



# Potential and challenges of ozonation for potable reuse in Brazil: an overview of general and practical aspects

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Received: 13 February 2025 / Revised: 28 February 2026 / Accepted: 5 April 2026 / Published online: 21 April 2026  
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## Abstract

Amidst the increasing challenges related to the quality and availability of water resources, the implementation of effective and safe technologies is crucial to ensure the preservation and security of potable water supply. Water reuse has emerged as a strategic approach to mitigate water scarcity and environmental degradation. However, its large-scale implementation remains limited by technical, regulatory, and public acceptance barriers. In this context, ozonation emerges as a promising alternative capable of purifying wastewater far beyond potable standards. It contributes to mitigating water scarcity and pollution while promoting environmental sustainability and providing significant economic benefits. This review critically evaluates the environmental potential and practical challenges of ozonation for potable water reuse, with a particular focus on the Brazilian context. A structured literature search of peer-reviewed studies (2014–2024) on ozonation for water and wastewater reuse was conducted, covering the fundamentals of ozonation, operational aspects, determination of the optimal ozone dose, application in water reuse, by-products formation, and future perspectives. The findings indicate that ozonation can significantly enhance water quality and safety when appropriately designed and operated, particularly as part of multi-barrier treatment systems. The discussion highlights the need for site-specific optimization, robust monitoring strategies, and effective communication to improve public acceptance, while demonstrating how ozonation can address key challenges in reclaimed water treatment and support sustainable water management practices.

**Keywords** Advanced treatment technologies · Environmental impact · Ozone · Potable water · Sustainable water supply

## Introduction

The preservation of natural resources is a permanent challenge for society and, among them, is the issue of maintaining the quality of water sources. The quality of drinking water distributed to the population is of vital importance for public health (Reis et al. 2017). In this context, population growth, urbanization and persistent drought are straining water resources in many regions of the world, while pollution and contamination exacerbate these problems (Oliveira 2020).

The continuous disposal of effluents and waste, even if in small quantities, in addition to industrial and urban activities located around springs and the contributions resulting from them, are critical factors that can compromise, to a greater or lesser extent, the catchment water and, as a consequence, water distributed to the population (Bentos et al. 2021). Also, water scarcity is a problem in arid, semi-arid regions and other regions with seasonally abundant water resources, but insufficient to satisfy high consumption demands. As this situation intensifies, it is suggested that water technology companies work to advance the discussion on sustainable water supply strategies, including the use of recycled water, or reused water, to combat pollution and water shortages, ensuring that the supply of drinking water is used for essential purposes (Hooper et al. 2020).

Advanced treatment technologies have demonstrated that wastewater can be purified far beyond potable water standards and safely reused for both potable and non-potable purposes. Still, the reuse of water can also bring numerous economic benefits, since reused water is cheaper than

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Editorial responsibility: Samareh Mirkia .

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the generation of water through other technologies, such as desalination, which means savings for both public services and for citizens (Deng and Zhao 2015). Among the technologies used worldwide are treatments such as adsorption, oxidation with ozone, chlorine dioxide and hydrogen peroxide, membrane separation, reverse electrolysis, ion exchange, distillation, chemical precipitation, among others (Teel et al. 2022). These technologies represent significant advances in the water treatment and there is a need for their real application in treatment systems.

The ozonation process has demonstrated high efficiency in removing various compounds, particularly resilient pollutants like contaminants of emerging concern (CECs), achieving degradation rates exceeding 90% (Mohsin and Mohammed 2021; Costa et al. 2024) due to ozone's high reactivity and hydroxyl radicals towards compounds in the aqueous matrix. Additionally, ozone is a powerful disinfectant capable of inactivating a broad spectrum of pathogens such as bacteria, viruses, protozoa, and prion proteins, without leaving toxic residues (Epelle et al. 2022; de Carvalho Costa et al. 2024). However, despite its advantages, the use of ozone in water reuse treatment faces challenges.

Variations in water characteristics such as pH and organic material content can affect ozone effectiveness, necessitating precise adjustments to maintain treatment efficiency. Therefore, the complexity of water matrices and their varying concentrations over time hinder the attainment and upkeep of ideal treatment conditions (Reggiane De Carvalho Costa et al. 2025). This requires an adaptive approach and advanced monitoring systems to adjust ozone dosage according to real-time water conditions. Moreover, ensuring that the ozonation process effectively degrades pollutants and inactivates pathogens without generating harmful by-products is critical in ozone water treatment system implementation.

The debate on the theme of water reuse has been a highlight among the scientific community, the productive sector, public agents and society for many years (Martin Barbara and Messner 2023; Hogard et al. 2023; Knap-Bałdyga et al. 2025). Expanding water reuse practices and customizing water treatment options are increasingly necessary for water utilities to build resilience against local water challenges ranging from protecting the environment to ensuring independence over supply of water in the long term. Therefore, the reuse is configured as an alternative application to the use of water for less demanding purposes.

In recent years, several review studies have systematically examined the role of advanced treatment technologies, including ozonation, in water reclamation and reuse. Roccaro (2018) reviewed the treatment processes for municipal wastewater reclamation and identified CECs and direct potable reuse as major challenges and research priorities, highlighting the importance of advanced oxidation processes in achieving

safe reuse applications. Yakameran et al. (2025) provides a comprehensive analysis of CECs in reclaimed wastewater and discusses their fate, transport, and implications for sustainable water use in agricultural irrigation systems. Additionally, Völker et al. (2019) have evaluated the efficacy of ozonation and other advanced oxidation processes for degrading trace organic contaminants and disinfection byproducts (DBPs), confirming that ozone-based treatment can significantly enhance removal efficiencies when appropriately applied.

These previous studies have provided important insights into oxidation mechanisms, degradation pathways, and treatment efficiencies, often focusing on laboratory-scale systems or on regions facing severe water scarcity. However, most existing reviews predominantly emphasize removal performance or transformation mechanisms, with limited integration of operational constraints, disinfection by-product formation, and real-scale applicability, especially in the context of potable water reuse systems. Furthermore, the majority of available reviews are centered on regions such as North America, Europe, and parts of Asia, where regulatory pressure and water scarcity have driven the implementation of advanced reuse schemes. In contrast, countries with relatively abundant water resources, such as Brazil, remain underrepresented in the scientific discussion, despite facing increasing challenges related to water quality degradation, urban pollution, climate variability, and extreme hydrological events. Therefore, while ozonation is internationally recognized as a mature and effective technology for disinfection and oxidation, its role in potable water reuse requires a more integrated and application-oriented assessment.

In this context, this study presents a critical and comprehensive review of the environmental potential and practical challenges of ozonation for potable water reuse, with a particular focus on the Brazilian scenario. By systematically analyzing peer-reviewed studies published between 2014 and 2024, this review bridges fundamental aspects of ozonation with operational considerations, multi-barrier treatment configurations, and risk management strategies. The analysis highlights how ozonation can contribute to improving water quality and safety when appropriately designed and operated, while also identifying key limitations related to by-product formation, monitoring requirements, and public perception. Ultimately, this work advances previous reviews by providing a framework that supports informed decision-making for the implementation of ozonation-based potable reuse systems in Brazil and in other regions with similar socio-environmental conditions.

## Methodology

For the critical review of practical aspects of potential and challenges of ozonation for potable reuse, Wiley, Scopus, Science Direct, and Web of Science were used as the main



repositories to find published references on the subject. The search strategy involved different combinations of the following main terms: “ozonation, water and wastewater reuse, advanced treatment technologies, potable reuse, environmental impact”. To filter the recovered sources, only research articles from the last 10 years (2014–2024) that used that use the ozonation treatment for water reuse were considered. Works where do not focus on reclaimed water or wastewater, as well as those that do not involve ozonation as a treatment method, were discarded. The Fig. 1 presents the number of chosen publications during this period.

Out of the total number of articles found, 47 articles that met the criteria were selected, with ~47% being published in the last 5 years. The studies took place in various countries worldwide and several aqueous matrices were evaluated, ranging from tertiary effluents to drinking water. Despite the increasing interest in the application of ozonation in water reuse over the years, it is observed that the number of studies has not followed this trend. This suggests a research gap. Therefore, more comprehensive studies are needed to better understand the challenges and prospects of ozonation for water reuse and to provide clear guidance for its application, increasing confidence in this technique and its applicability in different contexts.

The present review is structured according to the scope of the articles and grouped into 4 main topics and, future perspectives and challenges. The objective and main results made by the authors of the selected articles are analyzed and compared accordingly.

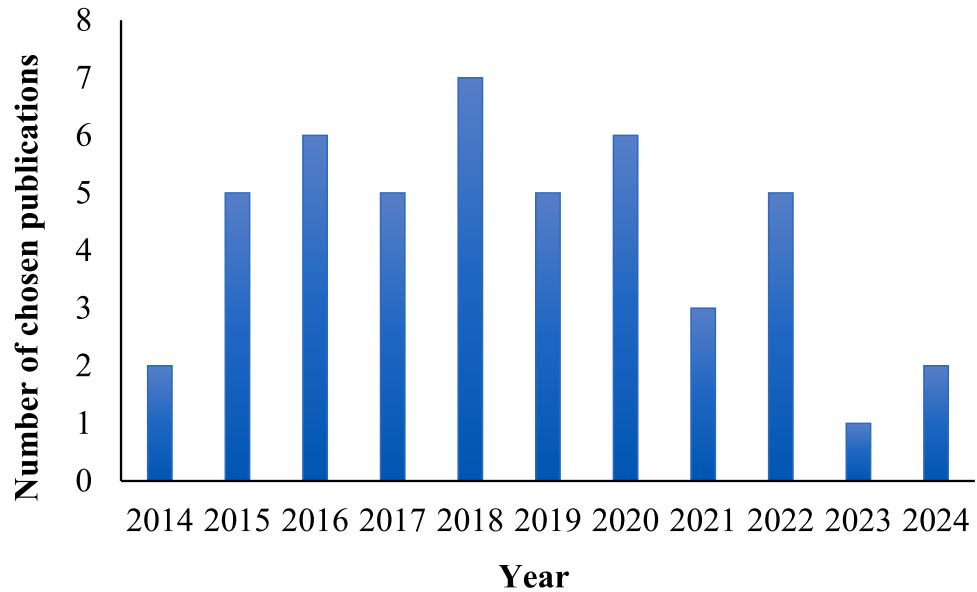
## Basic notions of ozonation in water and wastewater treatment

### Ozone characteristics and general concepts

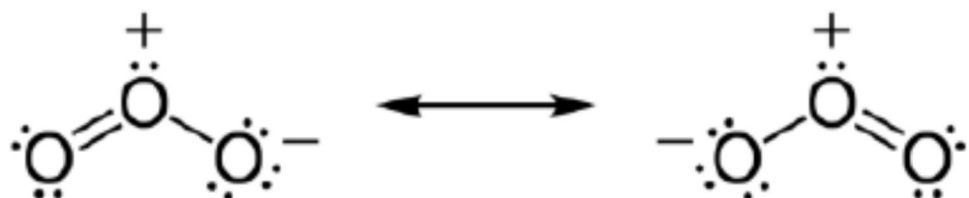
Characterized as a colorless gas at room temperature and with a characteristic pungent odor, ozone ( $O_3$ , Fig. 2) appears as a highly reactive compound (reduction potential 2.07 V) compared to other oxidants, such as hypochlorous acid (1.49 V) or chlorine (1.36 V) (Sonntag and Gunten 2012). At alkaline pHs, it can decompose, leading to the formation of hydroxyl radicals, whose reduction potential is even higher (2.80 V). These factors make ozone gas a strong oxidant and a corrosive and toxic substance to living beings.

Under normal water and effluent treatment conditions, ozone must be generated "in situ" for immediate use. There are different ways to generate it, from atmospheric air, oxygen gas or water. Among the mentioned methods, the most

**Fig. 1** Number of chosen publications that use the ozonation treatment for water reuse during 2014–2024



**Fig. 2** Molecular structure of ozone in resonance



viable are the electric and electrochemical ones, as they provide higher concentrations of ozone, the electrical discharge technique being the most widespread in treatment plants that use ozone (Sonntag and Gunten 2012). Electrolysis can be a convenient means of producing ozone in aqueous solution. The presence of nitrogen (1%) is reported to have a beneficial effect on ozone generation, increasing the yield of ozone compared to pure oxygen due to oxygen-forming reactions (Rakness 2005).

In the ozonation process, it is also important to know the effect produced by the decomposition of ozone in the liquid phase. In pure aqueous solution systems, the main parameters affecting ozone decomposition are temperature and pH. With increasing temperature, ozone becomes less soluble and less stable in water, however, rates of disinfection and chemical oxidation remain relatively stable (Langlais et al. 1991).

About ten times more soluble in water than in oxygen, the solubility of this gas strongly depends on temperature. According to Gottschalk et al. (2009), this solubility is about twice as high at 0 °C than at room temperature. Still, the effectiveness of the ozonation process depends on the introduction of ozone into the water or effluent, that is, the liquid/gas contact through the transfer of ozone mass from the gas phase to the liquid phase. Thus, in the process, it is extremely important to use diffusers capable of developing ozone microbubbles that increase the interfacial area for mass transfer (Gottschalk et al. 2009).

Treatment by ozonation of effluent containing the pharmaceutical tetracycline was evaluated by Wang et al. (2020). The authors evaluated five reaction temperatures to investigate the effect on compost degradation. The results suggested that the efficiency of the treatment is improved with the increase of the temperature, since the elevated reaction temperatures contributed to increase the performance in destroying the organic molecular structure of the compost and then transferring the organic compound to carbon dioxide (CO<sub>2</sub>) and reducing the toxicity. In another study, Lin et al. (2017) observed that when the process temperature increased from 20 to 60 °C, the degradation kinetic constant also increased, indicating that the removal of amaranth by ozone catalyzed by ferrocene is facilitated at temperatures high.

On the other hand, some authors claim that increasing the reaction temperature can reduce the dissolved ozone solubility and the ozone gas mass transfer between the gaseous and solution phases; therefore, lower reaction temperatures are also suitable to increase treatment efficiency (de Oliveira Souza et al. 2019). However, even if mass transfer is inhibited by increasing the reaction temperature, the reactivity between the microorganism, the organic compound and the ozone gas or dissolved ozone molecules can be increased (Wang et al. 2020). These factors will strongly depend on

the concentration of the compounds and the type of treated aqueous matrix.

Regarding stability, aqueous ozone solutions are unstable, which is contributed by effects such as those related to temperature and ozone concentration (Epelle et al. 2022). The dissociation rate from O<sub>3</sub> to oxygen (O<sub>2</sub>) is strongly dependent on these factors, since the higher the gas concentration and the higher the temperature of the matrix, the greater the dissociation of the molecule, and vice versa. In basic solutions, ozone is especially unstable. This is due the formation of •OH by <sup>-</sup>OH and the reaction of •OH with ozone (Nöthe et al. 2009; Sonntag and Gunten 2012).

Although the ozonation process is limited by the solubility of ozone in water, an increase in temperature implies a faster degradation reaction rate (Pinar Tanatti et al. 2019). In general, most ozonation experiments are carried out at room temperature and manage to achieve high degradation of pollutants. Higher temperature can increase reaction kinetics and can improve mass transfer between ozone gas and solution, although the overall solubility of ozone decreases. Another factor that contributes significantly to ozone depletion in natural waters is dissolved organic matter (DOM). The nature of the organic matter varies between waters of different origins, as well as its concentration, influencing the rate of reaction with ozone and, therefore, the useful life of the gas in these natural waters. This is of great importance, as the two desired effects of ozone, disinfection and reduction of micropollutants, depend on the useful life of ozone in these waters and on their composition (Costa et al. 2021; Costa and Féris 2023).

As an example, waters with low organic matter and high bicarbonate content show relatively high ozone stability. Conversely, the greater the amount of organic matter present in the water, the lower the stability of the gas. Thus, in the reduction of micropollutants, for example, the reactivity of a micropollutant determines the efficiency of its elimination by an ozone treatment (Nöthe et al. 2009). Therefore, it is observed that such differences are reflected in the differences in gas reactivity, showing its relevance in the degradation process.

### Definition of possible ozone configurations in a treatment

Treatment steps commonly adopted in treatment plants include a primary treatment and a secondary treatment. However, these steps are not adequate enough to achieve high removal efficiencies for the wide spectrum of existing emerging pollutants. Furthermore, low degradation/inactivation efficiencies can be achieved, even for the physical–chemical parameters of the process (biochemical oxygen demand, chemical oxygen demand, total suspended solids and total coliforms) (Verlicchi et al. 2015). Since the



end of the nineteenth century, the potential of ozone in the treatment of water and effluents has been explored for various purposes, such as bacterial control, oxidation of natural organic matter, removal of color, odor and metallic cations, such as iron and manganese, coagulation and flocculation process, reduction of sludge generation and, more recently, in the control of recalcitrant organic compounds (Langlais et al. 1991).

Exemplifying this statement, Table 1 considers a worldwide distribution of application of the integrated ozonation technique for the treatment of aqueous matrices, based on studies in the literature in the period 2014–2024.

All the cited studies are relevant for the development of technology, as they all apply ozonation in water and wastewater treatment plants on a real or on a pilot scale, aiming at removing emerging contaminants, pathogens and optimizing the process. The results obtained by the authors make it possible to evaluate the effectiveness of the process and the variety of contaminants that can be removed through it, and it is also possible to verify the different configurations in which ozone can be applied in the water and effluent treatment process (Fig. 3).

From the operational point of view of water treatment, processes involving ozone can be applied with high efficiency to treatment, both in the stage prior to secondary treatment and in the intermediate and final stages of the conventional treatment process (de Carvalho Costa and Féris 2023; Knap-Bałdyga and Żubrowska-Sudoł 2023).

The ozone application point depends on the type of water and the required objective. Pre-ozonation (applied before secondary treatment) is used in place of chlorination, before the coagulation and flocculation processes, and may reduce the amount of coagulants and flocculants used by precipitating metallic cations, removing color, odor and taste and rupture of algae and bacteria cells, in addition to providing a more biodegradable water/effluent since ozonation leads to low molar mass compounds, aldehydes and carboxylic acids (Gerrity and Snyder 2011). Low doses of ozone may be sufficient to transform bio refractory compounds and improve their biodegradability, thus reducing costs (Verlicchi et al. 2015). In the case of post-ozonation, the treatment is used as polishing, being responsible for the degradation and mineralization of organic compounds and for disinfection. A post-ozone step with activated carbon can be a good alternative to further reduce effluent constituent loads. In some cases, for logistical convenience, the process can also be inserted at some intermediate point in the process (inter-ozonation).

While the use of ozone in wastewater treatment is limited, there is renewed interest as legislation tightens, water shortages become more frequent, and public perceptions of water quality improve positively. In this configuration, potential ozone applications in wastewater treatment plants include secondary effluent disinfection (tertiary treatment),

post filtration and sedimentation sludge conditioning, odor control and primary effluent pre-oxidation. The integration of ozonation in the tertiary stage of the treatment process, acts as a polishing of the effluent, removing pathogenic organisms, organic matter and remaining nutrients (Castañeda-Retavizca et al. 2025). The current scenario is moving towards a growing need to reuse treated sewage and release better quality effluents into receiving bodies, aiming at faster self-purification of water bodies. In this sense, efficient technologies must be employed in the polishing of treated sewage.

According to Von Sperling (2016), unlike the disinfection treatments by chlorination and UV radiation, the disinfection treatment with ozone has great advantages, such as an increase in the level of dissolved oxygen, a decrease in the chemical demand for oxygen and an improvement in the aesthetic characteristics due to the reduction of turbidity and color of the final effluent. Also, since it can chemically degrade organic pollutants, it also reduces costs with chemical polymers and with the generation, drying and transport of sludge, usually formed at the end of the treatment (Von Sperling and Gonçalves 2001; Von Sperling 2016).

Research indicates that ozonation-return activated sludge (RAS) can reduce sludge production and improve sedimentation and dehydration (Oneby et al. 2010). In addition, ozone can be used to reduce odor that can affect adjacent properties by treating air collected from unit processes, particularly from preliminary treatment and inlet processes. In the pre-oxidation of the primary effluent, this oxidant may favor the biological removal of refractory or non-biodegradable organic compounds in the secondary treatment process (Loeb et al. 2012).

## Relevant operational aspects

### Ozone contactor selection

A reactor is understood to mean any and all containers in which reactions of consumption or decay of reagents and formation of products are taking place (Fogler 2004). According to Schmal (2010), there is a wide variety of types of reactors within the chemical industry, conventionally divided into discontinuous and semi-continuous, or continuous. Still, two extreme and ideal limits are considered in reactors: the plug flow and the complete mixture. Under non-ideal, or real, conditions, the flow regime lies between these two extremes.

The most important constituent part of an ozonation system is represented by contact reactors of the gaseous phase with the liquid phase (Tate 1991). The most common designs for gas–liquid contact systems are full-mix reactors, tubular reactors with countercurrent gas–liquid flow, tubular

**Table 1** Application of the integrated ozonation technique for the treatment of aqueous matrices based on studies in the literature in the period 2014–2024

Aqueous matrix / Treatment	Main results	References
Drinking water / Ozonation and granular activated carbon	Ozonation was shown to be an efficient measure to reduce the concentrations of a wide range of micropollutants (> 70%) and GAC is important for the final water quality	Ullberg et al. (2021)
Drinking water / pre-ozonation, pos ozonation, physical–chemical	Ozonation was shown to be an efficient measure to reduce the concentrations of pharmaceuticals (> 90%) and coagulants with the pre-ozonation	de Carvalho Costa and Féris (2023)
Wastewater / ozone and biological activated carbon	Based on sampling and treatment validation strategies, the three pathogen barriers can provide minimum log removal (LRVs) of 13–9–9.5 for virus, Giardia, and Cryptosporidium	Teel et al. (2022)
Wastewater / ozonation, ceramic membrane filtration and biologically active carbon filtration	Compared to pre-ozonation, in situ ozonation in the membrane tank was more effective in controlling membrane fouling and in degrading organic pollutants	Verdugo et al. (2020)
Wastewater / ozonation	Ozonation of small volumes of wastewater in lagoons may be an effective method for improving wastewater quality	Yargeau et al. (2023)
Wastewater / ozone-biofiltration (BAC)	Presence of N-nitrosodimethylamine (NDMA) is a limitation of ozone-biofiltration technology. PFOA removal across BAC appears to be heavily influenced by carbon-based removal mechanisms. Potable reuse BAC specific total organic carbon (TOC) mass removal it was higher than values observed in drinking water BAC systems	Sundaram et al. (2020)
Wastewater / UV + O <sub>3</sub> and GAC adsorption	UV + O <sub>3</sub> treatment could be applied after membrane filtration to remove all suspended solids of water matrix	Krakkó et al. (2021)
Drinking water and wastewater / Ozonation and adsorption hybrid	Ozonation transforms the larger natural organic matter (NOM) molecules into smaller molecular sizes with lower aromaticity and hydrophobicity, subsequently resulting in reduced adsorption	Loganathan et al. (2022)
Aqueous solution / ozone and adsorption	Approximately 0.17 mg/L (84.8%) of ACT and 0.16 mg/L (82.7%) of AMX were removed by ozonation and were not detected after adsorption	Mojiri et al. (2019)
Wastewater / activated carbon filtration and ozonation	Ozonation and the subsequent sand/antracite filtration was able to reduce the PM burden in wastewater from 40 µg/L to 19 µg/L, showing a higher removal efficacy than PAC	Neuwald et al. (2023)
Wastewater / adsorption and ozonation	The optimal conditions were obtained at the reaction time of 60 min, temperature of 60 °C, GAC dose of 10 g and ozone flowrate of 8 L/min, which resulted in Chemical Oxygen Demand (COD) removal of 98.5%	Rahimi et al. (2023)
Wastewater / ozonation-anaerobic membrane bioreactor	Approximately 90% COD removal efficiency was achieved by the combined system. Extracellular polymeric substance (EPS) decreased in the conditions of long sludge retention time, hydraulic retention time and low organic loading rate values	Kaya et al. (2017)
Wastewater / ultrafiltration, adsorption and advanced oxidative process	The phosphate, TRC and TRC byproducts removal degrees exceeded 90% both for adsorption in the fixed-bed column as well as the ozonation and ozonation + UV processes	Kamińska et al. (2022)
Industry wastewater / peroxi-coagulation and ozonation	In this novel process, synergistic effect between ozonation and peroxi-coagulation was observed, and beside O <sub>3</sub> direct oxidation, peroxone played a dominant role for phenol removal	Li et al. (2023)



Table 1 (continued)

Aqueous matrix / Treatment	Main results	References
Industrial and domestic wastewater / aerobic biological process with post-ozonation	The results including the crop growth outcomes indicate that SGBP-O <sub>3</sub> process has great potential to improve the quality of mixed industrial and domestic wastewater	Egbuikwem et al. (2020)
Wastewater / ozone-biologically activated carbon	Ozone alone can effectively degrade chlorinated trihalomethane (THM) and haloacetic acid (HAA) precursors, chloramine-reactive NDMA precursors, and 29 PPCPs	Sun et al. (2018)
Aqueous solution / ozonation-biotreatment process	The combined ozonation and biological treatment removed 82.5% of COD, whereas 38% of COD was removed in biological treatment alone	Mohan and Balakrishnan (2021)
Aqueous solution / ozone and percarbonate	Degradation effectiveness values of 99% and 81% were obtained by ozone combined with sodium percarbonate and hydrogen peroxide, respectively, demonstrating the superiority of sodium percarbonate over hydrogen peroxide in combination with ozone for the degradation of bisphenol S	Askarniya et al. (2023)
Municipal wastewater / simultaneous advanced oxidation and adsorption	The results revealed enhanced removal of biological oxygen demand (BOD: C <sub>0</sub> : 14.1 and Ct: 0 mg L <sup>-1</sup> (100%), chemical oxygen demand (COD: C <sub>0</sub> : 40.5 and Ct: 4 mg L <sup>-1</sup> (≤90%)), and total organic carbon (TOC: C <sub>0</sub> : 15.2 and Ct: 3.02–3.63 mg L <sup>-1</sup> (~80%))	Kumar et al. (2022)

reactors with co-current gas–liquid flow, or a combination of the latter two (reactor with counter-current and co-current flow regime) (Eiger et al. 1998; Lage Filho et al. 1998). Its good performance as a unit operation depends on several factors such as the liquid flow rate, gas flow rate, ozone concentration in the feed gas, the hydrodynamic characteristics of the reactors and the physic–chemical characteristics of the raw water (Tate 1991). The hydraulic detention time of the bubbles in the reactors also influences the characteristics of the system.

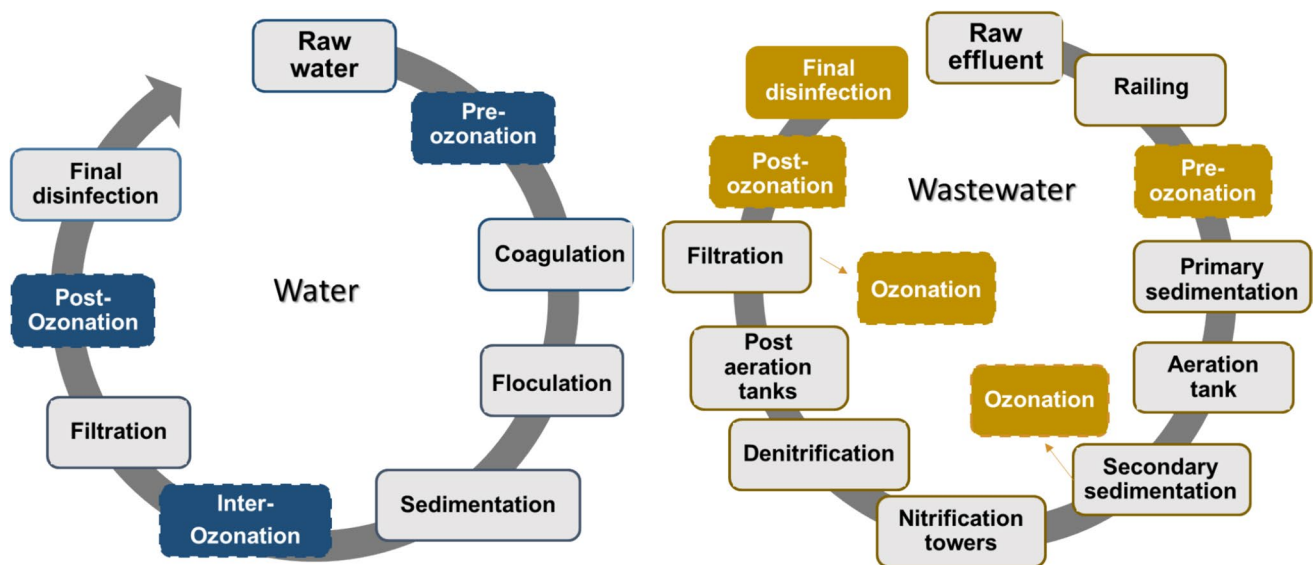
As an example of operation, in complete mixing systems, the gas containing ozone is introduced into the reactor through a turbine-type stirrer. In this type of reactor, as the liquid phase is in intense agitation, the ozone concentration throughout its volume is considered constant. Counter-current gas–liquid contact systems are characterized by having the liquid phase flowing in the opposite direction to the gas phase. In co-current gas–liquid contact systems, both the liquid phase and the gas phase flow in the same direction. In this type of system, the sections of the reactor where there is no introduction of ozone are called reactive sections.

For the adoption of ozonation systems, there is a greater preference for contact reactors composed of fine bubble diffusers and multi-compartments in counter-current, co-current and reactive sections. The advantage of this type of designs is its flexibility, which allows the application of different gas dosages in different compartments of the system. In addition, it is possible to perform its optimization regarding the fulfillment of one or more specific objectives (Eiger et al. 1998; Lage Filho et al. 1998).

There are few reports in the literature about the behavior dynamics for the design of an ozonation reactor. In their study of mathematical modeling for ozone contactor, (Eiger et al. 1998) identified that the concentration of ozone in the liquid phase is much better distributed in the column in co-current ozonation systems than when compared to counter-current ozonation systems. On the other hand, the authors also observed that the concentration of ozone in the column effluent is higher in counter-current systems than in co-current systems. This is one of the advantages of counter-current ozonation systems because, since it is possible to obtain higher values of ozone concentration in the liquid phase, it is possible not only to decrease the dose of ozone applied in subsequent columns (in the case of reactors in series), as well as optimizing the disinfection process by increasing the influent ozone concentration in the subsequent columns.

Still in the same study, the authors observed that the concentration of ozone in the gaseous phase is slightly higher in co-current systems than when compared to counter-current systems. This fact imposes some restrictions on the adoption of co-current ozonation systems. As the transfer of ozone from the gaseous phase to the liquid phase is not complete, this can lead to a higher financial cost when compared to





**Fig. 3** The different configurations in which ozone can be applied in the water and effluent treatment process

other types of system, given that a higher dose of ozone applied will be necessary to guarantee the same mass. of ozone transferred to the liquid phase.

Therefore, it is essential to thoroughly evaluate the characteristics of the matrix, the operating characteristics of the reactor and the type of reactor to be used within an ozonation process. The wrong choice of equipment can lead to significant losses in the process, from processing/treatment yield to extra operating costs.

### Continuous stirred tank reactor and plug flow reactor

Steady state mixed flow reactors or continuous stirred tank reactor (CSTR) or constant flow stirred tank reactor (CFSTR) are idealized flow reactors so that all contents inside the reactor are well mixed as well as in a batch reactor (Fogler 2004). This idealization makes the flow reactor analysis extremely simplified, making it possible to treat the entire reactor as a simple unit (Morais 2015). In this reactor, as the contents inside the reactor are well mixed, the concentrations and temperature are identical inside and are equal to those at the outlet. Entry conditions, on the other hand, may be different. Also, residence time is characterized by a distribution (residence time distribution, RTD) (Escotet-Espinoza et al. 2019). This happens because some components that enter the reactor can leave immediately, while others remain for longer periods (Bérard et al. 2020). Typically, a CSTR does not achieve complete conversion and serial CSTRs are used to approximate a PFR (Liu 2017).

CSTRs have great mechanical and heat transfer similarity to batch-type reactors. They are most often used in industrial

processing, especially in homogeneous liquid phase flow reactions where constant agitation is required. They are also widely used in the chemical, pharmaceutical and food industries (Hu 2021; Sabiani et al. 2022; Saravanan et al. 2023). The CSTR reactor is also one of the most commonly used in biological processes (Kumar et al. 2019), in synthesis gas fermentation (Wahid and Horn 2021) and continuous hydrogen production (Show et al. 2019).

The CSTR can produce large amounts of product per unit time and operate for long periods. In general, this type of stirred tank reactor has several advantages, characterized by its existing industrial capacity, proven performance, ease of maintenance of homogeneous conditions and ease of scale-up, since it is less expensive and easier to build than specially dedicated flow systems and also features easy temperature control (Uppal et al. 1976; Mukherjee et al. 2023). This type of reactor has the disadvantage of relatively slow heat and mass transfer (Klatt and Engell 1998). Also, an apparent difficulty in controlling the length of residence is reported (Escotet-Espinoza et al. 2019; Bérard et al. 2020). This happens, as mentioned earlier, due to the non-fluidity of molecules through the reactor at the same reaction rate. In view of this, the control of CSTRs is a challenging problem due to non-linear behavior, multiple steady states, heat effect of chemical reactions, time delay and the effect of various time-varying uncertainties (Luyben 2007). Additionally, CSTRs are typically larger than PFRs, which can be a challenge in applications where space is limited.

PFRs are reactors of wide industrial use, normally consisting of cylindrical tubes that operate in steady state, inside which the reaction medium circulates. In other words, reagents are pumped into this pipeline and react with each other



continuously. In plug flow, each liquid particle remains in the reactor for the same time, and there may be localized or transverse mixing, but never longitudinal or axial (Mushtaq 2014). Another factor to consider is that the chemical reaction occurs as the reactants travel through the reactor. Thus, the reaction rate creates a gradient in relation to the distance traveled, which is greater at the entrance and decreases over time, until a point where the system reaches a dynamic equilibrium (Schmal 2010).

They are mainly used for gaseous reactions, which can occur quickly and at high temperatures. However, they can also be used for liquid phase reactions. The main advantage is that they can quickly produce a large amount of product due to their high conversion rates. Also, because they have a larger contact surface, heat exchange is favored (Pereira Ishida 2017). Due to the high conversion rate of reagents, this can generate unwanted temperature gradients, that is, large temperature variations in a short time, and therefore it is known that temperature control in PFRs is complex. They are not normally used for highly exothermic reactions. In addition, compared to batch reactors and (CSTR, cleaning and maintenance of PFR is more difficult and expensive (Mushtaq 2014; Pereira Ishida 2017).

With this information, it is possible to have an idea of which type of reactor is best and fits into an industrial process. However, there is other essential information to use a reactor within the correct specifications, such as, for example, what are the dimensions of the equipment, what the operating parameters are and what material the reactor should be built from.

### Factors influencing reactor choice in practical applications

In a treatment process, factors such as mixing conditions and matrix flow in the tank/reactor used in the process must be controlled or known (for batch tests there is no flow), since the conversion efficiency of a chemical reaction or biochemistry does not depend only on the variables involved, such as temperature, pH, concentration of reagents and products and reaction speed (Von Gunten 2003; Sivagurunathan et al. 2016; Tabatabaei et al. 2019). Also, the enthalpy of the reaction is a parameter of great interest, since it determines the reaction conditions (e.g., pressure, temperature, catalyst) and the heating management of the reactor (Imamura et al. 2023). When full-scale systems are considered, in addition to laboratory activities, operational changes can occur that invariably result in process efficiency losses. Another extremely important factor, which directly influences the reactions, is the hydraulic retention time, that is, the time that the fluid particle remains in the reactor (de Carvalho Costa et al. 2024).

Sivagurunathan et al. (2016) performed a critical review on overcoming issues and strategies for improving dark fermentative hydrogen production in continuous systems. The authors listed some strategies to improve the performance of the rate and yield of hydrogen production, the factors of a) adequate initialization period; (b) pH optimization and control; (c) decrease in hydraulic retention time (HRT) and (d) control of operating temperature. Similarly, Tabatabaei et al. (2019) evaluated reactor technologies for biodiesel production and processing. As main factors to optimize biodiesel production, the authors listed characteristics of a) effect of concentration and type of catalyst; b) conditions and composition of reagents; c) mass transfer; d) mixing system; e) temperature; f) residence time and finally, g) technologies and characteristics of the reactors.

The design of an ideal process reactor also strongly depends on factors such as (i) size of the reactor (ii) type of reactor (iii) time or duration of the reaction (iv) temperature and composition of the material that reacts in the reactor (v) value added and (vi) standard flow rate of fluid in the reactor. For the latter, the reactor feed strategy greatly affects product mixing, so a reactor with optimal feed distribution and/or product separation can produce significantly more desired product. In the study conducted by Zhang et al. (2019), the authors investigated the effect of different mixing strategies on the anaerobic digestion of food waste in order to make the waste-to-energy conversion process of anaerobic digestion more energy-efficient. The results showed that intermittent blending is an alternative strategy to continuous or unmixed blending for high-efficiency and energy-saving biogas production. A fluid dynamic modeling was also performed, and, with that, it was possible to optimize the mixing time to 2 min/h, at which point the reaction mixture is almost completely homogeneous. Satisfactory results were also obtained by (Du et al. 2020) when applying the partial denitrification/anammox (PD/A) process through a gas mixture strategy. A high efficiency gas mixture was obtained which significantly promoted the nitrite production and anammox activities of PD/A.

Through these reports, the role of individual and multiple parameters combined in different aspects and process configurations, as well as the optimization of the reactor characteristics, are fundamental to increase the efficiency of the reactions and, has been and will still be the most adopted in the application of processes in industrial and laboratory studies.

### Impact of ozone dose selection on treatment efficiency and disinfection by-products formation

Several factors influence the selection of ozone dose in ozonation processes. These include the type and concentration of contaminants present in the water, the desired level

of treatment (e.g., disinfection, oxidation of specific compounds), water quality parameters (e.g., pH, temperature, organic content), and the characteristics of the treatment system (e.g., contactor design, mixing efficiency). The ozone dose must be carefully optimized to achieve the desired treatment objectives efficiently while minimizing operational costs and potential risks associated with ozone exposure.

The selection of ozone dose has a direct impact on treatment efficiency and the formation of DBPs. Higher doses of ozone can achieve greater contaminant removal and pathogen inactivation, but they also increase the risk of disinfection by-products (DBPs) formation, particularly bromate and NDMA. Figure 4 depicts the potential by-products formed in water and wastewater after ozone application over the years.

Since the twentieth century, ozone application in aqueous matrices has been associated with the formation of undesirable by-products. These by-products arise due to the complexity of aqueous matrices, which over time have been influenced by human activities such as intensive agriculture, industrial and urban discharge, and other sources of contamination. These activities introduce a variety of organic and inorganic contaminants into waters, which can react with ozone and produce by-products that are potentially harmful to the environment and public health. Therefore, it is essential to balance the need for effective treatment with the potential risks associated with high ozone doses. Optimizing

the ozone dose based on CT values can help achieve the desired treatment goals while minimizing DBPs formation. Additionally, the design and operation of the ozonation system, including factors such as ozone distribution and contact time, and different treatment techniques plays a crucial role in determining treatment efficiency and DBP formation.

Table 2 summarizes ozone treatment studies across various global regions and water matrices, revealing diverse ozone doses used and the formation of DBPs.

Studies span applications from wastewater and drinking water to synthetic and seawater, with ozone doses ranging widely from 0.1 gO<sub>3</sub>/gDOC to 90 mg/L. By-products include bromate, trihalomethanes (THMs), haloacetic acids (HAAs), and advanced by-products like brominated aliphatic acids and iodo-trihalomethanes (I-THMs). These findings underscore the complex balance between effective disinfection and DBP control, necessitating region-specific strategies to optimize treatment efficiency while ensuring water safety and quality.

In the study by Lee et al. (2023), the authors observed that for specific ozone doses of 0.3, 0.5, and 0.7 gO<sub>3</sub>/gDOC, the bromate concentration after ozonation was 2.8, 6.1, and 15.7 µg/L, respectively. They reported that the bromate concentration exceeded the drinking water standard of 10 µg/L at the ozone dose of 0.7 gO<sub>3</sub>/gDOC. The study indicated that the low bromate mitigation efficiencies observed may

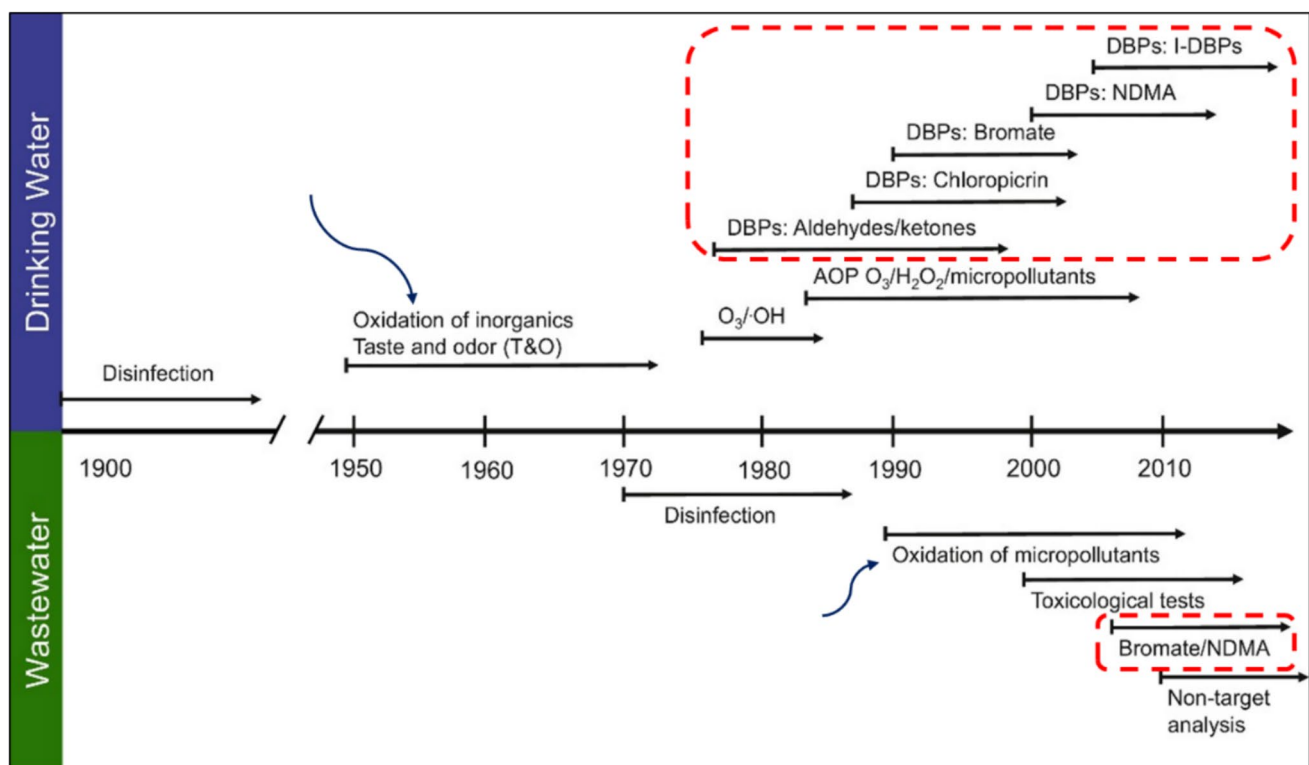


Fig. 4 Potential by-products formed in water and wastewater after ozone application



**Table 2** Studies on the direct impact of ozone dosage on process efficiency and disinfection byproduct formation

Authors/Reference	Region	Matrix Type	Ozone Dose Used	By-products Formed
Lee et al. (2023)	Republic of Korea	Wastewater effluent	0.1; 0.3 e 0.7 g <sub>O<sub>3</sub></sub> /g <sub>DOC</sub>	Bromate NMOR
Rougé et al. (2020)	Switzerland	Chlorinated synthetic and real waters	O <sub>3</sub> -t-BuOH; 36.1 and 94.3 µM	Br-DBPs Tribromomethane (TBM)
Hogard et al. (2023)	United States	Wastewater	0.25; 0.5; 0.75 and 1 O <sub>3</sub> :TOC	Bromate
Lin et al. (2020)	China	Raw water	0.5–1.5 mg/L pre-ozonation 0.5–3.0 mg/L post-ozonation	Trihalomethanes (THM) and haloacetic acids (HAA)
Zhu et al. (2020)	China	Artificial seawater	0–120 mg/L	Iodo-trihalomethanes (I-THMs)
Kozari et al. (2020)	Greece	Sewage effluents	1, 2, 5, 10 e 13 mg/L	Trichloronitromethane, DCP, TCP
Han et al. (2024)	China and United States	Simulated raw water	2, 4 or 6 mg/L	Brominated aliphatic acids, dihalonitromethanes, dihaloacetaldehydes
Luo et al. (2020)	China	Wastewater	10–90 mg/L	HKFP, TCNMF e CHF P
Gao et al. (2020)	Canada	Drinking water treatment plant (DWTP)	0.5 mg/L Pre-O <sub>3</sub> and 0.8 mg/L Post-O <sub>3</sub>	TBAL and DBAL
Sgroi et al. (2021)	Italy	Municipal wastewater	1.5–9 mg/L	Bromate and NDMA
Wang et al. (2022)	China	Advanced drinking water treatment	1.8–2.6 mg/L	Bromate, formaldehyde, methylglyoxal, other aldehydes

be due to water quality parameters (e.g., high dissolved oxygen), warranting further investigation. NMOR was detected at concentrations of 3 to 7 ng/L before and after ozonation, suggesting NMOR was originally present in the wastewater effluent and its formation during ozonation was minimal.

Similarly, Hogard et al. (2023) concluded that the average molar conversion of bromide to bromate (mol Br<sup>-</sup>/mol BrO<sub>3</sub><sup>-</sup>) increased from <0.1% to ~5% with increasing O<sub>3</sub> ratio from 0.25 to 1. Han et al. (2024) reported that increasing ozone dose slightly affected brominated aliphatic acids, as well as increasing dihalonitromethanes and dihaloacetaldehydes. Wang et al. (2022) applying ozone doses of 1.8–2.6 mg/L, noted that bromate concentrations exceeded the 10 µg/L standard. Concurrently, ozone treatment resulted in significant formation of formaldehyde, methylglyoxal, and other aldehydes. At an ozone dose of 3.0 mg/L, the total concentration of aldehydes reached a peak of 45.4 µg/L.

Rougé et al. (2020) observed that after pre-oxidation of the matrix with high doses of oxidants ClO<sub>2</sub> and O<sub>3</sub>-t-BuOH, there was an increase in the formation of brominated organic acids (AOBr) to 1.8 ± 0.3 µM and 1.1 ± 0.1 µM, respectively. Following ClO<sub>2</sub> pre-oxidation, traces of all four trihalomethanes (THMs) were detected (total THMs < 10 nM), whereas high doses of O<sub>3</sub>-t-BuOH resulted in the formation of primarily tribromomethane (TBM) (up to 69 ± 11 nM). The authors concluded that pre-oxidation was less effective in mitigating brominated disinfection byproducts (DBPs) and generally increased the bromine substitution factor. In a similar preoxidation process, Lin et al. (2020) observed an increase in both THM and haloacetic acid formation potentials (FPs), especially for brominated HAAs.

Gao et al. (2020) observed that as total ozone dosages increased (specifically, 1.3 mg/L (P2) > 0.8 mg/L (P1) > 0.5 mg/L (P4) > 0 (P3)), the concentrations of haloacetonitriles (HAL7) also increased. This trend is consistent with findings from Koudjonou et al. (2008), indicating that sequential ozone/chlorine disinfection promotes the formation of chloroform (CH). It is well-known that ozone can oxidize natural organic matter (NOM) in water, thereby increasing HAA precursors (Wang et al. 2017). The authors reported that in their study, DBAL (dibromoacetic acid and dichloroacetic acid) formed during pre-ozonation might have been more resistant to traditional water treatment processes and could therefore still be detected in treated water. However, they emphasized the need for further studies to draw definitive conclusions regarding the persistence and impact of these DBPs in water treatment systems.

In the study by Zhu et al. (2020), compared to iodinated trihalomethanes (I-THMs), THMs and HAAs were identified as the predominant DBPs formed during ozone treatment of the evaluated matrix. Specifically, HAAs and THMs accounted for approximately 50.3% and 38.5% of the total DBPs, respectively, while I-THMs constituted about 11.2%. The authors also noted that increased temperature enhanced the formation of brominated and iodinated DBPs such as dibromoacetonitrile (DBIM), bromodiiodomethane (BDIM), bromochloroiodomethane (BCIM), and tribromoiodomethane (TIM).

Conversely, Kozari et al. (2020) reported that concentrations of trichloronitromethane (TCNM) and the formation potential of dichloropropanone (DCP) and trichloropropanone (TCP) increased up to an ozone dose of 5 mg/L,

followed by a decrease at higher doses. This suggests an optimal dosage range where higher ozone concentrations may not be necessary due to gas saturation, low solubility, and high dissipation rates. Following ozone disinfection, (Luo et al. 2020) observed decreases in haloacetic acid formation potential (HAAFP), trihalomethane formation potential (THMFP), and haloacetonitrile formation potential (HANFP), but increases in haloacetaldehyde formation potential (HKFP), trichloronitromethane formation potential (TCNMFP), and chloroform formation potential (CHFP) compared to chlorine disinfection. This behavior could be attributed to ozone's reactions with aromatic double bonds and certain nitrogenous organic compounds, leading to increased formation of aldehydes, methyl ketones, nitromethane, and nitrophenol.

Overall, these studies underscore that ozone dosage in water treatment significantly influences the formation of disinfection byproducts. Variations in matrix composition, including parameters such as dissolved oxygen, pH, and the presence of compounds like bromide and iodide, critically affect ozone's efficacy and the quantity of DBPs produced. Therefore, careful control of ozone dosage is essential to minimize the formation of these undesirable compounds, ensuring the safety of treated water.

## Application of ozonation for potable reuse

The application of ozonation in potable reuse systems involves complex considerations. Ozonation works through direct reactions with contaminants, oxidizing them into less harmful by-products, thereby reducing TORCs and enhancing disinfection. However, challenges include high energy consumption, formation of DBPs, and the necessity for robust monitoring and control strategies. While TORCs drive the need for advanced treatment lines, their specific impact on design criteria for wastewater treatment processes remains uncertain.

As ozone use in water reuse expands, projects may shift focus to other treatment concerns. Indeed, design criteria may prioritize disinfection goals or mitigation of disinfection byproducts. Given ozone's effectiveness in inactivating vegetative bacteria, viruses, and parasitic protozoa, this benefit directly aligns with the aforementioned disinfection guidelines. Regarding disinfection byproducts, a key limitation hindering widespread ozone application in water and wastewater treatment is bromate formation.

Many recent studies on ozone treatment focus on laboratory-scale experiments aimed at elucidating oxidation mechanisms and transformation kinetics of contaminants. However, water and wastewater treatment technologies often face significant challenges when transitioning from laboratory-scale assessments to pilot and full-scale demonstrations.

While laboratory-scale experiments provide invaluable scientific foundations for a given process, the true value of innovative technology cannot be fully realized until it is implemented in the field. Pilot and full-scale facilities frequently uncover the limitations of specific technologies, yet they also provide a wealth of resources and information that cannot always be replicated in a laboratory setting, such as treating large volumes of water, integrating into larger treatment systems to assess synergistic or antagonistic relationships, environmental discharge considerations, among others.

Globally, the adoption of ozonation for potable reuse varies (Table 3), with notable implementations and regulatory frameworks established primarily in regions like the United States, Europe, and parts of Asia. These regions have recognized the potential of ozonation to enhance water treatment efficiencies and meet stringent water quality standards for reuse purposes.

It is observed that each implemented project employs a specific sequence of treatment technologies, many of which include ozone as an essential step. The table reflects the diversity and increasing use of ozonation technologies in global projects for wastewater reuse in potable applications, signaling a shift towards more sustainable and resilient water management practices. However, there is a notable absence of ozone implementation in Brazil, which can be attributed to several specific reasons within the country's context.

Brazil possesses one of the largest freshwater reserves globally, characterized by vast river basins and abundant water resources, which alleviates immediate pressure to adopt advanced water treatment technologies. In contrast to regions in Europe, Asia, and parts of the United States where water scarcity is more critical, prompting widespread and necessary practices of treated water reuse due to inadequate water resources. Additionally, existing infrastructure and technical capacity play crucial roles in the adoption of advanced treatment technologies such as ozonation. The investment required to implement and operate large-scale ozonation systems can be substantial, particularly in a country with regional inequalities and diverse infrastructure needs. This may limit the availability of financial and technical resources necessary to adopt this technology widely and uniformly across Brazilian territory.

In the United States, for example, where regulations governing water reuse vary by state, California plans to invest over \$11 billion in potable reuse initiatives by 2035, aiming to repurpose wastewater currently discharged into the ocean. California has enacted regulations for Direct Potable Reuse (DPR), overseen by an expert panel for review (SWRCB 2018). Historically, surface water augmentation in California has been restricted due to the absence of specific regulations permitting such practices. However, with the establishment of these regulations,



**Table 3** Wastewater reuse installations with ozone application

ID	Project Name	State/country	Year(s) op	Status	MLD	Process	Unit process technology sequence
1	Water Factory 21, Orange County	CA	1976–2004	Decommissioned <sup>a</sup>	57	GWR via SB	LC → Air Stripping → RO → UV/AOP → Cl
2	Denver Potable Reuse Demonstration	CO	1980–1993	– <sup>b</sup>	4	DPR <sup>b</sup>	LC → Recarbonation → Filtration → UV → GAC → RO → O <sub>3</sub> → Cl
3	Huecco Bolson Recharge Project, El Paso Water Utilities	TX	1985	Operational	38	GWR via DI	LC → Media Filtration → O <sub>3</sub> → GAC → O <sub>3</sub> → Cl
4	West Basin Water Recycling Plant	CA	1995–2014	Operational	66	GWR via DI	O <sub>3</sub> → MF → RO → UV/AOP
5	Gwinnett County	GA	1999	Operational	227	SWA	UF → O <sub>3</sub> → GAC
6	Arapahoe County/Cotton wood	CO	2009	Operational	34	GWR via RBF	Media Filtration → RO → UV/AOP → Cl
7	Orange County Groundwater Replenishment System (GWRS)	CA	2008–2014	Operational	378	GWR via DI & SG	UF → RO → UV/AOP
8	San Diego Advanced Water	CA	2012 <sup>b</sup>	Operational <sup>b</sup>	4	–	O <sub>3</sub> → BAC → MF → RO → UV/AOP
9	Village of Cloudcroft	NM	Future	Approved	–	DPR: Blending → AWT	MBR → RO → UV/AOP → Storage → UF → UV → GAC → Cl
10	Hampton Road Sanitation District SWIFT project	VA	Future	Under design	454	GWR via DI	–
11	Goreangab Water Reclamation Plant, Windhoek	Namibia	1969; e2002	Operational	21	DPR: Blending → AWT	PAC → O <sub>3</sub> → Clarification → DAF → Sand filt → O <sub>3</sub> /AOP → BAC/GAC → UF → Cl
12	Morbylånga Drinking Water Treatment Plant	Plant Sweden	2019	Operational	4	DPR (ind. effl/ BW blend)	Drum Screen → Coag/floc → DAF → SBR → CSF → Coag → UF → AOP/UV

Adapted from (Jeffrey et al. 2022); “e” expanded; GWE Groundwater recharge; SWA Surface water augmentation; DI direct injection; SB sea-water barrier; SG spreading ground; RBF riverbank filtration; BAC biological activated carbon; Cl chlorination; DAF dissolved air flotation; GAC granular activated carbon; LC lime clarification; MF microfiltration; O<sub>3</sub> ozone Disinfection; PAC powdered activated carbon; RO reverse osmosis; UF ultrafiltration; UV ultraviolet radiation; CSF continuous sand filtration;

<sup>a</sup>Superseded by GWRS

<sup>b</sup>Demonstration project: not put into service

surface water augmentation has become a primary focus for new projects in the state. While groundwater replenishment has traditionally been emphasized in California, other states like Nevada, Virginia, and Georgia have implemented several surface water augmentation projects.

Finally, environmental regulations and public policies also influence the adoption of new water treatment technologies. While Brazil has robust regulations to ensure the quality of drinking water and environmental protection, the focus may lean towards other technologies and treatment methods that meet the country's specific needs. Thus, while ozone treatment is internationally recognized as an effective technology for advanced water treatment, its less frequent application in Brazil reflects a context of relatively abundant water resources, infrastructural

challenges, and distinct regulatory priorities compared to other regions of the world.

### Future perspectives and challenges for ozonation in potable water reuse

Advanced treatment technologies have demonstrated that wastewater can be purified far beyond potable water standards and safely reused for both potable and non-potable purposes. The debate on the theme of water reuse has been a highlight among the scientific community, the productive sector, public agents and society for many years. Expanding water reuse practices and customizing water treatment options are increasingly necessary for water utilities to build

resilience against local water challenges ranging from protecting the environment to ensuring independence over water supply long-term. Still, the reuse of water can also bring numerous economic benefits, since reused water is cheaper than the generation of water through other technologies, such as desalination, which means savings for both public services and for citizens.

As ozonation continues to gain traction as a key treatment process for potable water reuse, several future perspectives and challenges emerge. In terms of future perspectives, integrating ozonation with other advanced treatment processes like membrane filtration, biological treatment, and activated carbon adsorption can enhance overall treatment efficacy and produce high-quality potable water. Continued research and development efforts are needed to optimize ozonation parameters such as dose, contact time, and reactor configuration to maximize contaminant removal efficiency and minimize the formation of disinfection by-products. Advances in online monitoring technologies and control strategies will enable real-time monitoring of ozonation performance and ensure the consistent production of safe drinking water. Moreover, implementing energy-efficient ozonation systems and strategies for managing ozone by-products will promote sustainable operation and minimize environmental impacts.

The matrix complexity and presence of emerging contaminants and recalcitrant organic compounds pose challenges for effective ozonation, requiring further appropriated research to understand their removal mechanisms and optimize treatment processes. Additionally, as related, despite its efficacy in contaminant removal, ozonation can generate disinfection by-products such as bromate and NDMA, necessitating strategies to mitigate their formation and ensure regulatory compliance. Moreover, the capital and operational costs associated with ozonation systems, including equipment, energy consumption, and maintenance, may present financial challenges for water utilities, particularly in smaller communities. The absence of standardized regulations specific to ozonation and its by-products in potable water reuse may create uncertainty for utilities and regulators, requiring the development of comprehensive guidelines to ensure public health protection.

Despite the need for additional guidelines, a critical argument against future regulations is the inability of many agencies to monitor concentrations of Trace Organic Contaminants (TOrC) due to lack of expertise, instrumentation, and/or associated costs of analysis. There is a need to develop surrogate frameworks for process control similar to the use of indicator bacteria for disinfection. Additionally, due to the high oxidative demand in wastewater matrices, dissolved ozone reacts rapidly, making it impractical to always maintain a residual.

Addressing these future perspectives and challenges will be essential for the widespread adoption of ozonation

in potable water reuse and the realization of its potential benefits for water sustainability and public health.

## Conclusion

In response to the global demand for improved wastewater treatment techniques for reuse, this review summarizes recent studies showcasing the challenges and effectiveness of ozone against a variety of microorganisms, organic and inorganic pollutants, emphasizing its applicability for water reuse. Ozone shows significant potential for potable reuse applications by effectively oxidizing organic contaminants and providing robust disinfection capabilities. However, challenges such as by-product formation, energy consumption, and microbial resistance underscore the need for careful process design, rigorous monitoring, and possibly integration with other treatment technologies to optimize performance and ensure water safety. Regarding implementation, while numerous lab-scale studies outline ozone's impact on water treatment, there are few reports on large-scale deployment in Brazil. Ozone's extensive use on a larger scale has been extensively studied in the United States, China, and European countries. Brazil's limited implementation may be attributed to its relative abundance of water resources, reducing the immediate need for advanced treatment technologies. In contrast, water scarcity in other countries drives the imperative for treated water reuse. Additionally, infrastructure availability and technical expertise influence the adoption of sophisticated treatment methods, while stringent environmental regulations globally drive investments in advanced disinfection technologies.

**Acknowledgements** The authors are thankful to the Federal University of Rio Grande do Sul (UFRGS) for the support offered throughout the research. The authors also gratefully acknowledge the Brazilian financial support of National Council for Scientific and Technological Development (CNPq), Grant Number 172837/2023-5.

**Author contribution** L. R. de Carvalho Costa: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Software, Validation and Writing—Original Draft; L. Amaral Férís: Supervision and Writing—Review & Editing.

**Funding** The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

**Data availability** Data will be made available on request.

## Declarations

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Conflict of interest** The authors declare that they have no competing financial interests or known personal relationships that could have influenced the work reported in this article.

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