

Review

Non-Thermal Plasma Review: Assessment and Improvement of Feasibility as a Retrofitted Technology in Tertiary Wastewater Purification

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Abstract: Chlorination, ozonation and non-thermal plasma water purification technologies were compared in terms of their effectiveness, efficiency, capital and operating costs, energy yield and chemical demand. Retrofitting plasma technology to chlorination plants offered the lowest capital cost (ZAR 14,000 or USD 253,376 based on the current South African Reserve Bank rate of ZAR/USD of 18.0983) and the most effective contaminant removal (of the three possible combinations). However, this combination yielded the highest operating costs (ZAR 586,000 per annum or USD 10.6 million) and the lowest energy efficiency. It was concluded that retrofitting chlorination plants with plasma technology is feasible. However, plasma generators should be redesigned to consume less energy or to operate using renewable energy. Furthermore, research should be performed on contaminants of emerging concern to establish a deadline after which their concentration must not exceed a specified limit. This will accelerate the implementation of plasma technology and secure the health of our posterity.

Keywords: endocrine-disrupting chemicals; contaminants of emerging concern; persistent organic pollutants; disinfection byproducts; energy yield; costing



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1. Introduction

Tertiary wastewater treatment involves the removal of organics, inorganics and pathogens [1]. It produces improved quality effluent that can be used for irrigation and that is safe to discharge into water bodies. This process is therefore crucial to the advancement of society, as it provides us with the water we require to live and to thrive.

Some of the mature technologies used on purification plants include chlorination, ultraviolet radiation and ozonation [2]. These processes offer low treatment times and highly effective purification, and they may be used individually or together.

Despite being well established, these technologies have drawbacks. These include, but are not limited to: high energy consumption, high operating and capital costs and significant chemical demands [2]. Furthermore, these technologies were introduced at a time when little was known about the behaviour and impact of endocrine-disrupting chemicals and persistent organic pollutants [3,4].

Since composition analysers have become more sophisticated, more data have been collected on the concentration and ubiquity of these endocrine-disrupting and persistent organic compounds in water. While their concentrations may be too low to affect us at present [5,6], our currently ineffective treatment methods can lead to their accumulation in our environment. This could have a major impact on the health and safety of future generations.

This dilemma places considerable demand on advanced oxidation processes [7]. Non-thermal plasma water purifiers exhibit the potential to remove these persistent organic pollutants. This nascent technology eliminates the aforementioned drawbacks with its low energy demands (depending on the plasma source), low chemical demands, and, by application, lower cost. It is also able to compete with the strengths of mature technologies

in terms of treatment times and the effectiveness of purification [8]. However, it has yet to reach acceptable maturity to suit large industrial applications.

This review was compiled to determine whether it would be feasible to retrofit existing wastewater treatment plants with non-thermal plasma technology, to effectively remove persistent pollutants. It was also compiled to determine which facets of plasma purification could be improved upon, such that this technology becomes more feasible and thus more readily implemented on a large scale.

To achieve these aims, an overview of each technology type is presented. Thereafter, the strengths and weaknesses of each technology are evaluated in terms of effectiveness, capital cost, operating cost, energy efficiency and chemical demand. The scope of the review was limited to only include plasma reactors that operate non-thermally.

At present, there are no comparison studies between plasma and mature technologies that simultaneously consider a broad range of pollutants and criteria (such as those mentioned above). However, the data do exist in isolation, and ongoing attempts are being made by researchers to compile this information. The lack of published comparison studies is likely due to the variability within the plasma field. There are dozens of different plasma reactor types, with different designs and power requirements. This makes it difficult for scientists to build on the work done by previous researchers. Furthermore, plasma is being applied to water, food and textiles, which introduces more variability into the field. Finally, there are hundreds of wastewater contaminants that can be passed through a plasma reactor, which implies that the experimental results are often not corroborated by others.

2. Mature Technologies for Water and Wastewater Remediation

2.1. Chlorination

2.1.1. Applications of Chlorination

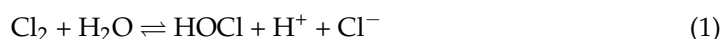
Chlorination is the most widely used disinfection technique globally for purifying drinking water [9]. South African tertiary water treatment plants utilise this technology, adopting chlorine and chloramine as the primary and secondary disinfectants, respectively [10].

2.1.2. Chlorination Process

Chlorine is a highly effective disinfectant, but its volatility leads to the production of DBPs (disinfection byproducts) when chlorine makes contact with organic matter. Furthermore, chlorine remains active in water for only 8 h after it is added. Chloramine, on the other hand, is a less effective disinfectant than chlorine. Hence, it is less reactive with organic matter and forms fewer DBPs. Chloramine remains in water for up to 8 days, which protects purified water from pathogens that may be introduced during the transportation process.

2.1.3. Mechanism of Chlorination

The reactions of chlorine in water are presented in Equations (1) and (2) [11]. Chlorine forms hypochlorous acid in the presence of water. This is demonstrated in Equation (1), where:



HOCl then partially decomposes, as shown in Equation (2):



These compounds initially react with inorganics (such as metals) in the water, usually forming insoluble compounds (such as $\text{Fe}(\text{OH})_3$), which can be filtered out. Thereafter, organic compounds (such as phenol) and pathogens are oxidised, which generally renders them harmless.

2.1.4. Advantages and Disadvantages of Chlorination

Chlorination presents several advantages. It is inexpensive with a quick application procedure [12], with kits such as the SE200 Community Chlorine Maker capable of purifying 200 L of water in under 5 min [13]. Chlorination is also highly effective, with the ability to remove organics, inorganics and most pathogens [14].

However, as mentioned previously, chlorination can form DBPs [15]. This includes trihalomethanes (THMs) and halogenetic acetic acids (HAAs). HAAs biologically decompose to eventually form THMs. The most notable of these THMs is trichloromethane (chloroform), an anaesthetic capable of damaging the liver and kidneys after chronic exposure. Furthermore, chlorination creates a smell in water, which may be unappealing or objectionable to some people. Chlorination utilises chlorine gas, a toxic chemical with inherent significant risk factors. The most crucial disadvantage is that chlorination cannot destroy protozoan cysts, as they possess a chlorine-resistant outer shell [14]. An example of a protozoan cyst is *Cryptosporidium*, a nefarious pathogen responsible for several outbreaks, such as the 2001 outbreak in northwest Saskatchewan, Canada [16].

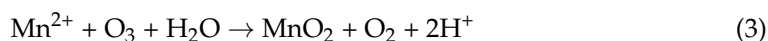
2.2. Ozonation

2.2.1. Applications of Ozonation

Ozonation is a trusted technology in the beverage industry and is utilised by Coca-Cola, SABMiller, Dasani and other companies for water purification processes [17]. Ozonation is also used in Olympic pools [18] and in hospitals [19] due to its reliably high oxidising potential.

2.2.2. Ozonation Process

A high-voltage electric discharge is applied to a stream of oxygen or air. The energy from the discharge splits the oxygen molecule into two oxygen atoms [20]. These unstable atoms then combine with other oxygen molecules to form ozone gas (O_3). Ozone is a powerful oxidiser that decomposes in water and reacts with metals, organics, inorganics and pathogens to form insoluble compounds that can be filtered out. An example of this interaction is displayed in Equation (3), where manganese is oxidised to form a precipitate [21]:



2.2.3. Advantages and Disadvantages of Ozonation

Ozonation is an excellent disinfectant and oxidising agent [22] that effectively removes odours and colours from water [23]. Furthermore, since excess ozone rapidly decomposes into oxygen, the purified water does not have a residual scent or taste, which justifies its popularity in the food and beverage industry. Industrial ozonation processes can purify between 10000 and 60000 L/h of water, which is relatively quick [17]. In these applications, ozone is generated on-site, so external chemicals are not usually required, unless liquid oxygen is utilised [21]. This eliminates the risk associated with the transportation, handling and storage of chemicals.

Ozonation also fulfils its primary role as a disinfectant in tertiary water purification. It virtually eliminates organics such as phenols [24] and can effectively oxidise inorganics (such as Mn and Fe) into insoluble particles [25]. It is also highly effective against pathogens, including *E. coli*, *Giardia* and *Cryptosporidium* (unlike chlorination) and viruses.

However, there are also disadvantages. Ozone produces DBPs when it reacts with endocrine-disrupting chemicals, even at high doses [26]. However, these are formed in small amounts and little is known about them. Ozone also produces HAAs and THMs, but in significantly smaller amounts than chlorination. The third and most problematic DBP is bromate, because it can be carcinogenic [27]. However, if the water contains a low bromide concentration, then the concentration of bromate produced may still be within acceptable levels. Other disadvantages include the nature of ozone: it requires vast amounts of energy [28] and capital [21], but because it rapidly decomposes in water, the excess ozone cannot be measured, so operators cannot minimise the amount of ozone used. Furthermore,

this rapid decomposition makes it unfeasible for long distribution pipelines, which could introduce contaminants downstream [22]. Finally, ozone must be safely contained within the operating environment, as the inhalation of ozone can cause severe lung damage [29].

2.3. Ultraviolet Radiation

2.3.1. Applications of UV Radiation

UV radiation is frequently used for water recycling systems in the electronics, pharmaceuticals and cosmetics industries. These industries do not often introduce organic contaminants into their water, which makes UV treatment feasible. On the other hand, European water treatment plants that do make use of UV are only certified to purify water that is visibly clear, and not wastewater [30].

2.3.2. UV Radiation Process

When UV radiation (frequently of 245 nm wavelength) is applied to contaminated water, the radiation penetrates microorganisms in the water and alters their DNA (Deoxyribonucleic Acid), rendering them unable to survive and incapable of reproduction. This puts the pathogen cells out of action, thereby effecting the decontamination requirement.

2.3.3. Advantages and Disadvantages of UV Radiation

While UV radiation poses many advantages, its disadvantages are more prominent in the context of tertiary wastewater treatment. Firstly, UV radiation does not improve the odour, taste or clarity of water [31]. It is unable to oxidise inorganic contaminants, such as iron and manganese [30] and can only oxidise some organic contaminants at very high concentrations [32]. Endocrine-disrupting chemicals (EDCs) are also not easily oxidised and require significantly high doses. While the oxidation of organics and EDCs may be possible, inorganic contaminants (which do not degrade) tend to absorb UV radiation and prevent the radiation from reaching the aforementioned contaminants. Thus, UV radiation is not feasible for the wastewater considered in this review. Finally, UV is a point source disinfectant, much like ozone, meaning that it cannot provide long-lasting disinfection. The method is therefore unfeasible for water distribution systems.

Despite UV radiation being unsuitable, for this review, its advantages should not go unappreciated: it is faster than chlorination, cheaper than ozonation [33] and has a power rating that is comparable to that of a light bulb [34]. It is highly effective at destroying virtually all pathogens and does not form DBPs when it reacts with water of a good quality (i.e., low organic content). Finally, UV radiation equipment requires frequent, but relatively easy and inexpensive maintenance [30].

3. More Recent Technology: Non-Thermal Plasma

3.1. Non-Thermal Plasma Overview

Plasma refers to the fourth state of matter: ionised gases. In this phase, electrons possess sufficient energy to escape from the atom. This can be achieved by using high temperatures to energise electrons (thermal plasma) or by using an electric field at lower temperatures (non-thermal plasma). The generation of non-thermal plasma requires significantly less energy [35].

3.2. Applications of Plasma Purification

There are several different techniques used to generate plasma. Popular techniques include gliding (glow) arc plasma (GAP), dielectric barrier discharge (DBD) and pulsed corona discharge (PCD). In a DBD, the electrical discharge is facilitated by the presence of two electrodes with one covered by a thin dielectric material and the application of a high voltage [36]. In the gas phase, the carrier gas will be broken down to generate active species and highly oxidative/reactive agents after further reactions, which are all useful in the degradation of contaminants. In the GAP, the plasma discharge is produced at a high working voltage by two or more diverging metallic electrodes placed in the gas flow

direction [37]. In a PCD, the discharge is generated when high voltage pulsed power is applied on sharp-pointed electrode tips (the high voltage electrode) and a working gas introduced in the electric field of the sharp electrode tips, generating a group of active species. The chemical characteristics of the oxidative species produced in each of the plasma discharges are dependent on the gas type (or composition), because sometimes a mixture of gasses is applied rather than a single gas type.

Due to the variety of plasma technologies, intensive research is being performed to determine the advantages that each type holds over the other. At present, DBD is one of the more energy-efficient plasma reactors [38]. Yusuf et al. [39] recounted the application of plasma technology to degrade different types of pollutants including dyes, organic compounds such as phenol, pesticides, emerging contaminants and pathogenic microorganisms. The authors further discussed the synergistic effect from the plasma with complementally processes such as catalysis, achieved through the increase in the production of reactive species, resulting in enhanced process performance.

However, many such studies have been conducted at laboratory scale involving small volumes of water and pollutant concentrations in more controlled environments.

The wide-scale implementation of plasma water purifiers has yet to be achieved. In our pragmatic line of thought and reality, the industrial scale plasma systems developed employ less complicated plasma degradation processes. The manufacturers are building small-scale reactors that display the benefits of this nascent technology [8].

3.3. Plasma Purification Process

When a large amount of energy is applied to a gas (usually air), plasma is generated. The air becomes an ionised gas, consisting of a wide group of active species. When these species enter water, they result in the formation of even more reactive OH⁻ radicals, which act as powerful oxidisers for the contaminants in the water [40].

3.4. Advantages and Disadvantages of Plasma Purification

Plasma shows significant potential in pollutant removal. It is capable of quickly oxidising organics, inorganics and pathogens with reasonable power consumption [8]. Since plasma only requires an energy source with no additional chemicals, it has the potential to be far more affordable than some of the mature counterparts such as chlorination. On a qualitative level, the research suggests that plasma is a suitable competitor to more established processes.

Plasma is most notable for its ability to remove persistent organic pollutants. Globally, concerns are rising over these compounds because our current purification systems are not highly effective at removing them. This creates the ideal opportunity for the mainstream adoption of plasma. If retrofitted to older plants, it could serve to eliminate these concerns.

Plasma purification is also likely to be more effective than ozone purification. This is because when plasma is generated, all of the radicals produced enter the water to provide a wide range of disinfection abilities. In contrast, during ozone production, when air is energised to create ozone, only the ozone molecules are applied to the water [40].

Furthermore, while plasma produces bromate (a DBP similar to that of ozonation) in treatment solutions containing bromide [41,42], it is also capable of removing chloroform, one of the major DBPs linked with chlorination [43].

Unfortunately, one of the major concerns associated with plasma is its high energy consumption in some cases, although significant progress has been made based on the use of pulsed and nanoseconds pulsed power supply units. The generation of non-thermal plasma with an efficient reactor type and power supply sources can substantially reduce the energy requirements [38].

4. Tertiary Water and Wastewater Pollutants

4.1. Contaminants of Emerging Concern

Contaminants of emerging concern (CECs) are defined as chemicals or organisms whose concentrations are not regulated at present [44]. These contaminants could have adverse effects on humans or the environment. As mentioned previously, they were not a concern when wastewater treatment plants were initially designed, so they are not effectively removed by these plants.

Endocrine-disrupting chemicals (EDCs) are a class of CECs that have been reported in drinking water in South Africa and other parts of the world [6,45]. EDCs can be classified according to their use, with the main categories being oestrogens, pharmaceuticals, pesticides, perfluorinated carbons and personal care products [46]. The negative effects of ingesting these compounds include decreased fertility and abnormal reproductive capacity [47]. While EDC concentrations are not yet high enough to affect humans, the impact is visible in wildlife. This includes declining populations of some reptile, amphibian and fish species [48]. Wildlife is affected more because our discharge points are often located in their water supplies and aquatic habitats, causing them to experience high contaminant concentrations, prior to the rectifying effect of infinite dilution.

The EDCs in each category may be further classified based on their persistence. While some EDCs decompose after being discharged, other EDCs act as persistent organic pollutants (POPs). POPs are problematic for water treatment plants, as their halogenated structure makes them stable and resistant to environmental degradation [49].

Naturally, some EDC categories are more commonly found in water than others. During a study of the influents of three South African wastewater treatment plants, the three most common EDC categories were oestrogens, perfluorinated compounds (PFCs) and pharmaceuticals [46]. Of the three, oestrogens were the most commonly found and their concentration is rapidly increasing [50]. The primary source of these oestrogens in surface waters is E1 (oestrone) [51], a POP [46] excreted by both humans and animals.

Pharmaceuticals were the most highly concentrated EDC group from the study (but not the most commonly found). The most persistent of these pharmaceuticals was carbamazepine (CBZ) [52]. This drug is used to treat epilepsy and bipolar disorder. CBZ is excreted by patients who make use of it, causing the drug to appear in the influent of wastewater plants [53]. Pharmaceuticals also enter wastewater plants when they are disposed of irresponsibly, such as when they are flushed down toilets or rinsed down basins. Furthermore, the concentration of CBZ in the plant effluent is sometimes higher than in the plant influent. This further reinforces the ineffectiveness of wastewater plants at removing EDCs. The presence of CBZ in water supplies is problematic because the unintentional consumption of it could lead to impaired red blood cell and platelet production [53].

Perfluorinated compounds (PFCs), also referred to as perfluorinated alkyl substances (PFASs), were the third most commonly found EDC from the same study. They possess a strong carbon–fluorine bond that makes them highly stable and therefore persistent [54]. They are used in stain repellents for carpets and textiles, non-stick coatings for cooking utensils and in paints and adhesives [55]. One of the most widely studied of these PFCs is PFOS (perfluorinated octane sulphonate). Communities exposed to high PFC concentrations via their drinking water exhibited higher cases of kidney and testicular cancers [56]. Furthermore, children exposed to PFCs may develop hormonal issues and decreased immunity.

4.2. Pathogens in Drinking Water

The three groups of pathogens that may be found in drinking water are: bacteria, viruses, and protozoa and helminths.

When testing for bacterial contamination, the most basic test used is the test for total coliform bacteria [57]. Coliform bacteria are found in water, soil and the digestive tracts of animals [58]. Faecal coliform bacteria are a subset of the total coliform bacteria group. These are found specifically in the gut and faeces of warm-blooded animals. Within this group of faecal coliforms, the major species is *Escherichia coli*. Since *E. coli* does not reproduce in

the environment, its presence is indicative of faecal contamination. *E. coli* is also easy and inexpensive to detect, making it historically one of the most common indicator organisms for pathogens [59]. It is also considered to be one of the best tests for the presence of pathogens [57]. These tests are important because while most strains of *E. coli* are harmless, some strains could result in death [60].

The second group (viruses) contains a multitude of pathogens. Comparing this list of viruses [61] with a list of the top ten pathogens responsible for outbreaks in public water systems [62] yielded the following result: the third most commonly reported cause for outbreaks, and the first virus on the list, was norovirus. This virus is highly contagious and causes vomiting and diarrhoea [63].

The list mentioned above also revealed that *Giardia* (from the protozoa and helminths group) is the pathogen responsible for the most disease outbreaks in public water systems. This is likely due to the ineffectiveness of chlorination against protozoans.

4.3. Inorganic Contaminants in Drinking Water

Metals are common inorganic contaminants [64], with iron and manganese being some of the more common contaminants [65]. They are not harmful in low concentrations [66] and their presence is likely due to the metal pipes in which water is transported, as well as due to groundwater, which travels through rocks containing iron and manganese [67]. The presence of these metals can lead to iron and manganese bacteria in the water supply. These bacteria form biofilms that clog sinks and toilets [68]. High metal concentrations will also create a bitter and metallic taste in drinking water.

5. Comparison between Mature Methods and More Recent Non-Thermal Plasma Technology

5.1. Materials and Methods

5.1.1. Plasma Applications in Water Purification

A detailed assessment of selected non-thermal plasma applications was carried out to appreciate the completed studies and outstanding results as presented in Table 1. The main attributes of this compilation are pollutant type, reactor operating conditions and degradation performance characterised by contact time and removal efficiency.

5.1.2. Planning-Energy and Costs

A selection of compounds was made using the research described under tertiary water and wastewater pollutants. Each considered compound fell into one of four groups: organics, inorganics, pathogens or CECs. The most problematic or most ubiquitous compounds were selected from each of the aforementioned groups. The selection process for this is described below.

To represent the organics group, phenol was selected. Phenol is a well-established model compound in the water purification industry [8,69] and is a good representation of the organic compounds one is likely to encounter when purifying water. For the CECs, one persistent contaminant was chosen from each of the three subgroups of EDCs: pharmaceuticals, oestrogens and PFCs. The EDC selected for pharmaceuticals was carbamazepine, because it was the most persistent in its subgroup. Oestrone was selected for the oestrogens group because it was the main source of oestrogens in water. Lastly, PFOS was selected to represent the PFCs group, because it is widely studied, thereby making literature data more readily available.

For each of the compounds, the efficiency and percentage removal for both chlorination and ozonation were determined. The efficiency was measured in terms of the CT value, which is the product of concentration (C) of the oxidant used with the contact time (T) [70]. However, for plasma processes, it is difficult to quantify a plasma concentration. Thus, it was more suitable to represent its performance in terms of power consumption and the percentage of contaminant removal. In some studies, only the voltage requirements of a

plasma reactor are reported. To obtain the corresponding power consumption, a graph was used that displays the current in a DBD reactor at varying voltages [71].

The literature data used were obtained between 25 °C and 30 °C, the ideal temperature for water treatment [72]. Furthermore, in this temperature range, additional heat exchanger equipment is not required, which keeps the operating costs lower.

Next, the results reported were obtained at a pH between 4 and 10. The range is wide because data are scarce in this field, and narrowing the pH range severely limits the number of studies that can be utilised.

For chlorination analysis, since chloramine is used to prevent contamination at later points in the pipeline, it is a secondary disinfectant. Hence, data surrounding chlorine as a disinfectant was used, as opposed to chlorine and chloramine as the disinfectants.

For the plasma reactors, PCD and DBD reactors are the most and second most energy-efficient plasma generators, respectively [38]. Gliding arc reactors lie below PCD and DBD reactors in terms of energy efficiency. Hence, emphasis was placed on finding results from PCD reactors first, and then DBD reactors, with gliding arc reactors only being considered as a last resort.

Finally, the literature indicates that UV radiation is unfeasible for tertiary wastewater purification. It was therefore not considered when gathering the results.

5.1.3. Calculations

For the operating cost, capital cost and energy yield calculations, phenol was selected as the model pollutant, for the reasons outlined previously.

Operating Cost Calculations

By calculating the operating costs first, assumptions were made and a basis was selected, which greatly simplified the subsequent capital cost calculations. For each technology type, a hypothetical wastewater treatment plant was designed. This design specified an arbitrary basis flow rate: 100 m³/day of wastewater influent. A maximum influent phenol concentration of 53 ppm was reported in literature [73]; this was adopted as the influent's phenol concentration.

Beginning with the hypothetical plasma plant, it was assumed that its operating costs are similar to those of the chlorination plant (apart from the electricity required for the plasma generator). This was justified because any water treatment plant will have similar equipment and maintenance demands. These costs are outlined in [21] and include maintenance, personnel and capital redemption costs (based on a 7% prime rate) [74]. Each of these costs was determined as a function of the capital investment cost. To determine the capital cost, the 0.6 rule [75] was used to scale down the capital cost approximation provided by [76]. The scaled capital cost was then adjusted for inflation [77] and used to calculate the maintenance, personnel and capital redemption costs.

From the reported experiment, the number of watts required to remove one gram of phenol every hour was determined. This value was then adjusted to the hypothetical plant (which removes 221 g of phenol every hour). Assuming the plant operates 24 h a day, for 365 days a year, the kWh demand was then calculated. Using Eskom's business rate of R 1.46/kWh, the annual electricity cost was determined [78]. This electricity cost was added to the previous expenses to determine the annual operating cost.

Then, the hypothetical chlorination and ozonation plants were investigated. Once the hourly chlorine and ozone dose is known, it can be used to determine the capital cost, which then specifies the operating cost [21]. Using the phenol experiments reported in Table 2, the mass of chlorine and the mass of ozone required to remove 1 g of phenol per hour was determined. This value was scaled up to the demands of the hypothetical plants to determine their capital costs. After adjusting the capital costs for inflation, the annual operating expense of each plant was determined.

Capital Cost Calculations

While performing the operating cost calculations outlined above, the capital expense for each plant was indirectly determined.

Energy Yield Calculations

Each technology type was compared based on its respective energy yield. This is defined as the mass of the pollutant removed per kWh supplied. A higher energy yield implies a more energy-efficient technology. As stated previously, phenol was selected as the model pollutant to be degraded.

The plasma's energy yield was first calculated using the phenol experiment reported in Table 3. The same table was utilised to calculate the electricity costs

For chlorination, a more complex approach was used. Using data from the phenol experiment reported in Table 2, the chlorine dose and effluent flowrate were calculated. This information was then used to determine the annual electricity cost of a plant operating under these conditions [21]. Next, using Eskom's business tariffs from 2009, the annual kWh consumption of the plant was found [79]. The energy yield was calculated thereafter. Finally, the ozonation experiment reported under the phenol results in Table 2 was used. The hourly ozone dosage required to remove 1 g of phenol was recorded, and it was noted that an ozone generator using air as feed gas consumes 13 kWh per kg ozone produced [80]. Using this information, the ozonation's energy yield was calculated.

Table 1. Plasma contaminant degradation technologies for typical pollutants.

Non-Thermal Plasma Reactor/Discharge Type	Pollutant Description		Operation Conditions	Degradation Performance	Ref.
	Type	Category/Class			
Plasma catalysis/dielectric barrier discharge (DBD)	Phenol	Organic	Applied voltage: 16 kV Frequency: 50 Hz Discharge current: 0.56 mA Gas flow rate: 3.2 mL/s	Contact time: 50 s Removal efficiency: 99%	[81]
Gas-liquid DBD reactor	Carbamazepine	Organic: EDC	Applied power: 0.7 W Air flow rate: 1 L/min Initial concentration (C ₀): 20 mg/L Liquid flow rate: 6 mL/min	Contact time: 3 min Removal efficiency: 100% Energy density: 25 kJ/L	[82]
DBD	Oestrone	Organic: EDC	Applied voltage: 80 kV Frequency: 50 Hz Initial concentration (C ₀): 2 mg/L	Contact time: 15 min Removal efficiency: >80% Energy yield: 777–737 × 10 ⁻⁶ g/kWh	[71]
DBD	PFOS	Organic: EDC	Applied voltage: 130 kV Frequency: 17 Hz Applied Power: 322 W Peak Current: 40A Initial concentration (C ₀): 1 ppb	Contact time: 60 min Removal efficiency: >85%	[83]
DBD	<i>E. coli</i>	Pathogen	Applied voltage: 4.16 kV Frequency: 27.6 Hz Discharge current: 13.01 A Initial concentration (C ₀): 1 × 10 ⁸ cfu mL ⁻¹	Contact time: 60 min Removal efficiency: >99% Energy (duty): 0.24 J/s	[84]
Cold atmospheric plasma jet	Cryptosporidium	Pathogen	Applied power: 549 W Frequency: 47 kHz	Contact time: 3 min Removal efficiency: 2.03 log inactivation	[85]
Radio-frequency (RF) atmospheric pressure plasma jet (APPJ)	Norovirus (feline calicivirus (FCV))	Pathogen	Applied power: 2.5 W Frequency: 13.36 MHz Ar gas flow rate: 1.5 standard litres per min (SLM)	Contact time: 15 s Removal efficiency: 6.0 log inactivation	[86]

Table 1. Cont.

Non-Thermal Plasma Reactor/Discharge Type	Pollutant Description		Operation Conditions	Degradation Performance	Ref.
	Type	Category/Class			
DBD photocatalyst	Chloroform	Disinfection byproduct	Applied high voltage (AC): 20 kV Frequency: 52–30,000 Hz Chloroform vapours (in air) flow rate: 0.3 L/min Initial concentration (C_0): 85 ppm	Contact time: 2 s Removal efficiency: 70%	[43]
Corona discharge	¹ Bromate	Disinfection byproduct	Peak voltage: 20 kV Current: 13.8 A Peak power: 203 kW Frequency: 30 Hz Initial concentration (C_0): 30 μ M	Contact time: 60 min Removal/reduction efficiency: 95% Energy: 0.16 J	[87]
Micro discharge plasma jet (MDPJ)/DBD	<i>E. coli</i>	Pathogen	Applied voltage: 1.01–1.66 kV Frequency (Transformer): 60 Hz Air/Nitrogen gas flow rates: 2–4 L/min Initial concentration (N_0): 2.4×10^7 CFU/mL	Contact time: 40 min Removal efficiency: 99.9%	[88]
Non-thermal plasma (NTP)/spark discharge plasma	<i>Enterococcus faecalis</i> (<i>E. faecalis</i>) and <i>E. coli</i>	Pathogens	Applied voltage: 10 kV Frequency: 30 Hz Initial concentration (N_0): 1×10^8 CFU/mL	Contact time: 12 min (<i>E. faecalis</i>) and 15 min (<i>E. coli</i>) Removal efficiency: 8-log CFU reduction (<i>E. faecalis</i> and <i>E. coli</i>)	[89]

¹ Reduction reported, assisted by the consumers of oxidative species.

Table 2. CT (concentration \times contact time) values and percentage removal of a variety of contaminants, with respect to chlorination and ozonation water purification technology. Data obtained between 25 and 35 °C, and between a pH of 4 and 10.

Type	Contaminant	Chlorination Technology			Ozonation Technology		
		CT (mg/L \times min)	Conc * \times Time #	% Removal	CT (mg/L \times min)	Conc * \times Time #	% Removal
Organic	Phenol	5570 [90]	5570 \times 1	99	1200 [91]	80 \times 15	>99
Organic: EDC	Carbamazepine	1065 [92]	17.75 \times 60	40	2.2 [93]	0.44 \times 5	>99.9
Organic: EDC	Oestrone	IDA ¹	IDA ¹	IDA ¹	0.06 [94]	4.4 \times 0.014	99.8
Organic: EDC	PFOS	1440 [95]	4 \times 360	83	840 [96]	3.5 \times 240	43
Inorganic	Manganese	1.161 [97,98]	2.322 \times 0.5	99	0.792 [99]	1.584 \times 0.5	99
Inorganic	Iron	0.496 [97,98]	0.992 \times 0.5	99	0.344 [99]	0.688 \times 0.5	99
Pathogen	<i>E. coli</i>	0.25 [100]	0.25 \times 1	99.99	0.05 [101]	IDA ¹	99.99
Pathogen	<i>Cryptosporidium</i>	7200 [102]	80 \times 90	99	6.2 [103]	IDA ¹	>99
Pathogen	Norovirus	2 [104]	IDA ¹	99.9	1.3 [105]	IDA ¹	99.99
Disinfection byproduct	Chloroform	+ ²			+ ²		
Disinfection byproduct	Bromate	+ ²			+ ²		

¹ Insufficient data available. ² This compound is formed by the technology, as opposed to being removed by it. * Concentration in mg/L. # Contact time in minutes.

Table 3. Reactor type, PT (power \times time) values and percentage removal of a variety of contaminants, when non-thermal plasma water purification technology is used.

Type	Contaminant	Non-Thermal Plasma Technology			% Removal
		Plasma Type	PT (W \times Min)	Power * \times Time #	
Organic	Phenol	DBD ¹	2430 [81]	9 \times 0.83	98
Organic: EDC	Carbamazepine	DBD ¹	36 [82]	12 \times 3	99.99
Organic: EDC	Oestrone	DBD ¹	60,000 [71]	4000 \times 15	83.6
Organic: EDC	PFOS	DBD ¹	19,320 [83]	322 \times 60	93.5
Inorganic	Manganese	IDA ²			
Inorganic	Iron	IDA ²			
Pathogen	<i>E. coli</i>	DBD ¹	1080 [84]	54 \times 20	99.9
Pathogen	<i>Cryptosporidium</i>	AC ³ Gliding Arc	1647 [85]	549 \times 3	>99
Pathogen	Norovirus	DBD1	24 [106]	12 \times 2	99.99
Disinfection by-product	Chloroform	DBD1	18 [43,71]	600 \times 0.03	80
Disinfection by-product	Bromate	+ ⁴			

¹ Dielectric barrier discharge reactor. ² Insufficient data available. ³ Alternating current. ⁴ This compound is formed by plasma technology, as opposed to being removed by it. * Power in Watts. # Time in Minutes.

6. Results

6.1. Typical Operating Conditions for Non-Thermal Plasma-Based Contaminant Degradation

A summary of the typical operation characteristics of non-thermal plasma generation systems for typical contaminants including EDCs (CECs) is presented in Table 1. Such conditions describe typical ranges of experimental variables and the results corresponding to such investigations. This serves, among other purposes, as a basis for further scientific investigation and general comparison of new findings with previously completed studies.

The information also gives ideas for the study and development of pilot/industrial systems.

6.2. Efficiency Tables

The effectiveness of contaminant removal, as stated earlier, was described using the concentration-(contact) time product (CT) and the reported (removal) percentage as shown in Table 2. The analysis of model pollutant, phenol gives CT values 5570 mg/L·min (chlorination) and 1200 mg/L·min (ozonation). The reported corresponding removal efficiencies are 99%(chlorination) and >99% (ozonation). The equivalent representative quantity under plasma technology for the same model contaminant (phenol) is the PT

(power \times time) value of 2430 W·min (as in Table 3) with associated removal efficiency of 98%. The breakdown of other contaminants by the three technologies may be compared in a similar way. This analysis of phenol removal and comparison among technologies gives basic knowledge for further investigations and scaling up to pilot schemes with respect to the plasma technology.

6.3. Operating Cost

The inflation-adjusted capital cost of the hypothetical plasma plant was ZAR 1.72 million. Hence, the combined maintenance, personnel and capital redemption cost was ZAR 240,000 per annum. The phenol experiment in Table 3 used a 9 W plasma generator to remove 0.183 g of phenol, from 0.09 L of effluent, in one hour. Scaling this to the hypothetical plant amounted to an annual electricity cost of ZAR 139,000. Therefore, the combined operating cost was ZAR 379,000 per annum.

The chlorination experiment for phenol removal in Table 2 required 5 kg of chlorine to remove 140 g of phenol, from 908 L of effluent, in one hour. This implied an hourly chlorine dose of 8 kg for the hypothetical chlorine plant. Hence, the inflation-adjusted capital cost was ZAR 1.2 million, while the annual operating cost was ZAR 207,000.

The ozonation experiment in Table 2 involving phenol removal required 1600 mg of ozone to remove 6638 mg of phenol, from 20 L of effluent, in one hour. Thus, the theoretical ozonation plant required 53.2 g of ozone per hour. This amounted to an inflation-adjusted capital cost of ZAR 8.57 million, with an annual operating cost of ZAR 14,000.

Figure 1 provides a summary of the operating costs presented above.

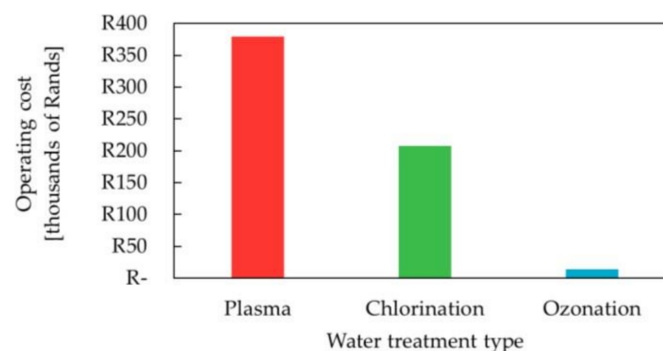


Figure 1. Operating cost for phenol removal using three different water treatment technologies. An effluent flowrate of 100 m³ of treated water per day was used, with a phenol concentration of 53 ppm.

6.4. Capital Cost

The capital costs calculated in the section above are presented in Figure 2.

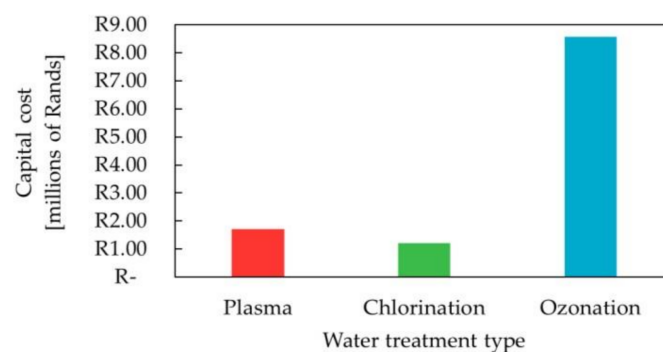


Figure 2. Capital cost for phenol removal using three different water treatment technologies. An effluent flowrate of 100 m³ of treated water per day was used, with a phenol concentration of 53 ppm.

6.5. Energy Yield

The phenol removal experiment (Table 3) utilised a 9 W plasma generator to remove 0.183 g of phenol in an hour: the energy yield was 20.3 g of phenol removed per kWh.

The chlorination experiment for phenol removal (Table 2) reported using 5 kg of chlorine to remove 140 g of phenol per hour. The capital cost for such a plant would be ZAR 550,000, with an annual electricity cost of ZAR 18,000. In 2009, this would have purchased 39,000 kWh for the year. Assuming 24 h, 365 days of operation, the plant would have used 4.5 kWh every hour. This implied an energy yield of 31.2 g of phenol removed per kWh.

The ozonation experiment for phenol removal (Table 2) removed 207 mg of phenol using 400 mg of ozone, which required 0.0052 kWh to produce. The energy yield was therefore 39.9 g of phenol removed per kWh.

The energy yields are presented graphically in Figure 3.

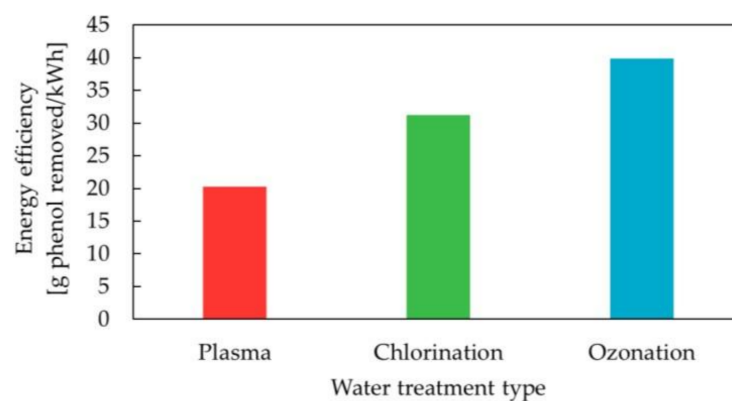


Figure 3. Energy efficiency associated with three different water treatment technologies when removing phenol as a contaminant.

6.6. Degradation Efficiency

The contaminant breakdown performance is described based on Table 4, from which it is observed that, for the selected model pollutant (phenol), the plasma technology, depending on the DBD reactor setup and optimization conditions, can achieve up to 98% contaminant degradation efficiency (as illustrated in Figure 4). Such plasma performance on phenol closely compares with well-established chlorination and ozonation technologies at 99% and >99%, respectively. The other illustrative comparisons for the listed contaminants are also accordingly shown in Table 4.

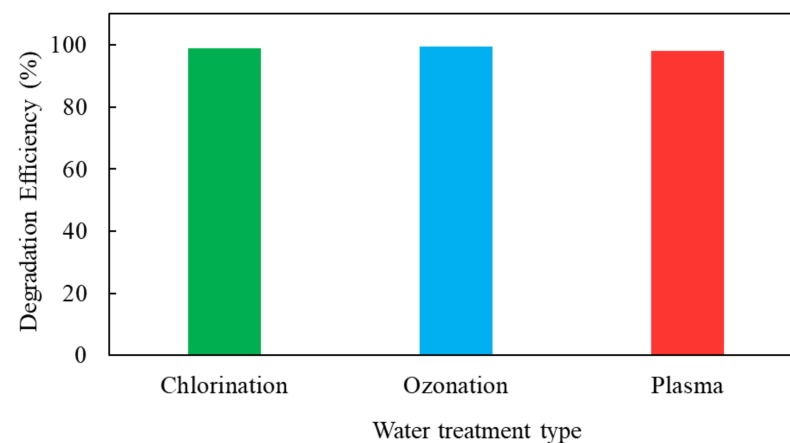


Figure 4. Contaminant removal efficiency by the different water treatment technologies considering phenol as a model pollutant.

Table 4. Comparison of power–time products of non-thermal plasma technology with concentration–time products of chlorination and ozonation technologies for the different contaminants.

Contaminant Description		Non-Thermal Plasma Technology			Chlorination Technology		Ozonation Technology	
		Plasma Type	PT (W × min)	% Removal	CT (mg/L × min)	% Removal	CT (mg/L × min)	% Removal
Organic	Phenol	DBD ¹	2430 [81]	98	5570 [90]	99	1200 [91]	>99
Organic: EDC	Carbamazepine	DBD ¹	36 [82]	99.99	1065 [92]	40	2.2 [93]	>99.9
Organic: EDC	Oestrone	DBD ¹	60,000 [71]	83.6	IDA ¹	IDA ¹	0.06 [94]	99.8
Organic: EDC	PFOS	DBD ¹	19,320 [83]	93.5	1440 [95]	83	840 [96]	43
Inorganic	Manganese	IDA ²			1.161 [97,98]	99	0.792 [99]	99
Inorganic	Iron	IDA ²			0.496 [97,98]	99	0.344 [99]	99
Pathogen	<i>E. coli</i>	DBD ¹	1080 [84]	99.9	0.25 [100]	99.99	0.05 [101]	99.99
Pathogen	<i>Cryptosporidium</i>	AC ³ Gliding Arc	1647 [85]	>99	7200 [102]	99	6.2 [103]	>99
Pathogen	Norovirus	DBD ¹	24 [106]	99.99	2 [104]	99.9	1.3 [105]	99.99
Disinfection byproduct	Chloroform	DBD ¹	18 [43,71]	80	+ ²		+ ²	
Disinfection byproduct	Bromate	+ ⁴			+ ²		+ ²	

¹ Dielectric barrier discharge reactor. ² Insufficient data available. ³ Alternating current. ⁴ This compound is formed by plasma technology, as opposed to being removed by it.

The operating parameters of the plasma reactor influence the performance outputs to a considerable extent, as demonstrated by Wang et al. [107] during the study of the degradation of phenolic compounds by DBD plasma. For their study case, the plasma discharge voltage, initial contaminant concentration, treatment liquid flow rate, solution matrix parameters (conductivity and pH) and structure of the organic pollutants were observed to influence the removal efficiency of the DBD plasma system. Murugesan et al. [37] complements the mentioned parameters with frequency (an electrical variable) and mode of contaminant exposure to the plasma. Thus, with well-optimised plasma treatment conditions and choice of suitable reactor structure, the plasma treatment can achieve close to 100% removal of pollutants. For example, Yang et al. [108], during their study of the degradation of bisphenol A using non-thermal DBD plasma, reported 100% elimination of contaminants in the treatment liquid within 25 min using an investigated optimum plasma discharge voltage of 16.8 kV.

7. Discussion

Prior to the adoption of the aforementioned experimental method, each of the technologies was compared using their weakest points (i.e., the highest CT and PT values from Tables 2 and 3, respectively, and combined presentation in Table 4). However, this yielded unrealistic costs and power requirements for each technology. This was the first indication that no singular technology is capable of removing all of the contaminants that may be present in wastewater.

7.1. Efficiency Table Analysis

Chlorination performed excellently in the inorganic contaminants category, as was expected from the literature. However, it was highly inefficient at removing organic contaminants. While phenol degraded in a minute, the chlorine concentration was high. These high doses could lead to a residual chlorine concentration beyond the maximum allowable limit of 4 mg/L if the contaminant concentration is insufficient. This would then require a dechlorination step on the plant, which increases the plant's capital and operating expenses. The two EDCs for which information was available was also poorly removed, with PFOS taking 6 h to degrade to only 83 %, and only 40 % of carbamazepine degrading in an hour. This unexpectedly poor performance from such a popular disinfectant highlights the need for advanced oxidation processes.

E. coli and norovirus were sufficiently degraded, which agreed with the literature. *Cryptosporidium* degradation was also as expected: reasonably high (99%), but at the expense of a high chlorine concentration and residence time. The chloroform and bromate degradation were not quantified because chlorination is more likely to produce these DBPs than to remove them.

Next, ozonation was considered. It displayed a low CT value (0.06) for oestrone, which is generally difficult to remove. It also offered far better performance for carbamazepine removal than chlorine. This agreed with the literature, since ozone is known for its high oxidising abilities. However, chlorine exhibited more efficient phenol degradation (CT of 430 as opposed to 1200) and more effective PFOS removal (83 % versus 43 %), although chlorine did have a greater contact time.

Ozone redeemed its superiority when analysing the organics: it had a CT value for iron and manganese that was approximately 30% lower than that of chlorine's. Ozone was also significantly superior to chlorine at pathogen degradation. Reductions of 99.99% were achieved for both *E. coli* and norovirus, with the CT values being respectively one-fifth and approximately half of the corresponding chlorination CT values. Ozone's oxidative prowess was furthered by its rapid degradation of *Cryptosporidium*, which is considered a resistant pathogen. Finally, DBP removal was not quantified, since ozonation is also more likely to produce these compounds than to remove them.

Next, non-thermal plasma was analysed. It displayed good oxidative abilities with a 98% removal of phenol in 50 s. While this may seem on par with chlorination (which also required one minute), the plasma only required electricity, whereas the fast chlorination process required large amounts of chlorine and a dechlorination stage. Relative to ozonation, plasma was faster at phenol degradation.

Plasma's potential was highlighted by the removal of carbamazepine (a persistent organic pollutant (POP)) because it was faster and achieved greater degradation than both ozone and chlorine. A similar trend applies to the removal of PFOS. Next, plasma's removal of oestrone was sufficient (83%), but not as effective or fast as ozone.

For metal oxidation, the literature data were insufficient due to the relative immaturity of plasma technology. Plasma's pathogen degradation proves that it is equally as effective as ozone and chlorine. It degraded *Cryptosporidium* significantly faster than chlorine, but is probably not as quick as ozone. Another interesting observation is that there is balance between chlorine and plasma: chlorine is more effective and faster at *E. coli* removal, but plasma is more effective at norovirus removal.

Lastly, plasma only removes the DBPs of chlorination, and not for ozonation. Furthermore, it removes this DBP (chloroform) to a large extent (80 %).

Considering the above, it is clear that if the objective is to provide a community with water that is free of endocrine-disrupting chemicals (EDCs), no single technology is sufficient. Combining ozone with plasma will be effective, since both are powerful oxidants. However, plasma would be unable to remove the DBPs of ozonation and will likely increase the bromate concentration. The most feasible option would be to combine chlorination with plasma. Both are powerful oxidants, with plasma offering good EDC removal where chlorine fails, and with chlorine offering good inorganic oxidation where data for plasma are unknown. Furthermore, chlorination offers more effective and faster *E. coli* reduction, while plasma offers more effective norovirus and *Cryptosporidium* reduction. To further reinforce this pairing, plasma is able to remove the DBPs associated with chlorination. However, other factors are yet to be considered, including costs, chemical demand and energy efficiency.

7.2. Operating Cost Analysis

The hypothetical plasma plant had the highest operating cost (ZAR 379,000 per annum). This was nearly double the cost of chlorination (ZAR 207,000) and many times greater than ozonation. This is because plasma operates solely on electricity, while chlorination requires chemicals, which can be obtained for relatively lower costs.

However, if the plasma generator could be powered using renewable energy, then the electricity costs and, hence, overall costs would be lower. However, the facilities required to utilise renewable energy would contribute to the plasma plant's overall cost.

Finally, the ozonation plant's operating costs appear negligible relative to plasma and chlorination. This is because despite ozone taking considerable power to produce (i.e., high electricity costs), it has a high oxidising potential, making small doses of it highly effective.

7.3. Capital Cost Analysis

The ozonation plant was the most capital-intensive (ZAR 8.57 million). This explains its low operating cost from earlier.

The chlorination plant offered the lowest capital cost (ZAR 1.2 million). However, chlorination is the world's oldest water purification technology and has many years of optimisation and cost-cutting research behind it.

The plasma plant was slightly costlier (ZAR 1.72 million) despite being a relatively new technology. As with all technology, it is expected that the equipment associated with plasma generation will decrease with time, making it even more affordable than chlorination. This effect on affordability will be further enhanced by the ongoing plasma research being conducted globally. Additionally, since operating costs were calculated as a function of capital costs, a lower capital cost implies a more economically feasible plasma plant.

Considering the results, the combination of plasma and ozonation is the most capital-intensive option. On the other hand, the combination of plasma and chlorination is less than half the cost of a single ozonation plant, making it the cheaper option.

7.4. Energy Yield Analysis

Plasma exhibited the lowest energy yield (20.3 g/kWh), while ozonation was nearly twice as energy efficient (39.9 g/kWh).

The combination of chlorination and ozonation was the most energy-efficient option. On the other hand, combining plasma and chlorination was the least energy-efficient option.

However, these conclusions were drawn based on data from pilot-scale plasma generators. Companies such as Flowrox OyTM now trading as Roxia OyTM are in the process of producing industrial-size plasma reactors with far greater energy yields: around 88 g/kWh, or more than double that of ozone.

7.5. Chemical Demand Analysis

Since both ozonation and chlorination require the use of hazardous chemicals, retrofitting plasma to either plant type is equally feasible. Furthermore, plasma does not require any dangerous chemicals, making it easy to retrofit plasma to either of its mature counterparts.

7.6. Degradation Efficiency

In terms of contaminant removal efficiency, using phenol as a model pollutant, chlorination and ozonation were superior. However, plasma (on phenol) scored closely at 98% compared to 99% (for chlorination) and >99% (for ozonation). If the plasma operation conditions are well optimised, coupled with a good reactor design, the performance can be considerably enhanced to achieve and possibly supersede chlorination and ozonation treatment efficiencies. Thus, if industrial-scale plasma applications are piloted following such assessed possibility of retrofitting chlorination plants with plasma, then an enhanced level of performance of (waste)water treatment plants can be achieved. The problem of such discussed recalcitrant pollutants would no longer be a treatment problem.

8. Conclusions

While vast amounts of data are available surrounding chlorination and ozonation, the data surrounding plasma water and wastewater purification are greatly limited. Not all wastewater contaminants have been passed through a plasma reactor (such as manganese and iron), and the experiments that have been completed were performed by different

researchers with different reactor designs. This implies different effectiveness values, efficiency values, energy yields, operating costs and capital costs. It is therefore difficult to formulate a comprehensive review of non-thermal plasma's capabilities.

From the available data, it was concluded that it is feasible to retrofit existing chlorination wastewater treatment plants with non-thermal plasma technology to ensure the removal of contaminants of emerging concern (CECs). This is favourable for South Africa, where chlorination plants are popular. However, it was not feasible to retrofit an ozonation plant with plasma technology, as both produce similar disinfection by-products. This could cancel out the advantages of pairing the technologies in the first place. The coupling of chlorination and non-thermal plasma treatment provided the most effective contaminant removal (of the three possible combinations), and their combined capital cost was less than half the capital cost of a single ozonation plant, making it highly feasible. Unfortunately, the aforementioned combination had the highest operating costs and lowest energy efficiency. This reduces the attractiveness of plasma, along with its chances of large-scale implementation.

We therefore state, from an application point of view, that chlorination plants can be furnished with plasma technology to achieve a combined (synergistic) treatment effect, with plasma units completing the treatment by removing the recalcitrant CECs. The combined process strategy is premised on the promise that it is possible to retrofit existing plants with sustainable plasma technology.

Three recommendations can be made regarding the plasma reactor's feasibility: firstly, the energy yield of non-thermal plasma reactors should be improved. This can be achieved through increased research and improved designs. Secondly, the operating cost of plasma reactors should be lowered, and this can be realised by redesigning them to utilise renewable energy sources. Thirdly, lowering the cost of plasma reactors (perhaps by utilising economies of scale) can reduce both capital and operating costs, making plasma a more attractive investment. In addition, the decontamination efficiency of the plasma can be improved through further studies, leading to suitable reactor design and operating conditions optimization to suit practical applications.

A final recommendation involves performing more research on contaminants of emerging concern. In the first case, the research should investigate how quickly CECs accumulate in the environment. This will provide an indication of the urgency with which plasma retrofitting should be approached. Secondly, the research should include determining the concentrations at which CECs become toxic to humans. This will provide us with both a timeframe and a maximum concentration limit and will ensure that the health of future generations is secured.

The discussion and information presented in this manuscript clarify that with the envisioned success of plasma technology at the industrial level, a plasma treatment unit should be incorporated following chlorination to deal with the recalcitrant pollutants such as EDCs and chlorination DBPs. Plasma, based on scientific evidence, can degrade a wide range of pollutants including CECs and microbes, organic compounds [39,71,81–83,109], inorganic residues causing water hardness [110], disinfection byproducts [43,71] and others. No standalone technology can truly meet all wastewater treatment requirements (even at the tertiary level), but combinations/synergies will assure commendable desired results, with chlorination–plasma among the feasible options.

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References

1. Brusseau, M.; Pepper, I.; Gerba, C. *Environmental and Pollution Science*, 3rd ed.; Academic Press: Cambridge, MA, USA, 2019; pp. 393–418.
2. Ameta, R.; Ameta, S.C. *Advanced Oxidation Processes for Waste Water Treatment*, 1st ed.; Academic Press: Cambridge, MA, USA, 2018; pp. 1–12.
3. Gago-Ferrero, P.; Gros, M.; Ahrens, L.; Wiberg, K. Impact of on-site, small and large scale wastewater treatment facilities on levels and fate of pharmaceuticals, personal care products, artificial sweeteners, pesticides, and perfluoroalkyl substances in recipient waters. *Sci. Total Environ.* **2017**, *601*, 1289–1297. [[CrossRef](#)] [[PubMed](#)]
4. Sorengård, M.; Campos-Pereira, H.; Ullberg, M.; Lai, F.Y.; Golovko, O.; Ahrens, L. Mass loads, source apportionment, and risk estimation of organic micropollutants from hospital and municipal wastewater in recipient catchments. *Chemosphere* **2019**, *234*, 931–941. [[CrossRef](#)] [[PubMed](#)]
5. Gadupudi, C.K.; Rice, L.; Xiao, L.; Kantamaneni, K. Endocrine disrupting compounds removal methods from wastewater in the United Kingdom: A review. *Sci* **2021**, *3*, 11. [[CrossRef](#)]
6. van Zijl, M.C. Estrogenic Activity, Target Endocrine Disrupting Chemical Levels and Potential Health Risks of Bottled Water and Water from Selected Distribution Points in Pretoria and Cape Town. PhD Thesis, University of Pretoria, Pretoria, South Africa, 2016.
7. Amor, C.; Marchão, L.; Lucas, M.S.; Peres, J.A. Application of advanced oxidation processes for the treatment of recalcitrant agro-industrial wastewater: A review. *Water* **2019**, *11*, 205. [[CrossRef](#)]
8. Flowrox Plasma Oxidizer. Available online: <https://flowrox.com/article/plasma-water-treatment/> (accessed on 5 July 2021).
9. Chlorine and Drinking Water. Available online: <https://chlorine.americanchemistry.com/Chlorine/DrinkingWaterFAQ/> (accessed on 5 July 2021).
10. Water Purification Methods-and the South African Position. Available online: <https://www.instrumentation.co.za/article.aspx?pkarticleid=2906> (accessed on 5 July 2021).
11. National Research Council (US) Safe Drinking Water Committee. *Drinking Water and Health*; National Academies Press (US): Washington, DC, USA, 1980; Volume 2. Available online: <https://www.ncbi.nlm.nih.gov/books/NBK234590/> (accessed on 3 April 2023).
12. Chlorination. Available online: <https://sswm.info/sswm-solutions-bop-markets/affordable-wash-services-and-products/> (accessed on 5 July 2021).
13. MSR SE200TM Community Chlorine Maker. Available online: <https://www.msrgear.com/ie/products/global-health/se200-community-chlorine-maker/10275.html> (accessed on 5 July 2021).
14. Safe Drinking Water Foundation. What is Chlorination Fact Sheet. Available online: <https://www.safewater.org/fact-sheets-1/2017/1/23/what-is-chlorination> (accessed on 3 April 2023).
15. Lenntech Disinfection By-products Types. Available online: <https://www.lenntech.com/processes/disinfection/byproducts/disinfection-byproducts-types.htm> (accessed on 5 July 2021).
16. Jameson, P.B.; Hung, Y.-T.; Kuo, C.Y.; Bosela, P.A. Cryptosporidium outbreak (water treatment failure): North Battleford, Saskatchewan, spring 2001. *J. Perform. Constr. Facil.* **2008**, *22*, 342–347. [[CrossRef](#)]
17. Bright Blue CCS Ozone Systems for Prepared Water Disinfection. Available online: <https://www.wassertec.co.za/ozone-water-products/bright-blue-ccs/> (accessed on 5 July 2021).
18. How Is Aqueous Ozone Used in Olympic Swimming Pools? Available online: <https://purozo.co.uk/aqueous-ozone-in-olympic-swimming-pools/> (accessed on 5 July 2021).
19. Eco-logical Technology: Medical Ozone Use in Hospitals, Clinics and Nursing Homes. Available online: https://www.eco3.co.za/medical_ozone.htm (accessed on 5 July 2021).
20. United States Environmental Protection Agency. *Wastewater Technology Fact Sheet: Ozone Disinfection*; Office of Water: Washington, DC, USA, 1999.
21. Van Der Walt, M.; Krüger, M.; Van Der Walt, C. *The South African Oxidation and Disinfection Manual*; Technical Report; Water Research Commission: Pretoria, South Africa, 2009; ISBN 9781770058637.
22. Ozone Applications: Drinking Water. Available online: <https://www.lenntech.com/library/ozone/drinking/ozone-applications-drinking-water.htm> (accessed on 5 July 2021).
23. Ozonation in Water Treatment. Available online: <https://www.knowyourh2o.com/indoor-4/ozonation-in-water-treatment> (accessed on 3 April 2023).
24. Gould, J.P.; Weber, W.J., Jr. Oxidation of phenols by ozone. *J. Water Pollut. Control Fed.* **1976**, *48*, 47–60.
25. Iron and Manganese Removal with Ozone. Available online: <https://ozonesolutions.com/blog/iron-and-manganese-removal-with-ozone/> (accessed on 3 April 2023).

26. de Oliveira Pereira, R.; de Alda, M.L.; Joglar, J.; Daniel, L.A.; Barceló, D. Identification of new ozonation disinfection byproducts of 17 β -estradiol and estrone in water. *Chemosphere* **2011**, *84*, 1535–1541. [CrossRef]
27. Richardson, S.D. Disinfection by-products and other emerging contaminants in drinking water. *Trends Analyt. Chem.* **2003**, *22*, 666–685. [CrossRef]
28. Environmental Technology Initiative. *What Is Ozone Disinfection?* Technical Report; United States Environmental Protection Agency: Washington, DC, USA, 2000.
29. Ozone Generators That Are Sold as Air Cleaners. Available online: <https://www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners> (accessed on 5 July 2021).
30. UV Disinfection Drinking Water Treatment. Available online: <https://www.knowyourh2o.com/indoor-4/ultraviolet-disinfection> (accessed on 3 April 2023).
31. Rhode Island Department of Health; University of Rhode Island Cooperative Extension Water Quality Program. *Ultraviolet Radiation Treatment of Drinking Water Supplies*; Technical Report; United States Environmental Protection Agency: Washington, DC, USA, 2007.
32. Lin, J. Conventional Water Treatment Processes for Removing Pharmaceutical and Endocrine Disrupting Compounds. Master's Thesis, Graduate School of the University of Massachusetts, Massachusetts, MA, USA, 2011.
33. American Air and Water: UV Water Disinfection. Available online: <https://www.americanairandwater.com/uv-water-applications.htm> (accessed on 5 July 2021).
34. Pros and Cons of UV filtration. Available online: <https://haguewaterofmd.com/pros-and-cons-of-uv-fil-tration/> (accessed on 5 July 2021).
35. Dave, H.; Ledwani, L.; Nema, S.K. *The Impact and Prospects of Green Chemistry for Textile Technology*, 1st ed.; Woodhead Publishing: Sawston, UK, 2019; pp. 199–249. [CrossRef]
36. Zeghioud, H.; Nguyen-Tri, P.; Khezami, L.; Amrane, A.; Assadi, A.A. Review on discharge Plasma for water treatment: Mechanism, reactor geometries, active species and combined processes. *J. Water Process Eng.* **2020**, *38*, 101664. [CrossRef]
37. Murugesan, P.; Moses, J.A.; Anandharamakrishnan, C. Water decontamination using non-thermal plasma: Concepts, applications, and prospects. *J. Environ. Chem. Eng.* **2020**, *8*, 104377. [CrossRef]
38. Malik, M.A. Water purification by plasmas: Which reactors are most energy efficient? *Plasma Chem. Plasma Process.* **2010**, *30*, 21–31. [CrossRef]
39. Yusuf, A.; Amusa, H.K.; Eniola, J.O.; Giwa, A.; Pikuda, O.; Dindi, A.; Bilad, M.R. Hazardous and emerging contaminants removal from water by plasma-based treatment: A review of recent advances. *Chem. Eng. J. Adv.* **2023**, *14*, 100443. [CrossRef]
40. Tak, G.; Gallagher, M.; Gangoli, S.; Gutsol, A.; Fridman, A. Use of non-thermal atmospheric pressure plasma for air cleaning and sterilization. In *IEEE Conference Record-Abstracts, Proceedings of IEEE International Conference on Plasma Science, Monterey, CA, USA, 20–23 June 2005*; IEEE: New York, NY, USA, 2005. [CrossRef]
41. Fridman, N.; Lahav, O. Formation and minimization of bromate ions within non-thermal-plasma advanced oxidation. *Desalination* **2011**, *280*, 273–280. [CrossRef]
42. Aljundi, I.H. Bromate formation during ozonation of drinking water: A response surface methodology study. *Desalination* **2011**, *277*, 24–28. [CrossRef]
43. Shahna, F.G.; Ebrahimi, H.; Jaleh, B.; Bahrami, A. Decomposition of gas-phase chloroform using nano-photocatalyst downstream the novel non-thermal plasma reactor: By-products elimination. *Int. J. Environ. Sci Technol.* **2015**, *12*, 3489–3498. [CrossRef]
44. Sciex: Contaminants of Emerging Concern. Available online: <https://sciex.com/applications/environmental-testing/contaminants-of-emerging-concern> (accessed on 5 July 2021).
45. Wee, S.Y.; Aris, A.Z.; Yusoff, F.M.; Praveena, S.M. Occurrence of multiclass endocrine disrupting compounds in a drinking water supply system and associated risks. *Sci. Rep.* **2010**, *10*, 17755. [CrossRef] [PubMed]
46. Coetzee, M.; Momba, M.; Kibambe, G.; Thobela, K.; Kgositau, T.; Mahlangu, P. *The Removal of Endocrine Disrupting Compounds by Wastewater Treatment Plants*; Technical Report to the Water Research Commission; Tshwane University of Technology: Tshwane, South Africa, 2017.
47. Gonsioroski, A.; Mourikes, V.E.; Flaws, J.A. Endocrine disruptors in water and their effects on the reproductive system. *Int. J. Mol. Sci.* **2020**, *21*, 1929. [CrossRef]
48. International Programme on Chemical Safety. *Global Assessment of the State-of-the-Science of Endocrine Disruptors*; Technical Report; World Health Organisation: Geneva, Switzerland, 2002.
49. Björvang, R.D.; Damdimopoulou, P. Persistent environmental endocrine disrupting chemicals in ovarian follicular fluid and in vitro fertilization treatment outcome in women. *Ups. J. Med. Sci.* **2020**, *125*, 85–94. [CrossRef]
50. Adeel, M.; Song, X.; Wang, Y.; Francis, D.; Yang, Y. Environmental impact of estrogens on human, animal and plant life: A critical review. *Environ. Int.* **2017**, *99*, 107–119. [CrossRef]
51. Wise, A.; O'Brien, K.; Woodruff, T. Are oral contraceptives a significant contributor to the estrogenicity of drinking water? *Environ. Sci. Technol.* **2011**, *45*, 51–60. [CrossRef]
52. Ebele, A.J.; Abdallah, M.A.-E.; Harrad, S. Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerg. Contam.* **2016**, *3*, 1–16. [CrossRef]

53. Gwanzura, E. Degradation Studies of Carbamazepine and *Escherichia coli* in Wastewater Using a Non-Thermal Electrical Discharge Reactor. Master's Thesis, University of KwaZulu-Natal, KwaZulu-Natal, South Africa, 2020.
54. Corsini, E.; Luebke, R.W.; Germolec, D.R.; DeWitt, J.C. Perfluorinated compounds: Emerging POPs with potential immunotoxicity. *Toxicol. Lett.* **2014**, *230*, 263–270. [CrossRef] [PubMed]
55. Petrovic, M.; Farré, M.; Eljarrat, E.; Diaz, S.; Barceló, D. *Liquid Chromatography*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 389–410.
56. Environmental and Occupational Health Surveillance Program. *Perfluorinated Chemicals (PFCs) in Drinking Water*; Technical Report; New Jersey Department of Health: Trenton, NJ, USA, 2016.
57. Coliform Bacteria in Drinking Water Supplies. Available online: https://www.health.ny.gov/environmental/water/drinking/coliform_bacteria.htm (accessed on 5 July 2021).
58. Coliform Bacteria? Examples, Characteristics, Fecal/Total Count Tests. Available online: <https://www.microscopemaster.com/coliform.html> (accessed on 5 July 2021).
59. Indicators of Drinking Water Quality. Available online: <https://waterandhealth.org/safe-drinking-water/indicators-drinking-water-quality> (accessed on 5 July 2021).
60. *E. coli* Infection from Food or Water. Available online: <https://www.healthlinkbc.ca/health-top-ics/hw133795> (accessed on 5 July 2021).
61. World Health Organisation. *Guidelines for Drinking-Water Quality*, 4th ed.; World Health Organisation: Geneva, Switzerland, 2017; pp. 30–630. ISBN 978-92-4-154995-0.
62. Centers for Disease Control and Prevention: Water-Related Diseases and Contaminants in Public Water Systems. Available online: https://www.cdc.gov/healthywater/drinking/public/water_diseases.html (accessed on 5 July 2021).
63. National Health Service Norovirus: Vomiting Bug. Available online: <https://www.nhs.uk/conditions/norovirus/> (accessed on 5 July 2021).
64. South Dakota Department of Agriculture and Natural Resources: Inorganic Contaminants. Available online: <https://denr.sd.gov/des/dw/IOCs.aspx> (accessed on 5 July 2021).
65. American Water Works Association: Contaminants of Concern. Available online: <https://www.awwa.org/Resources-Tools/Resource-Topics/Inorganic-Contaminants> (accessed on 5 July 2021).
66. Penn State Extension: Iron and Manganese in Private Water Systems. Available online: <https://extension.psu.edu/iron-and-manganese-in-private-water-systems> (accessed on 5 July 2021).
67. Bruce, I.D.; Sharon, O.S.; Wayne, E.W. Drinking Water: Iron and Manganese. NebGuide Series. *Natural Resources/Water Management*. 2021, G1714, pp. 1–6. Available online: <https://extensionpubs.unl.edu/publication/9000016364707/drinking-water/> (accessed on 5 July 2021).
68. Manganese: Get Informed. Available online: <https://www.knowyourh2o.com/indoor-6/manganese> (accessed on 3 April 2023).
69. Rana, A.G.; Tasbihi, M.; Schwarze, M.; Minceva, M. Efficient advanced oxidation process (AOP) for photocatalytic contaminant degradation using exfoliated metal-free graphitic carbon nitride and visible light-emitting diodes. *Catalysts* **2021**, *11*, 662. [CrossRef]
70. Office of Water. *Disinfection Profiling and Benchmarking Technical Guidance Manual*; Technical Report; United States Environmental Protection Agency: Washington, DC, USA, 2020.
71. Sarangapani, C.; Danaher, M.; Tiwari, B.; Lu, P.; Bourke, P. Efficacy and mechanistic insights into endocrine disruptor degradation using atmospheric air plasma. *Chem. Eng. J.* **2017**, *326*, 700–714. [CrossRef]
72. How Temperature Impacts Onsite Wastewater Treatment. Available online: https://www.onsiteinstaller.com/online_exclusives/2017/05/how_temperature_impacts_onsite_wastewater_treatment (accessed on 5 July 2021).
73. Division of Toxicology and Environmental Medicine, Applied Toxicology Branch. *Toxicological Profile For phenol*; Technical Report; Agency for Toxic Substances and Disease Registry: Atlanta, GA, USA, 2008.
74. Trading Economics: South Africa Prime Lending Rate. Available online: <http://www.tradingeconomics.com/south-africa/bank-lending-rate> (accessed on 28 September 2021).
75. Tribe, M.A.; Alpine, R.L.W. Scale economies and the “0.6 Rule”. *Eng. Cost. Prod. Econ.* **1986**, *10*, 271–278. [CrossRef]
76. Barillas, L. Design of a prototype of water purification by plasma technology as the foundation for an industrial wastewater plant. *J. Phys. Conf. Ser.* **2015**, *591*, 012057. [CrossRef]
77. STATSSA: South Africa Consumer Price Index (CPI) (1960–2021). Available online: <https://tradingeconomics.com/south-africa/consumer-price-index-cpi> (accessed on 28 September 2022).
78. Eskom. *Eskom Tariffs & Charges Booklet 2020/2021*; Technical Report; Eskom: Sunninghill, South Africa, 2020.
79. Eskom. *Tariffs & Charges 2009/10*; Technical Report; Eskom: Sunninghill, South Africa, 2009.
80. Loitech Ozone Generators. Available online: www.loitech.ee/eng/ozone-generators (accessed on 28 September 2021).
81. Bubnov, A.G.; Burova, E.Y.; Grinevich, V.I.; Rybkin, V.V.; Kim, J.K.; Choi, H.S. Plasma-catalytic de-composition of phenols in atmospheric pressure dielectric barrier discharge. *Plasma Chem. Plasma Process.* **2006**, *26*, 19–30. [CrossRef]
82. Liu, Y.; Mei, S.; Iya-Sou, D.; Cavadias, S.; Ognier, S. Carbamazepine removal from water by dielectric barrier discharge: Comparison of ex situ and in situ discharge on water. *Chem. Eng. Process. Process Intensif.* **2012**, *56*, 10–18. [CrossRef]

83. Palma, D.; Papagiannaki, D.; Lai, M.; Binetti, R.; Sleiman, M.; Minella, M.; Richard, C. PFAS degradation in ultrapure and groundwater using non-thermal plasma. *Molecules* **2021**, *26*, 924. [CrossRef]
84. Akter, M.; Yadav, D.K.; Ki, S.H.; Choi, E.H.; Han, I. Inactivation of infectious bacteria using nonthermal biocompatible plasma cabinet sterilizer. *Int. J. Mol. Sci.* **2020**, *21*, 8321. [CrossRef]
85. Craighead, S.; Hertrich, S.; Boyd, G.; Sites, J.; Niemira, B.A.; Kniel, K.E. Cold atmospheric plasma jet inactivates *Cryptosporidium parvum* oocysts on cilantro. *J. Food Prot.* **2020**, *83*, 794–800. [CrossRef] [PubMed]
86. Aboubakr, H.A.; Williams, P.; Gangal, U.; Youssef, M.M.; El-Sohaimy, S.A.; Bruggeman, P.J.; Goyal, S.M. Virucidal Effect of Cold Atmospheric Gaseous Plasma on Feline Calicivirus, a Surrogate for Human Norovirus. *Appl. Environ. Microbiol.* **2015**, *81*, 3612–3622. [CrossRef] [PubMed]
87. Lakhian, V.; Dickson-Anderson, S.E. Reduction of bromate and chlorate contaminants in water using aqueous phase corona discharge. *Chemosphere* **2020**, *255*, 126864. [CrossRef]
88. Ma, S.; Kim, K.; Huh, J.; Hong, Y. Characteristics of microdischarge plasma jet in water and its application to water purification by bacterial inactivation. *Sep. Purif. Technol.* **2017**, *188*, 147–154. [CrossRef]
89. Rashmei, Z.; Bornasi, H.; Ghoranneviss, M. Evaluation of treatment and disinfection of water using cold atmospheric plasma. *J. Water Health* **2016**, *14*, 609–616. [CrossRef]
90. Cleary, E.J. *Phenol Wastes Treatment by Chemical Oxidation*, 1st ed.; Ohio River Valley Water Sanitation Commission: Cincinnati, OH, USA, 1951; pp. 17–34.
91. Mooketsi, O.I. Evaluation of Ozone for the Removal of Phenolic Compounds in Wastewater from the Merisol Plant (Sasolburg). Master's Thesis, University of the Witwatersrand, Johannesburg, South Africa, 2008.
92. Zhou, S.; Xia, Y.; Yao, T.; Shi, Z.; Zhu, S. Degradation of carbamazepine by UV/chlorine advanced oxidation process and formation of disinfection by-products. *Environ. Sci. Pollut. Res.* **2016**, *23*, 16448–16455. [CrossRef] [PubMed]
93. Kraakström, M.; Saeid, S.; Tolvanen, P.; Kumar, N.; Salmi, T.; Kronberg, L.; Eklund, P. Ozonation of carbamazepine and its main transformation products: Product determination and reaction mechanisms. *Environ. Sci. Pollut. Res.* **2020**, *27*, 23258–23269. [CrossRef] [PubMed]
94. Pešoutová, R.; Stríteský, L.; Hlavínek, P. A pilot scale comparison of advanced oxidation processes for estrogenic hormone removal from municipal wastewater effluent. *Water Sci. Technol.* **2014**, *70*, 70–75. [CrossRef]
95. Belkouteb, N.; Franke, V.; McCleaf, P.; Köhler, S.J.; Ahrens, L. Removal of per- and polyfluoroalkyl substances (PFASs) in a full-scale drinking water treatment plant—Long-term performance of granular activated carbon (GAC) and influence of flow-rate. *Water Res.* **2020**, *182*, 115913. [CrossRef]
96. Yu-Chen Lin, A.; Sri Chandana, P.; Chang, C.-Y.; Hong, P.A.; Hsueh, H.F. Removal of perfluorooctanoic acid and perfluorooctane sulfonate via ozonation under alkaline condition. *J. Hazard. Mater.* **2012**, *243*, 272–277. [CrossRef]
97. Clean Water Store: How much Chlorine to Inject to Treat Iron & Manganese before Iron Filters? Available online: <https://www.cleanwaterstore.com/blog/much-chlorine-inject-treat-iron-manganese-iron-filters/> (accessed on 5 July 2021).
98. Khadse, G.K.; Patni, P.M.; Labhasetwar, P.K. Removal of iron and manganese from drinking water supply. *Sustain. Water Resour. Manag.* **2015**, *1*, 157–165. [CrossRef]
99. Gates, D.; Krasner, S. *Guidance Manual: Alternative Disinfectants and Oxidants*; Technical Report; United States Environmental Protection Agency: Washington, DC, USA, 1999.
100. Bowman, G.; The Wisconsin State Lab of Hygiene; Mealy, R. *The Role of Chlorine in Dealing with Water Contamination*; Technical Report; The Wisconsin Department of Natural Resources: Wisconsin, WI, USA, 2004.
101. Huizenga, J. How much Ozone Do I Need to Destroy Bacteria and Viruses? Available online: <https://www.oxidationtech.com/blog/how-much-ozone-do-i-need-to-destroy-bacteria-and-viruses/> (accessed on 5 July 2021).
102. Korich, D.G.; Mead, J.R.; Madore, M.S.; Sinclair, N.A.; Sterling, C.R. Effects of ozone, chlorine dioxide, chlorine, and monochloramine on *Cryptosporidium parvum* oocyst viability. *Appl. Environ. Microbiol.* **1990**, *56*, 1423–1428. [CrossRef] [PubMed]
103. United States Environmental Protection Agency. *Guidance Manual for Compliance with the Filtration and Disinfection Required for Public Water Systems Using Surface Water Sources*; Technical Report; United States Environmental Protection Agency: Washington, DC, USA, 1991.
104. Kanna, C.R. Inactivation of Viruses in Water by Chlorination Using Bacteriophages as Model Organisms. Master's Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2015.
105. Concept of Ozone Disinfection. Available online: <https://spartanwatertreatment.com/ozone-disinfection-ct/> (accessed on 5 July 2021).
106. Mohamed, H.; Nayak, G.; Rendine, N.; Wigdahl, B.; Krebs, F.C.; Bruggeman, P.J.; Miller, V. Nonthermal plasma as a novel strategy for treating or preventing viral infection and associated disease. *Front. Phys.* **2021**, *9*, 683118. [CrossRef]
107. Wang, J.; Li, L.; Cao, H.; Yang, C.; Guo, Z.; Shi, Y.; Li, W.; Zhao, H.; Sun, J.; Xie, Y. Degradation of phenolic compounds by dielectric barrier plasma: Process optimization and influence of phenol substituents. *Chem. Eng. J.* **2020**, *385*, 123732. [CrossRef]
108. Yang, J.; Zeng, D.; Hassan, M.; Ma, Z.; Dong, L.; Xie, Y.; He, Y. Efficient degradation of Bisphenol A by dielectric barrier discharge non-thermal plasma: Performance, degradation pathways and mechanistic consideration. *Chemosphere* **2022**, *286*, 131627. [CrossRef]

109. Mok, Y.S.; Jo, J.-O.; Whitehead, J.C. Degradation of an azo dye Orange II using a gas phase dielectric barrier discharge reactor submerged in water. *Chem. Eng. J.* **2008**, *142*, 56–64. [[CrossRef](#)]
110. Vasikaran, E.M.; Murugesan, P.; Moses, J.A.; Anandharamakrishnan, C. Performance of non-thermal plasma reactor for removal of organic and inorganic chemical residues in aqueous media. *J. Electrostat.* **2022**, *115*, 103671. [[CrossRef](#)]

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