key parameters (SANS Abbreviated) have been analysed.

In general, some authors have listed the types of water quality parameters that we suggest to be of primary interest during water quality assessment as (i) physical parameters including turbidity, temperature, colour, taste and odour, solids and electrical conductivity, (ii) the chemical parameters to include pH, acidity, alkalinity, chloride, chlorine residual, sulfate (sulphate), nitrogen, fluoride, iron and manganese, copper and zinc, hardness, dissolved oxygen, biochemical oxygen demand (BOD), chemical oxygen demand (COD), toxic inorganic substances, toxic organic substances and radioactive substance, and (iii) the biological parameters to consist of bacteria, algae, viruses and protozoa (Jiang et al., 2014).

However, most bottled water commercially available currently on the South African consumer market contains the following elements based on the production company's industry analytical measurements: calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl^-), sulphate (SO_4^{2-}), alkalinity ($CaCO_3$), nitrate (as N), fluoride (F), iron (Fe), aluminium (Al), total dissolved solids (TDS) and pH.

The aforementioned quality parameters, together with the SANS, 241 and WHO guidelines provide useful basis for discussing the results of the treated surface water of the LC De Villiers Sports Centre stream.

The study of the analytical test results of untreated and treated water of LC De Villiers Sports Centre stream shows that most of the parameters of the treated water comply with the SANS 241, 2015 and WHO guidelines. The pH, conductivity, total dissolved solids (TDS), colour, turbidity, chlorides, sulphates and fluoride are in acceptable limits with respect to SANS 241 and WHO after treatment. Other parameters including sodium,

potassium, calcium, magnesium and aluminium were also in permissible limits (based on SANS, 2015) and WHO.

However, some treated water parameters, specifically nitrates (NO_3^-), nitrites (NO_2^-) and E. *coli* were above the minimum permissible values (**Table 5-8**). The untreated/raw water has a high E. *coli* load of 770 MPN/100 mL which could be a result of the stream collecting animal waste from adjacent land. Plasma reduced the E. *coli* to 6 MPN/100 mL after 30 minutes of treatment. Further reduction of the load to undetectable levels (0 or < 1) required, as one of the options, increasing the plasma discharge or treatment time (to an estimated of 60 minutes) than the 30 minutes applied, for such an *E. coli* laden stream.

The nitrates increased from 0.9 mg/L (untreated water) to 6.0 mg/L (treated water), had been thought to be possible ingress of air containing nitrogen (N_2) into the reactor leading to generation of the NOx species in the plasma region. The reactor was tightened by checking and fixing the reactor end caps, connecting tubes and joints such as the connection from the oxygen concentrator (PSA, OC or OX10) to the top end cap and the treatment bottle, but the challenge has persisted and will be investigated further in future.

Table 5-8. Summary of main analytical water quality test results for LC De Villiers Sports Centre Stream

Parameter	Unit	Untreated water	Treated	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.
pH - Value @ 25 ºC		7.5	7.6	≥5 to ≤ 9.7	6.5 – 9.5	Operational	(WHO, 2007)
Electrical Conductivity @ 25°C	mS/m	34.2	34.7	≤170	≤170 / ≤2700 µS/cm	Aesthetic /Operational	(WHO, 2018a)
Total Dissolved Solids @ 180°C	mg/L	332	328	≤1200	600 – 1000	Acceptability	(WHO, 2022b)
Colour	PtCo Units	16	10	≤15	15 TCU (True Colour Units)	Acceptability	(WHO, 2022b)
Turbidity	N.T.U	9.2	4.7	≤1 / ≤5	<1 / <5 NTU	Aesthetic	(WHO, 2017)
Chloride as Cl	mg/L	32	32	≤300	≤ 250	Acceptability	(WHO, 2003b)
Sulphate as SO$_4$	mg/L	18	24	≤500 / ≤250	≤ 500	Acceptability	(WHO, 2004b)
Fluoride as F	mg/L	0.4	0.2	≤1.5	1.5	Chronic health	(WHO, 2022b)
Nitrate as N	mg/L	0.9	6.0	≤11	50 mg/L (as NO$_3^-$)[#2]	Acute health	(WHO, 2022b)
Nitrite as N	Mg/L	0.08	1.5	≤0.9	3 mg/L (as NO$_3^-$)[#3]	Acute health	(WHO, 2022b)
Combined Nitrate & Nitrite	mg/L	0.2	2.3	≤1	≤1 (ratio)[#4]	Acute health	(WHO, 2022b)
Total Organic Carbon as C	mg/L	4.0	5.3	≤10	Not mentioned		
E. *coli*	(MPN/100 mL)	770	6	Not detected	Not be detectable in any 100 mL	Acute health	(WHO, 2022b)
Free and Saline Ammonia as N	mg/L	0.2	0.2	≤1.5	≤35 (as Cation)	Acceptability	(WHO, 2003a, WHO, 2022b)
Sodium as Na	mg/L	13	13	≤200	≤200	Acceptability	(WHO, 2003d)
Aluminium as Al	µg/L	110	167	≤300	≤100 / ≤200	Operational	(WHO, 2010)
Copper as Cu	µg/L	<10	16	≤2000	≤2000	Operational /health	(WHO, 2004a)
Iron as Fe	µg/L	422	295	≤2000 / ≤300	≤300	Acceptability	(WHO, 2003c)
Lead as Pb	µg/L	1	1	≤10	≤10 (A)	Chronic health	(WHO, 2016a)
Manganese as Mn	µg/L	69	35	≤400 / ≤100	≤80 (P) (Total)	Chronic health / Acceptability	(WHO, 2022b)

A, P = WHO Provisional Guideline Value (WHO, 2022); *#1* = unit is same as column 2 from left if not specified; *#2* = nitrate can be converted to nitrate as N using: 1 mg/L as nitrate = 0.266 mg/L nitrate as N; *#3* = nitrite can be converted to nitrite as N using: 1 mg/L as nitrite = 0.304

Parameter	Unit	Untreated water	Treated	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.

*mg/L nitrite as N (WHO, 2022); **#4** = Combined nitrate plus nitrite: the sum of the ratios of the concentrations of each of nitrate and nitrite to its guideline value should not exceed 1.*

b) Second water treatment experiments for LC De Villiers stream

(i) Reactor conditions, sampling and treatment

In the second treatment of surface water from the LC De Villiers Sports Centre Stream was carried out with reactor R2 with a new set of reactor operating conditions (**Table 5-9**) derived after a number of preliminary parametric studies to determine the optimal electrical parameters. A different power source as HV AC PSU (high voltage alternating current power supply unit) was utilised, which relates well to the industrial or real energy supply for water works. The implemented conditions are presented in **Table 5-9.**

Table 0-9. Reactor operating conditions for surface water treatment

Experimental condition	Parameter Value (Unit)
Solution volume	1100 mL
Oxygen gas flow rate	8 L/min
Water flow rate	400 mL/min
Applied voltage	12 kV
Frequency	5.0 kHz
Plasma discharge time	60 minutes
Water Treatment time	60 minutes
Reactor mode	Continuous flow-recirculating mode

A second water sample was taken in November 2024 at the same location as before (as shown in **Figure 5-8**, at approx. Lat: -25.747°, Long: 28.248°). A volume of 5 litres was collected, from which 1100 mL was drawn and treated with plasma.

Plasma water treatment was carried out by the plasma through the interaction of the generated oxidants with the water plus other phenomenon in the plasma region. The runtime was 60 minutes, because in the previous experiment where the discharge time was 30 minutes, the initial E. *coli* load of 770 MPN/100 mL was not fully removed, 6 MPN/100 mL was detected in the treated water and failing to meet both WHO and SANS 241, 2015 requirements of no detection.

(ii) Performance evaluation of water treatment – Second Sample for LC De Villiers Stream

Both the raw (untreated) and plasma remediated water samples were delivered to the Environmental Pollution Laboratory (EPL), South Africa, an independent laboratory for quality analysis, and the results are presented in **Table 5-10**. The second sample was taken on the same stream, same location and treated under improved experimental conditions. However, in the previous analytical results, plasma reduced the high E. *coli* load of 770 MPN/100 mL to 6 MPN/100 mL after 30 minutes of treatment, which did not comply with undetectable levels (0 or < 1) required (WHO and SANS 241, 2015). In the second test, after increasing the treatment time to 60 minutes, the detected 450 colonies/100 mL in raw water was eliminated. Also, raw water total coliform load of 24000 colonies/100 mL was fully removed. This implies the plasma technology is able to improve the microbiological quality of drinking water.

The only challenge still under study is the issue of the nitrites and nitrates. In the 1st treatment and test, the nitrates increased from 0.9 mg/L (untreated water) to 6.0 mg/L (treated water), same as nitrites from 0.08 mg/L

to 1.5 mg/L. A similar trend has been observed from the treatment and testing of the second LC De Villiers sample, where the nitrates and nitrites of <0.5 mg/L and 0.17 mg/L, respectively, in the untreated sample increased to 11.62 mg/L (Nitrate) and 3.69 mg/L (nitrite) after treatment. This aspect will continue to be investigated in future.

Table 5-10. Comparison of microbiological parameters first (30 mins) and second (60 mins) plasma treatments

Parameter	Unit	Test 1 (30 mins)		Test 2 (60 mins)		SANS 241, 2015 Limits	WHO Guideline	Ref.
		Untreated	Treated	Untreated	Treated			
E. coli	# (MPN /100 mL	770	6	450	0	Not detected	Not be detectable in any 100 ml	(WHO, 2022b)
Total Coliforms	colonies/ 100 mL	-	-	24000	0	≤10	Not be detectable in any 100 ml	(WHO, 2022b)

 # 1 colony forming unit (CFU) / 100 mL is equivalent to 1 Most probable number (MPN)/ 100 mℓ

Table 5-11: Summary of main analytical water quality test results for LC De Villiers Sports Centre Stream (Second test)

Parameter	Unit	Untreated water	Treated	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.
pH - Value		8.08	8.36	≥5 to ≤ 9.7	6.5 – 9.5	Operational	(WHO, 2007)
Electrical Conductivity	mS/m	334	323	≤170	≤170 / ≤2700 µS/cm	Aesthetic /Operational	(WHO, 2018a)
Total Dissolved Solids	mg/L	233	204	≤1200	600 – 1000	Acceptability	(WHO, 2022b)
Colour	Hazen	62.83	76.51	≤15	15 TCU (True Colour Units same as Hazen)	Acceptability	(WHO, 2022b)
Turbidity	N.T.U	7.50	9.85	≤1 / ≤5	<1 / <5 NTU	Aesthetic	(WHO, 2017)
Chloride as Cl	mg/L	22.09	21.83	≤300	≤ 250	Acceptability	(WHO, 2003b)
Sulphate as SO$_4$	mg/L	18.07	13.19	≤500 / ≤250	≤ 500	Acceptability	(WHO, 2004b)
Fluoride as F	mg/L	0.23	0.32	≤1.5	1.5	Chronic health	(WHO, 2022b)
Nitrate as N	mg/L	<0.5	11.62	≤11	50 mg/L (as NO$_3^-$)[#2]	Acute health	(WHO, 2022b)
Nitrite as N	mg/L	0.17	3.69	≤0.9	3 mg/L (as NO$_3^-$)[#3]	Acute health	(WHO, 2022b)
Combined Nitrate & Nitrite	mg/L	<0.5	15.31	≤1	≤1 (ratio)[#4]	Acute health	(WHO, 2022b)
Total Organic Carbon as C	mg/L	<10	11.32	≤10	Not mentioned		
E. coli	(MPN/100 mL)	450	0	Not detected	Not be detectable in any 100 mL	Acute health	(WHO, 2022b)
Total coliforms	Colonies /100 mL	24000	0	≤10	Not be detectable in any 100 mL	Acute health	(WHO, 2022b)
Ammonia as N	mg/L	0.09	0.14	≤1.5	≤35 (as Cation)	Acceptability	(WHO, 2003a, WHO, 2022b)
Sodium as Na	mg/L	17.09	16.43	≤200	≤200	Acceptability	(WHO, 2003d)
Aluminium as Al	mg/L	0.19	0.07	≤300 µg/L	≤100 µg/L / ≤200 µg/L	Operational	(WHO, 2010)
Copper as Cu	mg/L	0.11	<0.05	≤2000 µg/L	≤2000 µg/L	Operational /health	(WHO, 2004a)
Iron as Fe	mg/L	0.90	0.42	≤2000 µg/L / ≤300 µg/L	≤300 µg/L	Acceptability	(WHO, 2003c)
Lead as Pb	mg/L	<0.05	<0.05	≤10 µg/L	≤10 µg/L(A)	Chronic health	(WHO, 2016a)

Parameter	Unit	Untreated water	Treated	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.
Manganese as Mn	mg/L	0.07	<0.05	≤400 µg/L / ≤100 µg/L	≤80 µg/L(P) (Total)	Chronic health / Acceptability	(WHO, 2022b)

A, P = WHO Provisional Guideline Value (WHO, 2022); *#1* = unit is same as column 2 from left if not specified; *#2* = nitrate can be converted to nitrate as N using: 1 mg/L as nitrate = 0.266 mg/L nitrate as N; *#3* = nitrite can be converted to nitrite as N using: 1 mg/L as nitrite = 0.304 mg/L nitrite as N (WHO, 2022); *#4* = Combined nitrate plus nitrite: the sum of the ratios of the concentrations of each of nitrate and nitrite to its guideline value should not exceed 1. For untreated is described as *"Free and Saline Ammonia as N"*.

5.3.2.2 Mutshedzi River and Spring Water (Mamvuka and Manyii springs)

a) Location, water sampling and study choice

Mutshedzi River is located between latitudes 22°56'44.3" S and 22°53'25.0" S, and longitudes 30°09'50.0" E and 30°08'19.6" E in Nzhelele, Makhado local municipality, situated in the Vhembe district of the Limpopo Province, South Africa. Annual precipitation in this region varies from 300 mm in the Nzhelele Valley to 1000 mm on the slopes of the Soutpansberg (Kapangaziwiri et al., 2021). Temperatures range from 8°C to 31°C throughout the year, with an average of 21°C (Time and Date, 2024). The area has a semi-arid climate, with seasonal rainfall occurring during the summer and spring months (September to March).

Mamvuka (22˚ 86' 42" S, 29˚ 93' 46" E), and Manyii (22˚ 87' 16" S, 29˚ 94' 33" E) villages are situated at Nzhelele in the Vhembe district within the Limpopo Province. Vhembe district comprises four local municipalities, namely: Collins Chabane, Makhado, Musina, and Thulamela, and these villages are in the Makhado municipality. These areas are in the Savannah biome, which has low-veld bushveld vegetation. They have wet and hot summers and dry and cool winters, and receive high rainfall in the summer seasons (September to March). The temperatures in these communities range from 13°C to 31°C.

Mutshedzi River (surface water) and Manyii and Mamvuka Springs (groundwater) are sources of water to the close communities for domestic use, including drinking. The investigated sample was collected from the sources on 12th November 2024 and stored in a cold room at 4˚C. It was appreciated that the sources are typical of rural drinking/domestic use water sources and therefore well-fitting the objectives of the project. Many rural sources may show acceptable physical quality expressed by key parameters such as turbidity being within permissible limits, as exhibited by Mutshedzi River in the dry season with a turbidity of 0.86-4.67 NTU, the period when the river flow is predominantly baseflow. The same with spring water having turbidity of 0.13-5.61 NTU (dry season) and 0.03-6.53 NTU (wet season).

The major challenge with such sources would be the chemical and, more critically, the microbiological quality that could lead to disease spread. Thus, the microbiological parameters are the primary treatment focus for which different methods have been tested to compare with plasma performance.

b) Reactor conditions for water treatment

Similar reactor conditions as for the second treatment of the LC De Villiers stream were implemented as described in **Table 5-9.** The HV AC PSU fully utilised the solar energy supply for the three experiments for the surface (Mutshedzi River) and groundwater (Manyii and Mamvuka springs). These sources were found to have excessive microbiological contamination explained by the high bacterial loads. Mutshedzi River had at testing time, *E. coli* levels ranging from 1750 -7175 CFU/100 mL (dry season) and from 1750-9925 CFU/100 mL (wet season), while spring water was contaminated with *E. coli* pathogens ranging from 140-893 CFU/100 mL (dry

season) and 95-2340 CFU/100 mL (wet season). This is very important for testing the performance of the plasma-ozonation device with respect to removal of bacteria from drinking water. The detailed raw water quality characteristics of Mutshedzi River, Mamvuka and Manyii springs are presented in **Tables 5-12, 5-13** and **5-14,** respectively.

Table 5-12. Physicochemical and microbial parameters of Mutshedzi River in dry and wet seasons.

Parameters	Dry season	Wet season	WHO	SANS 241, 2015
pH	6.92 - 7.82	6.94 - 7.99	≥6.5 - ≤8.5	≥5.0 - ≤9.7
EC (µs/cm)	65 - 533	72 - 555	-	≤1700
TDS (mg/l)	33 - 270	36 - 278	≤1000	≤1200
Turbidity (NTU)	0.86 – 4.67	0.26 – **118.76**	≤5	≤5
Temperature (ºC)	20.2 – 25.2	22.1 – 25.3	-	-
Heavy Metals				
Aluminium (mg/l)	0.135 – 0.235	0.11 – **0.33**	-	≤0.3
Antimony (mg/l)	BDL	BDL	≤0.02	≤0.02
Arsenic (mg/l)	**0.036 – 0.060**	BDL	≤0.01	≤0.01
Cadmium (mg/l)	BDL	BDL	≤0.003	≤0.003
Chromium (mg/l)	**0.197**	BDL	≤0.05	≤0.05
Copper (mg/l)	0.130 – 0.455	0.05 – 0.12	-	≤2
Iron (mg/l)	0.130 – 1.900	0.26 – **2.22**	≤2	≤2
Lead (mg/l)	0.001	**0.05**	≤0.01	≤0.01
Manganese (mg/l)	0.075 – **0.850**	0.07- 0.23	-	≤0.4
Mercury (mg/l)	0.002	BDL	≤0.006	≤0.006
Nickel (mg/l)	**0.093**	BDL	≤0.07	≤0.07
Selenium (mg/l)	0.001 – 0.002	BDL	≤0.04	≤0.04
Zinc (mg/l)	0.060 – 0.294	0.05 – 0.12	-	≤3
Anions				
Chloride (mg/l)	4.74 – 27.81	5.88 – 141.2	-	≤300
Fluoride (mg/l)	0.06 – 0.47	0.06 – 0.87	≤1.5	≤1.5
Nitrate (mg/l)	BDL	BDL	≤50	≤11
Nitrite (mg/l)	BDL	BDL	≤3	≤0.9
Phosphate (mg/l)	0.22 – 1.01	2.03 – 6.88	-	-
Sulphate (mg/l)	2.44 – 5.00	BDL	-	≤500
Microbial				
E coli (CFU/100ml)	**1750 - 7175**	**1750 - 9925**	0	0
Total coliform (CFU/100ml)	**4725 - 17925**	**10150 - 45950**	0	≤10

*Notes: *BDL - Below detection limit, *Dry season- average of July and August, *Wet season- average of September and November.*

Table 5-13. Physicochemical and Microbiological parameters for Mamvuka spring water in the dry and wet seasons.

Parameters	Dry season	Wet season	WHO	SANS 241
Physical				
Temperature (ºC)	25.7-29.30	23.4-27.8	-	-
Conductivity (µS/cm)	115-122	119-125	-	≤1700
Total Dissolved Solids (mg/l)	55-62	11-52	-	≤1200
Turbidity (NTU)	0.28-1.13	0.09-0.91	≤5	≤5
pH (at 25 ºC)	5.55-5.71	5.67-5.84	≥6.5 to ≤8.5	≥5 to ≤9.7
Chemical				
Nitrate (mg/L)	1.36-1.44	1.08	≤50	≤11
Nitrite (mg/L)	BDL	BDL	≤3	≤0.9
Sulphate (mg/L)	BDL	5.73	-	≤250

Parameters	Dry season	Wet season	WHO	SANS 241
Phosphate(mg/L)	BDL	BDL	-	-
Fluoride (mg/L)	0.06-0.07	0.05-0.08	≤1.5	≤1.5
Chloride (mg/L)	11.26-127.6	9.71-22.87	≤250	≤300
Zinc (mg/L)	0.05	0.08-0.13	-	≤5
Arsenic (mg/L)	0.002	BDL	≤0.01	≤0.01
Cadmium(mg/L)	BDL	BDL	≤0.003	≤0.003
Chromium(mg/L)	BDL	BDL	≤0.05	≤0.05
Copper (mg/L)	0.013-0.06	0.11-0.16	≤2	≤2
Iron (mg/L)	0.21	0.12-2.57	-	≤2
Lead (mg/L)	BDL	BDL	≤0.01	≤0.01
Manganese(mg/L)	0.15	0.31	-	≤0.1
Mercury (mg/L)	BDL	BDL	≤0.006	≤0.006
Nickel (mg/L)	BDL	BDL	≤0.07	≤0.07
Aluminium(mg/L)	0.17-0.18	0.14-1.43	0.14-0.55	≤0.3
Antimony (mg/L)	BDL	BDL	≤0.02	≤0.02
Selenium (mg/L)	BDL	BDL	≤0.04	≤0.04
Microbiological				
E. coli or Faecal Coliforms (CFU/100 ml)	305-395	680-1975	Not Detected	Not Detected
Total Coliforms (Count per 100 ml)	4145-8925	4900-10575	-	≤10

Table 5-14. Physicochemical and Microbiological parameters for Manyii spring water in the dry and wet seasons.

Parameters	Dry season	Wet season	WHO	SANS 241
Physical				
Temperature (ºC)	25.7-29.30	25.6-28.6	-	-
Conductivity (µS/cm)	115-122	186-200	-	≤1700
Total Dissolved Solids (mg/l)	55-62	94-99	-	≤1200
Turbidity (NTU)	0.28-1.13	22.6-51.7	≤5	≤5
pH (at 25 ºC)	5.55-5.71	6.18-6.22	≥6.5 to ≤8.5	≥5 to ≤9.7
Chemical				
Nitrate (mg/L)	1.4-2.57	1.76	≤50	≤11
Nitrite (mg/L)	BDL	BDL	≤3	≤0.9
Sulphate (mg/L)	2.3-12.21	3.87	-	≤250
Phosphate(mg/L)	BDL	BDL	-	-
Fluoride (mg/L)	0.07	0.09-0.12	≤1.5	≤1.5
Chloride (mg/L)	9.45-13.21	16.22-20.46	≤250	≤300
Zinc (mg/L)	0.05	0.07-0.26	-	≤5
Arsenic (mg/L)	BDL	BDL	≤0.01	≤0.01
Cadmium(mg/L)	BDL	BDL	≤0.003	≤0.003
Chromium(mg/L)	BDL	BDL	≤0.05	≤0.05
Copper (mg/L)	0.05	0.05-0.12	≤2	≤2
Iron (mg/L)	0.55	0.87-2.23	-	≤2
Lead (mg/L)	BDL	BDL	≤0.01	≤0.01
Manganese(mg/L)	BDL	0.15	-	≤0.1
Mercury (mg/L)	BDL	BDL	≤0.006	≤0.006
Nickel (mg/L)	BDL	BDL	≤0.07	≤0.07
Aluminium(mg/L)	0.31	0.53-0.55	0.14-0.55	≤0.3
Antimony (mg/L)	BDL	BDL	≤0.02	≤0.02
Selenium (mg/L)	BDL	BDL	≤0.04	≤0.04
Microbiological				
E. coli or Faecal Coliforms (CFU/100 ml)	15-1070	1535-3145	Not Detected	Not Detected
Total Coliforms (Count per 100 ml)	410-9015	12385-14745	-	≤10

*Notes: Physicochemical ranges are the actual minimum and maximum values, *Microbiological ranges are the minimum and maximum averages for dry (July and August) and wet (September and November) seasons, *BDL-Below Detection Limit.*

c) *Performance of plasma as per WHO and SANS 241 criteria*

In order to argue the performance of the point of use plasma device developed, the treatment results were compared with other available common methods. The results of E. *coli* removal with (i) boiling, (ii) chlorine tablet, (iii) ceramic filter and (iv) bleach are presented in **Table 5-12** and Table **5-13**, in comparison with plasma

treatment. All these are typical household water treatment (HWT) or point-of-use (POU) technologies that can be well compared with plasma technology.

Heavily contaminated Mutshedzi River having E. *coli* and total coliform loads of 11400 CFU/100 mL and 73150 CFU/100 mL were respectively reduced by plasma to 2 CFU/100 mL (99.99% removal) and 11 CFU/100 mL (99.985% removal) in 60 minutes. This performance can only be compared to chlorine tablet that completely removed E. coli but still had 4 CFU/100 mL total coliforms. Moreover, the chlorine tablet effective treatment takes 2 hours which is longer than plasma's 60 minutes.

Plasma completely inactivated E. *coli* from Manyii and Mamvuka springs (groundwater sources) after 60 minutes of treatment. The initial high E. *coli* contaminant loads of 3145 CFU/100 mL (Manyii) and 1975 CFU/100 mL (Mamvuka) were reduced to **0** after 60 minutes of exposure to plasma action in the plasma chamber. In this case plasma stands out as a POU treatment method, followed by chlorine tablet and boiling. It should be noted that, even boiling a common HWT method did not kill all the pathogens in Manyii spring (17 CFU/100 mL out of the initial 3145 CFU/100 mL remained). For Mamvuka spring, plasma again fully removed total coliforms (i.e., from initial 10575 CFU/100 mL to 0 CFU/100 mL) but exhibited less performance on E. *coli* by achieving 99.82% removal (2.75 log reduction, from 14745 CFU/100 mL to 26 CFU/mL). Moreover, all these experiments were conducted using solar energy unit installed for powering the plasma reactor system.

Table 5-15. Treatment options for E. *coli* and total coliform in Mutshedzi River (P7).

Treatment Option	Initial *E coli* (CFU/100 ml)	Final *E coli* (CFU/100 ml)	Percentage removal (%)	Log reduction	Initial total coliform (CFU/100 ml)	Final total coliform (CFU/100 ml)	Percentage removal (%)	Log reduction
Boiling	11400	14	99.88	2.91	73150	34	99.950	3.35
Chlorine tablet	**11400**	**0**	**100**	**5.06**	73150	4	99.995	4.86
Ceramic filter	11400	3	99.97	3.58	73150	623	99.150	2.11
Bleach	11400	2	99.99	3.88	73150	222	99.700	2.55
Plasma	**11400**	**2**	**99.99**	**3.76**	**73150**	**11**	**99.985**	**3.82**
*Treatment for November sample.								

Table 5-16. Water purification methods applied for Manyii and Mamvuka springs

Manyii Spring					Mamvuka S2				
Method	Initial (CFU/100 ml)	Final (CFU/100 ml)	% Removal	Log Reduction	Method	Initial (CFU/100 ml)	Final (CFU/100 ml)	% Removal	Log. Reduction
E. coli									
Ceramic Filter	3145	19	99.4	2.22	Ceramic Filter	1975	15	99.24	2.12
Chlorine Tablets	3145	0.1	100	4.5	Chlorine Tablets	1975	9	99.54	2.34
Boiling	3145	17	99.46	2.27	Boiling	1975	0.1	99.99	4.3
Bleach	3145	38	98.79	1.92	Bleach	1975	9	99.54	2.34
Plasma	**3145**	**0**	**100**	**Complete removal**	**Plasma**	**1975**	**0**	**100**	**Complete removal**
Total Coliform									
Ceramic Filter	14745	142	99.04	2.02	Ceramic Filter	10575	74	99.3	2.16
Chlorine Tablets	14745	6	99.96	3.39	Chlorine Tablets	10575	9	99.91	3.07
Boiling	14745	173	98.83	1.93	Boiling	10575	104	99.02	2.01
Bleach	14745	236	98.40	1.8	Bleach	10575	132	98.75	1.9
Plasma	**14745**	**26**	**99.82**	**2.75**	**Plasma**	**10575**	**0**	**100**	**Complete removal**

Notes: The November 2024 water samples for the most contaminated springs (Manyii and Mamvuka S2) were used.

5.3.2.3 Water Treatment Plant and Community Tap

a) Purpose of investigation

The purpose of the investigation was to examine the effect of plasma treatment on treated water ready for the distribution network and its state in the distribution network at the point of abstraction or the tap. Two water samples were collected from one water treatment plant (WTP) and a community water tap (TAP) served by the plant, analysed in an independent laboratory to establish the state of its quality. The samples were stored in the cold room at 4°C for other experiments. Based on the results of the untreated WTP and TAP samples, plasma treatment was carried out, and analysis was carried out as before.

b) Untreated water quality and reactor conditions for treatment

The analytical results of untreated WTP and TAP samples (**Table 5-15**) show that most of the physicochemical parameters were compliant with the WHO and SANS 241:2015. However, electrical conductivity at 945 µS/cm (WTP) and 967 µS/cm (TAP), colour at 77.78 Hazen (WTP) and 85.21 Hazen (TAP), total organic carbon (TOC) at 20.22 mg/L (WTP) and 20.02 mg/L (TAP), and ammonia at 22.02 mg/L (WTP) and 24.56 mg/L (TAP) were all above the permissible limits.

Conductivity is of concern mainly for aesthetic reasons, but can signal the presence of dissolved salts or mineral substances in water. The presence of colour signifies aesthetic non-compliance, by irritating the sense of sight. Normally, one would prefer to take clear water, free of colour. Ammonia is important for aesthetic reasons, while the risks associated with excess TOC are chronic health issues and the possibility of organic pollution. Also, the microbiological quality failed on total coliforms for both WTP and TAP water samples, recording 14 colonies/100 mL (WTP) and 1 colony/100 mL (TAP).

The two samples were thus remediated in the plasma-ozonation system, which employed mainly plasma treatment alone under the same electrical, gas flow and liquid flow parameters as the second treatment of LC De Villiers Stream (**Table 5-9**). The applied voltage from HV AC PSU was 12 kV, at a frequency of 5 kHz and a gas flow rate of 8 L/min. The water was circulated as before by a peristaltic pump at a rate of 400 mL/min for 60 minutes (1 hour).

Table 5-17. Summary of main analytical water quality test results for Water Treatment Plant (WTP) and Community Tap (TAP) before plasma treatment.

Parameter	Unit	Water Treatment Plant (WTP)	Community Tap (TAP)	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.
pH - Value		7.54	8.03	≥5 to ≤ 9.7	6.5 – 8.5	Operational	(WHO, 2007)
Electrical Conductivity	µS/m	945	967	≤170	≤170 / ≤2700 µS/cm	Aesthetic /Operational	(WHO, 2018a)
Total Dissolved Solids as TDS	mg/L	609	601	≤1200	600 – 1000	Acceptability	(WHO, 2022b)
Colour	Hazen	77.78	85.21	≤15	15 TCU (True Colour Units, same as Hazen)	Acceptability	(WHO, 2022b)
Turbidity	NTU	4.25	3.35	≤1 / ≤5	<1 / <5 NTU	Aesthetic	(WHO, 2017)
Chloride as Cl	mg/L	82.54	79.07	≤300	≤ 250	Acceptability	(WHO, 2003b)
Sulphate as SO$_4$	mg/L	44.89	42.96	≤500 / ≤250	≤ 500	Acceptability	(WHO, 2004b)
Fluoride as F	mg/L	0.29	0.28	≤1.5	1.5	Chronic health	(WHO, 2022b)
Nitrate as N	mg/L	2.27	<0.5	≤11	50 mg/L (as NO$_3^-$)[#2]	Acute health	(WHO, 2022b)

Parameter	Unit	Water Treatment Plant (WTP)	Community Tap (TAP)	SANS 241, 2015 Limits	WHO Guideline		
					Parameter Value[#1]	Risk	Ref.
Nitrite as N	mg/L	<0.13	<0.13	≤0.9	3 mg/L (as NO_3^-)[#3]	Acute health	(WHO, 2022b)
Combined Nitrate & Nitrite as N	mg/L	2.27	<0.5	≤1	≤1 (ratio)[#4]	Acute health	(WHO, 2022b)
Total Organic Carbon	mg/L	20.22	20.02	≤10	Not mentioned		
E. *coli*	(Colonies /100 mL)	0	0	Not detected	Not be detectable in any 100 mL	Acute health	(WHO, 2022b)
Total Coliforms	(Colonies /100 mL)	14	1	Not detected	Not be detectable in any 100 mL	Acute health	(WHO, 2022b)
Ammonia as N	mg/L	22.02	24.56	≤1.5	≤35 (as Cation)	Acceptability	(WHO, 2003a, WHO, 2022b)
Sodium as Na	mg/L	95.83	90.48	≤300 µg/L	≤100 µg/L/ ≤200 µg/L	Acceptability	(WHO, 2003d)
Aluminium as Al	mg/L	0.17	0.15	≤2000 µg/L	≤2000 µg/L	Operational	(WHO, 2010)
Copper as Cu	mg/L	<0.05	<0.05	≤2000 µg/ℓ / ≤300 µg/ℓ	≤300 µg/L	Operational /health	(WHO, 2004a)
Iron as Fe	mg/L	0.23	0.17	≤10 µg/ℓ	≤10 µg/L (A)	Acceptability	(WHO, 2003c)
Lead as Pb	mg/L	<0.05	<0.05	≤400 µg/ℓ / ≤100 µg/ℓ	≤80 µg/L (P) (Total)	Chronic health	(WHO, 2022b)
Manganese as Mn	mg/L	0.24	0.22	≤300 µg/ℓ	≤100 µg/L / ≤200 µg/L	Chronic health / Acceptability	(WHO, 2022b)
Calcium as Ca	mg/L	43.90	44.17		No guideline value	-	-
Carbonates as CO_3	mg/L	0.00	0.00		No guideline value	-	-
Hydrogen carbonates as HCO3	mg/L	359.20	409.00		No guideline value	-	-

Notes: *A, P* = WHO Provisional Guideline Value (WHO, 2022); *#1* = unit is same as column 2 from left if not specified; *#2* = nitrate can be converted to nitrate as N using: 1 mg/L as nitrate = 0.266 mg/L nitrate as N; *#3* = nitrite can be converted to nitrite as N using: 1 mg/L as nitrite = 0.304 mg/L nitrite as N (WHO, 2022); *#4* = Combined nitrate plus nitrite: the sum of the ratios of the concentrations of each of nitrate and nitrite to its guideline value should not exceed 1.

c) Performance of plasma based on WHO and SANS 241 criteria (WTP & TAP)

The effect brought about by plasma treatment on the WTP and TAP water is shown in **Table 5-18**. Based on selected key parameters, the results show that the pH is compliant according to SANS 241:2015, however in both cases, it increased for WTP from 7.54 to 8.76 and for TAP from 8.03 to 8.79 before and after plasma treatment. Plasma alone further reduced electrical conductivity (in WTP & TAP), colour in TAP, total organic carbon (TOC) in both WTP & TAP and eliminated total coliforms in WTP. The value of increased total coliforms in TAP from 1 colony/100 mL to 8 colonies/100 mL after treatment will be further checked because it does not carry treatment logic compared to the excellent performance of plasma on highly contaminated waters.

The challenge is to further examine the increase in nitrite from 2.27 mg/L (WTP) and <0.5 mg/L (TAP) before plasma treatment to 20.55 mg/L (WTP) and 18.78 mg/L (TAP) respectively after plasma treatment. A similar trend is observed with nitrate when it increased from <0.13 mg/L (WTP) and <0.13 mg/L (TAP) before plasma treatment to 41.14 mg/L (WTP) and 40.27 mg/L (TAP), respectively, after plasma treatment. A similar issue was observed during the treatment of LC De Villiers stream water. This will be further studied under a different project as a follow-up research problem.

Table 5-18. Analytical water quality test results for selected parameters of WTP and TAP after plasma treatment.

Parameter	Unit	Before Plasma Treatment (Untreated)		After Plasma Treatment (Treated)		SANS 241, 2015 Limits	WHO Guideline
		Water Treatment Plant (WTP)	Community Tap (TAP)	WTP	TAP		
pH		7.54	8.03	8.76	8.79	≥5 to ≤ 9.7	6.5 – 8.5
Electrical Conductivity	µS/m	945	967	890	880	≤170	≤170 / ≤2700 µS/cm
Colour	Hazen	77.78	85.21	82.41	63.55	≤15	15 TCU (True Colour Units, same as Hazen)
Turbidity	NTU	4.25	3.35	12.02	13.09	≤1 / ≤5	<1 / <5 NTU
Total Organic Carbon	mg/L	20.22	20.02	13.82	14.36	≤10	Not mentioned
E. coli	(Colonies /100 mL)	0	0	0	0	Not detected	Not be detectable in any 100 mL.
Total Coliforms	(Colonies /100 mL)	14	1	0	8	Not detected	Not be detectable in any 100 mL
Nitrites as N	mg/L	2.27	<0.5	20.50	18.78	≤11	50 mg/L (as NO_3^-)[#2]
Nitrates as N	mg/L	<0.13	<0.13	44.14	40.27	≤0.9	3 mg/L (as NO_3^-)[#3]
Combined Nitrites & Nitrates as N	mg/L	2.27	<0.5	64.64	59.50	≤1	≤1 (ratio)[#4]
Ammonia as N	mg/L	22.02	24.56	170.4	163	≤1.5	≤35 (as Cation)

#2 = nitrate can be converted to nitrate as N using: 1 mg/L as nitrate = 0.266 mg/L nitrate as N; #3 = nitrite can be converted to nitrite as N using: 1 mg/L as nitrite = 0.304 mg/L nitrite as N (WHO, 2022); #4 = Combined nitrate plus nitrite: the sum of the ratios of the concentrations of each of nitrate and nitrite to its guideline value should not exceed 1.

5.3.3 Reference to WHO Protocol on Evaluation of HWT Technologies

The WHO performance criteria for bacteria removal (WHO, 2019) outlines the following performance criteria and classification with reference to bacteria:

(i) Log reduction >4, classified as 3-star (★★★) and interpreted as *comprehensive protection*.

(ii) Log reduction >2, classified as 2-star (★★) and interpreted as *comprehensive protection*.

(iii) Able to meet at least 2-star (★★) criteria for two classes of pathogens and interpreted as *targeted protection*.

(iv) Failed to meet WHO performance criteria, interpreted as *little or no protection*.

The plasma device (R2) achieved complete inactivation (100% removal) of E. *coli* from surface (LC De Villiers Stream, **Table 5-10**) and groundwater samples (Manyii and Mamvuka springs, **Table 5-16**). In the heavily contaminated surface water source (Mutshedzi River, **Table 5-15**), plasma achieved up to > 3.7 Log removal value (LRV) in such a bacteria-laden source containing 11400 CFU/100 mL of E. *coli*. The complete removal ability and the achievement of > 3.7 Log10 reduction imply that the device meets the WHO protocol of having the HWT technology able to remove bacteria up to: (i) Log10 reduction ≥ 4 (comprehensive protection and is classified as 3-star performance that can be described as very high pathogen removal) and (ii) Log10 reduction ≥ 2 meaning comprehensive protection and is classified as 2-star performance (high pathogen removal) (WHO, 2019). This shows that the designed device (R2) and process comply with these requirements when referring to bacteria removal.

CHAPTER 6: CONCLUSIONS & RECOMMENDATIONS

6.1 CONCLUSIONS

This document represents the final reporting on the research project "A Novel Solar-Powered Cold Plasma-ozonation System for Point-of-Use Drinking Water Treatment" supported by the Water Research Commission (WRC) of South Africa (Project No.: C2022-2023-00897) undertaken in the period 2022-2025 at the University of Pretoria, South Africa. The literature review as the main activity of the initial stage (together with inception) formed a good basis for the entire project execution and was a continuous activity till the end of the project. Enormous volumes of articles were consulted from the commonly recommended databases, notably Scopus, Web of Science, PubMed, and other online resources for grey literature, and the search window was at first limited to the period 2003 to 2022 (20 years), then extended during the project to end of 2024. The search words generally centred on cold or non-thermal plasma, ozonation and water treatment. Several manuscripts have been studied to date, but the gateway was based on (i) (Pooi and Ng, 2018), (ii) (Dorevitch et al., 2020), (iii) (Dong et al., 2017) and (iv) (Hendrickson et al., 2020). The review established the diverse applications of plasma technology (in brief), applications in water treatment, the point-of-use treatment methods available on the market, studies in water treatment at the household level related to plasma, ozonation and plasma-ozonation applications to pathogen destruction. The other information of great significancy searched in many other articles pertained study of reactor operating parameters and evaluation of the device performance on removal of bacteria from water basing on national South African standards and WHO guidelines.

On design, the initial plasma-ozonation system consisted of a plasma-ozone generation unit, a power conversion unit and a water disinfection tank. The system utilised air to produce ozone using an electric field from a high-voltage power supply. The ozone was bubbled into the contaminated water in the disinfection tank. The power supply unit was to consist of a solar photovoltaic system, lithium-ion battery and an inverter which is able to convert DC to AC power supply. This was maintained in the final designed system. The final system consisted of two reactor modules (R1 and R2) used to explore a variety of operational options and functions. R1 is a DBD plasma reactor consisting of a 30 mm x 300 mm x 2.3 mm borosilicate glass tube with copper tape wrapped around the tube and a stainless steel (non-spiked) high voltage (HV) electrode, while R2 (main reactor) consists of a 40 mm x 300 mm x 2.3 mm tube of the same material but with a spiked stainless steel high voltage (HV) electrode. R1 utilised oxygen from a cylinder while R2 was fed with oxygen generated by a pressure swing adsorption (PSA) oxygen concentrator. The solar power system provided by GreenHouse Solar Energy, South Africa consists of solar panels mounted on the rooftop to produce direct current (DC) which is converted by an inverter into the required alternating current (AC) voltage. The components of the full solar power supply system are provided in Table 3-1 of this report. The oxygen generator was provided by Wassertec Ozone Systems, South Africa designed to generate oxygen > 93% purity at a rate of 0 – 10 L/m by means of a pressure swing adsorption (PSA) principle, fed with atmospheric air at a pressure of 1 bar. The main reactor device R2 components and descriptions are provided in Table 3-4 of this report. R2 is able to purify water by operating in four modes that include; ozonation alone, plasma treatment alone but with recirculation of the liquid under treatment, plasma-ozonation and plasma alone – single pass mode where the

liquid goes through the reactor once. Further details on these operation models can be found in section 3.4.2 of this report.

The activity of user participation evaluation was based on the importance and common practice that prospective user communities are engaged and their views/opinions are provided for in the development of household water treatment (HWT) technologies or point-of-use methods usually employed to provide additional water treatment where its inadequate. To fulfil this important requirement, Hammanskraal community, City of Tshwane (CoT), South Africa (SA) was selected and visited to introduce plasma-ozonation HWT technology and to evaluate the user acceptability, design and useability. This was carried out through a focus group discussion (FGD) of 14 members, questionnaire transmission and retrieval of responses from the engaged representative community members. All relevant ethical clearances were acquired as per the requirements. It was established that the community was open to using the green energy- powered POU water treatment technology and they accepted it, fulfilling the acceptability requirement. On design, the community members accepted the current design described as the community module consisting of a reactor device R2 and its process components housed in a container/housing unit of size: 3 m (L) x 2 m W) x 2.4 m (H) but also ideated to have a household tap module, which can be fixed on the tap for the individual household. However, this research has delivered the community module and the tap module could not be accommodated in the current project parameters but may be investigated in future in a different project. The aspect of user participation evaluation was thus fulfilled.

The performance of rector device (main R2) was evaluated by (i) studying the effect of experiment conditions on reactor efficiency and efficacy, (ii) evaluating efficiency/efficacy of treatment technology – WHO Criteria and SANS 241: 2015 standards – where real water was treated, and key water quality parameters checked against permissible limits and (iii) checking the device performance against the WHO protocols for evaluation of HWT technologies. The study of experimental conditions focused on establishing optimal conditions for production of ozone. The outcomes of the investigation led to valuable ideas for determining suitable conditions for studying reactor R2 during the treatment of real surface water. The efficiency and efficacy of the treatment technology was investigated using (i) surface water sources (LC De Villiers, Sports Centre stream, near University of Pretoria, and Mutshedzi River in Limpopo province, South Africa), (ii) groundwater (Manyii and Mamvuka springs, located in Limpopo province), (iii) treated water from a water treatment plant and (iv) sampled water from a community tap. The reactor device was able to completely remove E. *coli* from surface water (LC De Villiers, Sports Centre stream) and from groundwater sources (Manyii and Mamvuka springs). In raw surface water from LC De Villiers, Sports Centre stream, the E. *coli* and total coliform loads of 450 colonies/100 mL and 24000 colonies /100 mL respectively were fully removed within 60 minutes of treatment. The initial Manyii and Mamvuka E. *coli* contaminant loads of 3145 CFU/100 mL and 1975 CFU/100 mL respectively were reduced to 0 after treatment in the plasma chamber of R2. Also E. *coli* and total coliform removal percentages of 99.99% (log10 reduction = 3.76) and 99.985% (log reduction of 3.86) were reported for heavily contaminated Mutshedzi River. The system performed well on water treatment plant and tap water which had E. *coli* bacteria count of 14 colonies/100 mL (treatment plant) and 1 colony/100 mL (tap water). The device (R2) was able to comply with the WHO protocol of evaluating HWT (or POU) technologies (WHO, 2019). The reported challenge of increased nitrate levels after treatment with the reactor device was marked for further investigation in future under another project arrangement.

It is therefore concluded that the aim of designing a novel solar powered plasma-ozonation system for point-of-use (POU) drinking water treatment was achieved based on the outcomes of the investigations carried out on surface and groundwater sources.

6.2 FUTURE ASPECTS AND RECOMMENDATIONS

The design, fabrication, construction, process build-up and testing are highly engaging tasks. These have been carried out with support from WRC, and the project outcomes have been as described in different manuscripts prepared for publication. The designed reactors have been used to study plasma-ozonation applications to water treatment. The current complete unit consists of (i) a housing unit with solar panels mounted on its rooftop (ii) a solar energy system, (iii) a high voltage alternating current power supply unit (HV AC PSU), (iv) a plasma reactor: R2: 40 mm (diameter) x 300 mm (length) x 2.3 mm (thick) borosilicate glass tube, (v) PSA Oxygen Concentrator (>93% purity, O_2 flow 0 - 10 L/min), (vi) Treatment tank (vessel), (vii) Other components such as Oscilloscope, peristaltic pump and connecting tubings. This is classified as a community module fitting in a small space of 3 m (L) x 2 m (W) x 2.4 m (H) that can be carefully lifted by a crane and transported to another point for demonstration purposes. All components can be supplied nationally from South Africa; thus, reconstruction and reconfiguration are possible with nationally (locally) available skills and materials.

The interaction with the community (Hammanskraal, CoT, SA as a case study) revealed further research needs, such as having an individual household module that can be fixed on the tap. This can be described as farfetched and not feasible under the key current project parameters of time and resources. It can be considered as a future undertaking after further planning, mainly the estimation of resource requirements and technical feasibility. Also, although a lot more is desired to be investigated with respect to (surface and ground) drinking water, several other applications on different kinds of effluents from industries, tertiary municipal wastewater and others can be explored.

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APPENDIX A: PLASMA-OZONATION SYSTEM COMPONENTS AND PROCESS

APPENDIX A-1: INITIAL SYSTEM PLAN AND COMPONENTS

a)   Plasma Process and Schematic Diagram
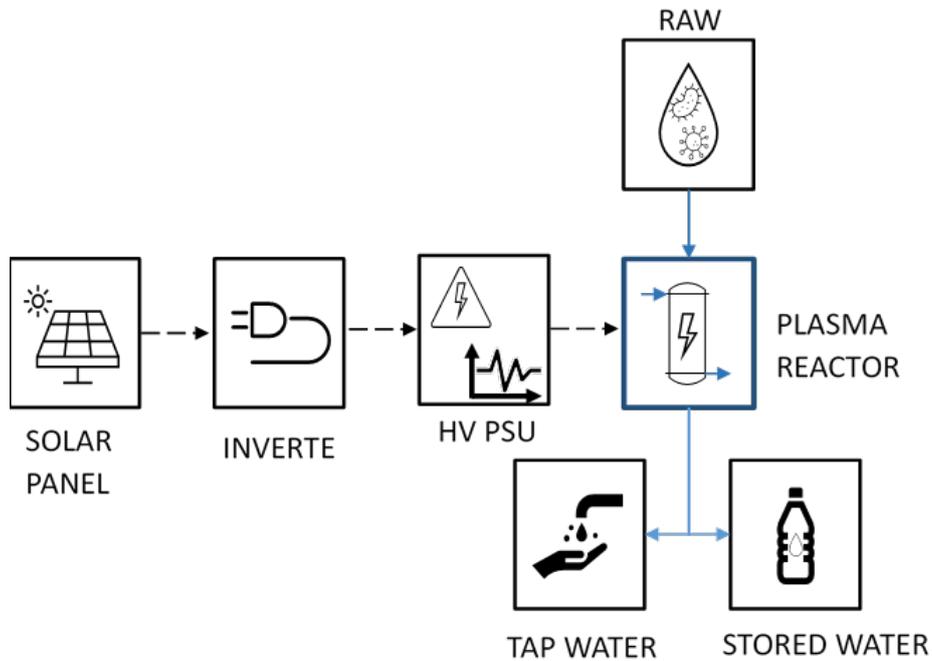
b)   Schematic of a Demonstration Unit
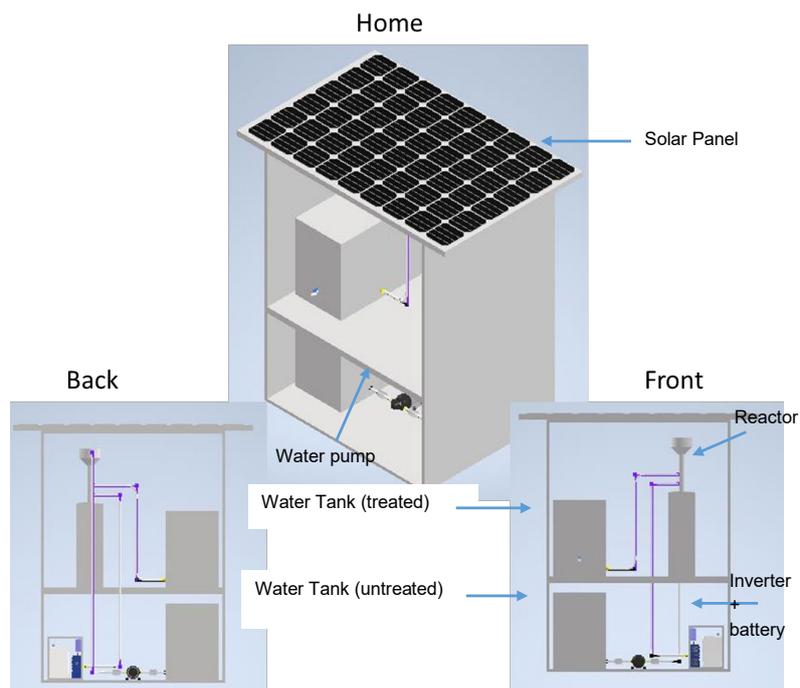
APPENDIX A-2: SOLAR POWER SUPPLY UNIT AND COMPONENTS

a) Solar Panels Installation

b) Solar Power Unit

APPENDIX A-3: PRESSURE SWING ADSORPTION (PSA) OXYGEN CONCENTRATOR

(Wassertec Ozone Systems, 2023)

APPENDIX A-4: MASS TRANSFER AND OTHER PROCESS DEVICES

a) Venturi Injector

(Mazzei Venturi Injectors and Wassertec
Ozone Systems, 2023),

b) Ceramic Nanobubble stone disk stone
(Fengkangyuan, 2024)

APPENDIX B: TYPICAL WATER QUALITY ANALYSIS RESULTS

APPENDIX B-1: LC DE VILLIERS SPORTS CENTRE STREAM RAW AND TREATED WATER QUALITY RESULTS (EXPERIMENT 1, 30 MINUTES),

The first set of results from the independent laboratory for the untreated (Raw surface water) and treated (using the plasma-ozonation setup) are attached. The key parameters that are generally focused on have been highlighted in yellow colour. The system was further studied and optimised based on those highlighted. Currently, reference has been made to the SANS 241, 2015 and the WHO guidelines for each of the selected parameters. WHO guidelines are important because SANS 241 is currently under review. The results of the second test are accordingly attached (B-2).

BEFORE TREATMENT (UNTREATED)

Analyses in mg/ℓ (Unless specified otherwise)		UOM %	Method ID	Risk	SANS 241 : 2015 Limits	Sample Identification LC Villiers Stream Untreated
Sample Number						23-36743
Date/Time Sampled						N/A
pH - Value @ 25 ºC	A	7.7	WLAB065	Operational	≥5 to ≤ 9.7	7.5
Electrical Conductivity in mS/m @ 25°C	A	7.0	WLAB065	Aesthetic	≤170	34.2
Total Dissolved Solids @ 180°C	A	5.6	WLAB027	Aesthetic	≤1200	332
Colour in PtCo Units	A	---	WLAB006	Aesthetic	≤15	16 ↓
Turbidity in N.T.U	A	7.6	WLAB005	Operational/Aest	≤1 / ≤5	9.2 ↓
Total Alkalinity as CaCO₃	A	10	WLAB007	---	---	96
Langelier Index at 25°C	A	---	WLAB053	---	---	-0.6
Chloride as Cl	A	8.0	WLAB046	Aesthetic	≤300	32
Sulphate as SO₄	A	8.4	WLAB046	Acute health/Aest	≤500 / ≤250	18
Fluoride as F	A	6.7	WLAB014	Chronic health	≤1.5	0.4
Nitrate as N	A	4.8	WLAB046	Acute health	≤11	0.9
Nitrite as N	A	3.0	WLAB046	Acute health	≤0.9	0.08
Combined Nitrate & Nitrite	A	---	WLAB046	Acute health	≤1	0.2
Silica as SiO₂	N	---	WLAB046	---	---	7.0
Total Organic Carbon as C	A	---	WLAB060	Chronic health	≤10	4.0
E. coli (MPN/100 mℓ)	A	5.0	WLAB021	Acute health	Not detected	770 ↓
Free and Saline Ammonia as N	A	10	WLAB046	Aesthetic	≤1.5	0.2
Sodium as Na	A	8.3	WLAB015	Aesthetic	≤200	13
Potassium as K	A	7.9	WLAB015	---	---	2.9
Calcium as Ca	A	9.5	WLAB015	---	---	29
Magnesium as Mg	A	9.5	WLAB015	---	---	12
Aluminium as Al (µg/ℓ)	A	8.1	WLAB015	Operational	≤300	110
Antimony as Sb (µg/ℓ)	A	9.4	WLAB050	Chronic health	≤20	<1
Arsenic as As (µg/ℓ)	A	9.6	WLAB050	Chronic health	≤10	1
Barium as Ba (µg/ℓ)	A	9.4	WLAB015	Chronic health	≤700	75
Boron as B (µg/ℓ)	A	9.7	WLAB015	Chronic health	≤2400	<25
Cadmium as Cd (µg/ℓ)	A	8.5	WLAB050	Chronic health	≤3	<1

						.
Total Chromium as Cr (µg/ℓ)	A	7.8	WLAB015	Chronic health	≤50	<25
Copper as Cu (µg/ℓ)	A	7.7	WLAB015	Chronic health	≤2000	<10
Iron as Fe (µg/ℓ)	A	8.1	WLAB015	Chronic health/Aest	≤ 2000 / ≤300	422 ↓
Lead as Pb (µg/ℓ)	A	9.7	WLAB050	Chronic health	≤10	1
Manganese as Mn (µg/ℓ)	A	8.3	WLAB015	Chronic health/Aest	≤ 400 / ≤100	69
Mercury as Hg (µg/ℓ)	A	16	WLAB050	Chronic health	≤6	<1
Nickel as Ni (µg/ℓ)	A	7.7	WLAB015	Chronic health	≤70	<25
Selenium as Se (µg/ℓ)	A	9.4	WLAB050	Chronic health	≤40	<1
Uranium as U (µg/ℓ)	A	8.5	WLAB050	Chronic health	≤ 30	<1
Zinc as Zn	A	8.0	WLAB015	Aesthetic	≤5	<0.025
% Anion-Cation Balance	N	---	---	---	---	96.9

A = Accredited N = Not Accredited S = Subcontracted UoM=Uncertainty Of Measurement ↑ = Lower Limit exceeded ↓ = Upper Limit exceeded
Tests marked "Not SANS Accredited" In this report are not included in the SANS Scope of Accreditation for this Laboratory.
Results marked "Subcontracted Test" in this report are not included in the SANS Scope of Accreditation for this Laboratory.

AFTER TREATMENT (TREATED)

Analyses in mg/ℓ (Unless specified otherwise)		UOM %	Method ID	Risk	SANS 241 : 2015 Limits	Sample Identification LC Villiers Stream Treated
Sample Number						23-36742
Date/Time Sampled						N/A
pH - Value @ 25 °C	A	7.7	WLAB065	Operational	≥5 to ≤ 9.7	7.6
Electrical Conductivity in mS/m @ 25°C	A	7.0	WLAB065	Aesthetic	≤170	34.7
Total Dissolved Solids @ 180°C	A	5.6	WLAB027	Aesthetic	≤1200	328
Colour in PtCo Units	A	---	WLAB006	Aesthetic	≤15	10
Turbidity in N.T.U	A	7.6	WLAB005	Operational/Aest	≤1 / ≤5	4.7↓
Total Alkalinity as CaCO₃	A	10	WLAB007	---	---	72
Langelier Index at 25°C	A	---	WLAB053	---	---	-0.7
Chloride as Cl	A	8.0	WLAB046	Aesthetic	≤300	32
Sulphate as SO₄	A	8.4	WLAB046	Acute health/Aest	≤500 / ≤250	24
Fluoride as F	A	6.7	WLAB014	Chronic health	≤1.5	0.2
Nitrate as N	A	4.8	WLAB046	Acute health	≤11	6.0
Nitrite as N	A	3.0	WLAB046	Acute health	≤0.9	1.5↓
Combined Nitrate & Nitrite	A	---	WLAB046	Acute health	≤1	2.3↓
Silica as SiO₂	N	---	WLAB046	---	---	8.1
Total Organic Carbon as C	A	---	WLAB060	Chronic health	≤10	5.3
E. coli (MPN/100 mℓ)	A	5.0	WLAB021	Acute health	Not detected	6↓
Free and Saline Ammonia as N	A	10	WLAB046	Aesthetic	≤1.5	0.2
Sodium as Na	A	8.3	WLAB015	Aesthetic	≤200	13
Potassium as K	A	7.9	WLAB015	---	---	2.9
Calcium as Ca	A	9.5	WLAB015	---	---	28
Magnesium as Mg	A	9.5	WLAB015	---	---	12
Aluminium as Al (µg/ℓ)	A	8.1	WLAB015	Operational	≤300	167
Antimony as Sb (µg/ℓ)	A	9.4	WLAB050	Chronic health	≤20	<1
Arsenic as As (µg/ℓ)	A	9.6	WLAB050	Chronic health	≤10	1
Barium as Ba (µg/ℓ)	A	9.4	WLAB015	Chronic health	≤700	62
Boron as B (µg/ℓ)	A	9.7	WLAB015	Chronic health	≤2400	<25
Cadmium as Cd (µg/ℓ)	A	8.5	WLAB050	Chronic health	≤3	<1
Total Chromium as Cr (µg/ℓ)	A	7.8	WLAB015	Chronic health	≤50	<25
Copper as Cu (µg/ℓ)	A	7.7	WLAB015	Chronic health	≤2000	16
Iron as Fe (µg/ℓ)	A	8.1	WLAB015	Chronic health/Aest	≤ 2000 / ≤300	295
Lead as Pb (µg/ℓ)	A	9.7	WLAB050	Chronic health	≤10	1
Manganese as Mn (µg/ℓ)	A	8.3	WLAB015	Chronic health/Aest	≤ 400 / ≤100	35
Mercury as Hg (µg/ℓ)	A	16	WLAB050	Chronic health	≤6	<1
Nickel as Ni (µg/ℓ)	A	7.7	WLAB015	Chronic health	≤70	<25
Selenium as Se (µg/ℓ)	A	9.4	WLAB050	Chronic health	≤40	<1
Uranium as U (µg/ℓ)	A	8.5	WLAB050	Chronic health	≤ 30	<1
Zinc as Zn	A	8.0	WLAB015	Aesthetic	≤5	<0.025
% Anion-Cation Balance	N	---	---	---	---	96.2

A = Accredited N = Not Accredited S = Subcontracted   UoM=Uncertainty Of Measurement ↑ = Lower Limit exceeded ↓ = Upper Limit exceeded
Tests marked "Not SANAS Accredited" In this report are not included In the SANAS Scope of Accreditation for this Laboratory.
Results marked "Subcontracted Test" in this report are not included in the SANAS Scope of Accreditation for this Laboratory.

APPENDIX B-2: LC DE VILLIERS SPORTS CENTRE STREAM RAW AND TREATED WATER QUALITY RESULTS (EXPERIMENT 2, 60 MINUTES)

BEFORE TREATMENT

| Units: | mg/l [ppm] (unless stated elsewhere) | | Container: Glass | | Date Issued: | 2024/12/17 |

Cations and Metals

Al	0.19	Cd	<0.05	Mg	10.67	Sb	<0.05		
As	<0.05	Cr	<0.05	Mn	0.07	Se	<0.1		
B	<0.5	Cu	0.11	Na	17.09	Zn	0.06		
Ba	0.30	Fe	0.90	Ni	<0.05	U*	<0.03		
Ca	28.19	K	4.96	Pb	<0.05				

Anions (Discrete Analyser)

Cl	22.09	NO2 as N	0.17	SO4	18.07	NO3 + NO2 as N	<0.5
F	0.23	NO3 as N	<0.5				

Other Parameters

pH	8.08	Turbidity (NTU)*	7.50	CO3*	0.00
EC (µs/cm)	334	P-Alk as CaCO3	<0.6	HCO3*	152.50
TDS	233	M-Alk as CaCO3	125.00	Hg*	<0.005
TOC*	<10	Colour (hazen)*	62.83	E.coli (colonies/100ml)*	450
LSI*	0.01	NH3 as N*	0.09	Total Coliforms (colonies/100ml)*	24000

Balance

Total Cation (meq/l)*	3.23
Total Anion (meq/l)*	3.58
Cation - Anion Difference (meq/l)*	-0.35
% Difference*	-5.16

AFTER TREATMENT

| Units: | mg/l [ppm] (unless stated elsewhere) | | Container: Glass | | Date Issued: | 2024/12/17 |

Cations and Metals

Al	0.07	Cd	<0.05	Mg	10.28	Sb	<0.05		
As	<0.05	Cr	0.14	Mn	<0.05	Se	<0.1		
B	<0.5	Cu	<0.05	Na	16.43	Zn	<0.05		
Ba	0.06	Fe	0.42	Ni	<0.05	U*	<0.03		
Ca	25.92	K	4.90	Pb	<0.05				

Anions (Discrete Analyser)

Cl	21.83	NO2 as N	3.69	SO4	13.19	NO3 + NO2 as N	15.31
F	0.32	NO3 as N	11.62				

Other Parameters

pH	8.36	Turbidity (NTU)*	9.85	CO3*	6.00
EC (µs/cm)	323	P-Alk as CaCO3	5.00	HCO3*	67.10
TDS	204	M-Alk as CaCO3	65.00	Hg*	<0.005
TOC*	11.32	Colour (hazen)*	76.51	E.coli (colonies/100ml)*	0
LSI*	-0.10	NH3 as N*	0.14	Total Coliforms (colonies/100ml)*	0

Balance

Total Cation (meq/l)*	3.03
Total Anion (meq/l)*	3.27
Cation - Anion Difference (meq/l)*	-0.24
% Difference*	-3.78