

Review

Ozone for Industrial Wastewater Treatment: Recent Advances and Sector Applications

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Abstract

Ozonation and ozone-based advanced oxidation processes, including ozone/hydrogen peroxide and ozone/ultraviolet irradiation, have been extensively studied for their efficacy in treating wastewater across various industries. While sectors such as pulp and paper, textile, food and beverage, microelectronics, and municipal wastewater have successfully implemented ozone at full scale, others have yet to fully embrace these technologies' effectiveness. This review article examines recent publications from the past two decades, exploring novel applications of ozone-based technologies in treating wastewater from diverse sectors, including food and beverage, agriculture, aquaculture, textile, pulp and paper, oil and gas, medical and pharmaceutical manufacturing, pesticides, cosmetics, cigarettes, latex, cork manufacturing, semiconductors, and electroplating industries. The review underscores ozone's broad applicability in degrading recalcitrant synthetic and natural organics, thereby reducing toxicity and enhancing biodegradability in industrial effluents. Additionally, ozone-based treatments prove highly effective in disinfecting pathogenic microorganisms present in these effluents. Continued research and application of these ozonation and ozone-based advanced oxidation processes hold promise for addressing environmental challenges and advancing sustainable wastewater management practices globally.



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1. Introduction

Ozone (O₃) is a strong oxidizing agent and broad-spectrum disinfectant that can effectively destroy many recalcitrant organic pollutants and inactivate pathogens in water and wastewater. Its oxidation potential (2.07 V) allows it to break down persistent compounds such as solvents [1], pesticides [2,3], surfactants [4], pharmaceuticals and personal care products [5–7], endocrine-disrupting compounds [7–9], and many other industrial chemicals [1,10]. In addition to its chemical oxidation capabilities, ozone is also effective against a wide range of pathogenic microorganisms, including viruses, bacteria, helminths, and protozoa [11–14], making it a valuable tool for safe drinking water production, wastewater treatment, environmental protection, and water reuse.

Ozone treatment technologies have been extensively applied in municipal drinking water and wastewater treatment facilities, where their use is supported by decades of

engineering experience, regulatory guidance, and proven performance [15–17]. Beyond the municipal settings, ozone has found diverse applications across various industrial sectors. Industries such as pulp bleaching, semiconductors, textiles, petrochemicals, and electroplating, among others, have explored ozone technologies for purposes ranging from product processing (e.g., pulp bleaching or wafer cleaning) to pollution abatement [e.g., reducing chemical oxygen demand (COD), color in effluents]. In other sectors, such as aquarium life support systems or landfill leachate treatment, ozone has emerged as a niche but highly effective treatment option due to its versatility and on-site generation potential.

Despite these varied applications, a comprehensive and up-to-date synthesis of the use of ozone in industrial wastewater treatment is lacking. More than two decades ago, Rice [18,19] published two fundamental review articles summarizing industrial uses of ozone, highlighting both its promise and technical challenges. Since then, significant progress has been made in improving ozone generator and contactor designs, including integrated treatment systems combining ozone and biological treatment alongside various ozone-based advanced oxidation processes (AOPs), such as ozone/hydrogen peroxide (O_3/H_2O_2), ozone/ultraviolet (O_3/UV), and various catalytic ozonation (e.g., O_3/TiO_2). At the same time, new drivers such as stricter discharge regulations, a growing emphasis on water reuse, and the emergence of novel contaminants have renewed interest in advanced treatment solutions for industrial wastewater.

This review article aims to fill this gap by compiling and synthesizing recent research on ozone treatment technologies applied to industrial wastewater. The focus is on evaluating ozone's role as a standalone or integrated treatment step in addressing key pollutants across a range of industrial sectors. While the review does not provide a detailed economic analysis due to limited cost data in the literature, it seeks to highlight technical feasibility, treatment outcomes, and emerging trends that inform future industrial applications of ozone. Nevertheless, key cost considerations and challenges associated with economic evaluations are discussed in the later sections to support a broader context and decision-making.

To develop this review, we conducted a literature search using the Web of Science database with keywords such as “ozone,” “ozonation,” and “industrial wastewater,” with an emphasis on peer-reviewed articles published over the past 20 years. Additional searches were performed using combinations of ozone with sector-specific terms (e.g., textile, pharmaceutical, pulp and paper), and targeted searches were conducted in specialty journals, such as *Ozone: Science & Engineering*. The selection of industrial sectors was informed by prior knowledge of ozone's potential applicability, as well as the availability of recent research highlighting its performance in diverse wastewater matrices. Importantly, we prioritized studies that used real industrial effluents, excluding those based solely on synthetic wastewater models, except in a few cases where synthetic systems were justified for mechanistic insight. The review prioritizes studies that reported treatment outcomes, process configurations, or integration strategies relevant to real-world scenarios. While not exhaustive or systematic, this targeted approach aims to synthesize recent advancements and practical insights into ozone-based industrial wastewater treatment.

2. Ozone-Based Industrial Wastewater Treatment

Like municipal water and wastewater applications, ozone serves dual roles in industrial sectors, as a potent chemical oxidant for degrading contaminants and as an effective biocide/disinfectant for microbial control. This section outlines these two primary functions and discusses key considerations relevant to industrial applications, including the formation and control of oxidation byproducts, limitations in treatment performance, and safety and material handling challenges. For readers unfamiliar with the fundamental

properties of ozone or its general behavior in aqueous systems, several comprehensive reviews and textbooks are available that cover ozone chemistry, generation, and reactions mechanisms in detail [10,20–23].

2.1. Contaminant Oxidation and Abatement

The most remarkable property of ozone as an oxidant is its ability to degrade and detoxify numerous synthetic and natural organic and inorganic compounds that can be found in both municipal and industrial wastewater. Inorganics that could be oxidized/degraded include cyanide (CN^-) [24], hydrogen sulfide/bisulfide ($\text{H}_2\text{S}/\text{HS}^-$) [25,26], arsenite [As(III)] [27], reduced iron [Fe(II)], and manganese [Mn(II)] [28,29] through oxidation-reduction reactions. The ozone oxidation results in either the formation of benign products [e.g., bicarbonate (HCO_3^-), nitrogen gas (N_2), and oxygen (O_2) from cyanide ozonation and sulfate (SO_4^{2-}) from sulfide ozonation] or oxidized products that could be readily removed by adsorption [e.g., As(VI) from As(III) ozonation] and/or precipitation [Fe(III) and Mn(IV) and from Fe(II) and Mn(II) ozonation].

As mentioned earlier, numerous recalcitrant organic compounds, including chlorinated pesticides, solvents, pharmaceuticals, and personal care products, could be oxidatively degraded by ozonation [2–4,6]. It is well known that ozone reacts with aqueous solutes through two distinct pathways, namely the direct ozone (molecular ozone) and indirect (hydroxyl radical, $\text{HO}\bullet$) pathways [22]. In the direct pathway, molecular ozone reacts with selected functional groups, including unsaturated carbon–carbon bonds via cycloaddition, aliphatic amines via electrophilic addition, and aromatic rings via electrophilic substitution [22,30,31], as shown in Figure 1. Usually, the primary products further react with additional ozone molecules and/or hydroxyl radicals to form smaller, more stable end products, which are typically less toxic than the parent compounds.

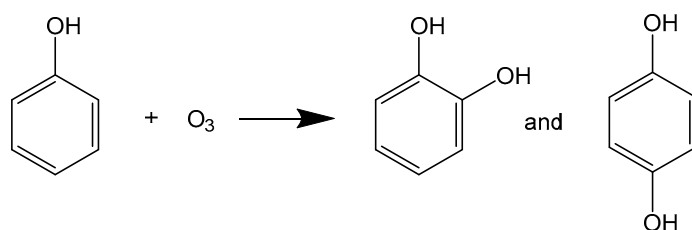


Figure 1. Example of electrophilic substitution (ozonation of phenol).

The indirect pathway involves the self-decomposition of ozone molecules into many reactive oxygen species (e.g., $\text{HO}\bullet$, $\text{HO}_2\bullet$, $\text{O}_2^-\bullet$, $\text{HO}_3\bullet$, H_2O_2) through a series of radical chain reactions and subsequent reactions of these reactive oxygen species with aqueous contaminants [22]. Hydroxyl radicals are even more reactive than molecular ozone (1.35 times) and are responsible for the non-selective oxidation of a wider variety of organic compounds. The ozone self-decomposition process is accelerated under alkaline conditions, as well as by the addition of auxiliary chemicals and/or agents [e.g., H_2O_2 , UV radiation, or ultrasonic]. The latter are collectively called AOPs. Common ozone-based AOPs include $\text{O}_3/\text{H}_2\text{O}_2$ (also known as peroxone), O_3/UV , and $\text{O}_3/\text{H}_2\text{O}_2/\text{UV}$ processes [22]. The organic molecules can be fully destroyed into inorganic ions (i.e., mineralization) via the indirect, hydroxyl radical pathway, if enough oxidants are provided.

Ozonation and ozone-based AOPs are also often considered for the treatment of bulk organics [measured as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), or dissolved organic carbon (DOC)] in industrial wastewaters. However, it is not economically feasible to attempt complete mineralization of all the organic compounds in industrial wastewaters. Instead, combining ozonation and ozone-based AOPs with biological treatment will be more cost-effective because the

products of ozonation and AOPs tend to be more biologically degradable [32–35], which can be assessed by the BOD/COD ratio.

It should be noted that ozonation and ozone-based AOPs are not effective in degrading ammonia ($\text{NH}_3/\text{NH}_4^+$), as well as fully oxidized compounds such as perchlorate (ClO_4^-) and selenate (SeO_4^{2-}), and perchlorinated/brominated/fluorinated compounds [e.g., carbon tetrachloride, perfluorooctanesulfonic acid (PFOS)]. These compounds need to be removed from wastewater by other means such as powdered or granular activated carbon (PAC/GAC) adsorption, ion exchange, nanofiltration and reverse osmosis, and anaerobic biological treatment.

2.2. Microbial Inactivation

The excellent biocidal properties of ozone and its usefulness in water and wastewater disinfection are very well documented [11,36–38]. Ozone can be used to control pathogenic microorganisms in industrial wastewaters and any unwanted microorganisms in industrial process water and cooling water [18]. In addition, ozone can be used to disinfect the surface of perishable food products, including seafood, meat, cheese, eggs, fruits, and vegetables, to enhance their quality and extend their shelf lives [39–43]. Ozone can effectively inactivate a very wide range of bacteria (e.g., coliforms, *Escherichia coli*, *Salmonella* spp., *Legionella* spp., *Listeria* spp.), viruses, fungi, and protozoa (e.g., *Giardia* spp., *Cryptosporidium* spp.) cysts/oocysts by chemically disturbing the integrity of cell membranes or viral capsids by oxidizing phospholipids, glycoproteins, and/or proteins. Ozone gas and ozonated water are also useful for surface sterilization and personal protective equipment decontamination at dentists, medical clinics, and hospitals to prevent infections, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [44–47].

2.3. Challenges and Trade-Off in Ozone-Based Treatment

Despite its versatility, ozone is not universally suitable for all industrial wastewater treatment scenarios. Its relatively high capital and operational costs, combined with system complexity due to gas–liquid transfer dynamics, can hinder cost-effectiveness in certain applications. Moreover, ozone's performance is highly dependent on wastewater matrix characteristics, such as pH, temperature, and the presence of radical scavengers [20,21,23]. In some cases, alternative AOPs, such as the Fenton and photo-Fenton processes, or non-oxidative approaches like membrane separation or adsorption, may offer more practical or economical treatment solutions. A careful evaluation of site-specific goals, infrastructure, and regulatory requirements is essential when selecting among these technologies.

Another well-documented challenge in ozonation is the formation of oxidation byproducts, including low-molecular-weight aldehydes, ketones, carboxylic acids, and bromate (especially in bromide-containing waters). Some of these byproducts can exhibit elevated toxicity, such as genotoxicity, especially when ozonation is applied as a stand-alone treatment without adequate post-treatment [2,4]. Moreover, ozonation alone is generally insufficient to achieve complete mineralization of organic contaminants; doing so would require extremely high ozone doses on the order of grams per liter, which are economically and operationally impractical for most industrial applications. To mitigate these risks, ozone is often paired with subsequent biological treatment processes, such as biofiltration, moving bed biofilm reactors, or membrane bioreactors (MBRs), which can effectively remove biodegradable byproducts and reduce toxicity levels in treated effluents. The formation and control of ozonation byproducts remain critical considerations in the design and optimization of industrial ozone treatment systems.

In addition to operational and treatment-related challenges, ozone itself poses significant safety and material handling concerns [20,21]. As a highly reactive and toxic gas, ozone

can cause respiratory irritation and other adverse health effects upon inhalation, even at low concentrations. Its strong oxidative potential also makes it corrosive to many common construction materials, necessitating the use of ozone-resistant components such as stainless steel, polytetrafluoroethylene, or glass-lined reactors. Industrial implementation, therefore, requires robust safety protocols, continuous ozone monitoring, and proper ventilation and ozone destruction systems to ensure occupational safety and prevent accidental exposure. These factors add to the overall complexity and cost of ozone system design and operation in industrial settings.

3. Recent Advances in Industrial Ozone Applications

In this section, recent reports on the ozone use in various industry sectors, including food and beverage, textile, agriculture, aquaculture, pulp and paper, oil and gas, and medical and pharmaceuticals, as well as several miscellaneous industries, namely pesticides, cosmetics, rubber, tobacco, cork, semiconductor, and electroplating industries, are reviewed.

3.1. Food and Beverage Industry

The food and beverage industry consumes a large volume of water and produces various wastewaters, mainly due to intensive equipment cleaning processes and specific product production requirements. These wastewaters contain raw ingredients and additives such as flavorings, dyes, emulsifiers, sweeteners, and byproducts of chemical cleaning processes like alkaline and acidic solutions [48]. These wastewaters are typically high in organic matter (measured as BOD, COD, and TOC) and exhibit high color and objectionable odors, necessitating treatment before discharge into the environment or sewage systems. Given that wastewaters are usually generated in batch mode, they are often treated biologically due to lower costs and energy requirements. Most constituents are biodegradable, originating from plants, meat, and seafood. However, when biological treatment alone is insufficient, advanced treatments like ozonation can supplement or replace existing methods [49]. Ozone is effective in color and odor removal and disinfection of pathogenic microorganisms [50]. Additionally, minimizing wastewater and innovating in wastewater recovery and recycling are becoming key topics in food and beverage industrial wastewater management [48,51].

Karamah et al. [52] investigated the use of ozonation and GAC to treat wastewater from a tofu production plant (initial COD concentration: 780–850 mg/L) in South Jakarta, Indonesia. In the laboratory, a semi-batch ozone study was conducted with different applied ozone dosages (calculated as 16, 28, and 39 mg/L) and different amounts of GAC media (50, 75, and 100 g), where 4 L of diluted tofu production plant wastewater was recirculated continuously for one to two hours. They found that treating this wastewater with an applied ozone dose of 39 mg/L yielded a COD removal of 54 mg/L in one hour. When the ozone treatment was combined with GAC treatment with 100 g of media, the COD removal was increased to 310 and 377 mg/L in one and two hours, respectively. It was suggested that enhanced production of hydroxyl radicals and adsorption were responsible for the improved COD removal in the combined treatment system. Martins and Quinta-Ferreira [53] investigated ozonation, O_3/H_2O_2 AOP, and catalytic ozonation to treat biologically treated milk whey wastewater from a cheese production facility in the north region of Portugal. The biologically treated wastewater contained approximately 520 mg/L of COD, 215 mg/L of TOC, and 151 mg/L of five-day BOD (BOD_5). At the same time, the wastewater had a grey color and an objectionable odor and was not suitable for discharge to the aquatic environment. A laboratory-scale ozone study was conducted in a semi-batch setup with a 0.5 L reactor with diffusers applying ozone gas at a rate of 10 mg/L/min. After 420 min of continuous ozonation (applied ozone dose: 4.2 g/L), approximately 67%

of TOC could be removed at pH 7.5. Upon the ozone treatment, the concentration of COD was reduced to 280 mg/L, while BOD₅ increased to 200 mg/L, which indicated that the biodegradability increased. The addition of 33 mM of H₂O₂ improved COD, BOD₅, and TOC removal and allowed complete mineralization. Ozonation also helped decolorize and remove the odor from the cheese factory wastewater. The authors also found that the addition of 10 g/L of Mn-Ce-O or N-150 (Fe₂O₃-MnO_x) catalysts to ozonation improved the TOC removal as well, although the adsorption of organic matter onto the heterogenous catalyst surface was observed.

Benincá et al. [54] investigated the effects of ozonation on degrading azo dye Ponceau 4R and other constituents in raw wastewater from a confectionery factory in Brazil. Using a 1.54 L semi-batch reactor with ozone gas injected for 2 h at a flow rate of 1.16×10^{-6} kg/s, experiments were conducted at pH levels of 4.7 and 9.4. The dye was degraded 70% within 2 min and completely degraded after 10 min, but TOC removal only reached a maximum of 60%, indicating limited efficiency in reducing TOC. Ozone reacted efficiently with larger organic compounds but struggled with smaller species formed over time. Higher color removal was observed at pH 9.4, attributed to increased hydroxyl radical production, breaking down aromatic rings. However, negligible COD removal was noted in all experiments. The authors suggested that while ozonation was effective for color removal, it should be combined with other treatment processes to effectively remove TOC, BOD, and COD from confectionery wastewater. Garcia-Morales et al. [55] studied the effectiveness of ozonation and O₃/H₂O₂ AOP combined with chemical coagulation for the treatment of raw and biologically treated wastewater from a soft drink production process in Mexico. A 1 L laboratory-scale semi-batch ozone reactor was employed in this study (ozone gas injection rate: 5.2 g/h, with or without 50 mM H₂O₂). By combining coagulation with polyaluminum chloride (0.03 mg/L), ozonation could achieve effective color and turbidity removal from both raw and biologically treated wastewater [color: 1035 and 38 PtCo unit, turbidity: 190 and 4 formazin nephelometric unit (FTU), respectively]. The raw wastewater was weakly acidic (pH: 4.9), while the biologically treated effluent was slightly basic (pH: 7.9). The coagulation–ozone treatment was more effective if it was used as a tertiary treatment after biological treatment (5 min ozonation, calculated applied ozone dose: 433 mg/L). The addition of H₂O₂ to ozonation did not provide any benefit on color and COD removal from the raw wastewater treatment. Sripiboon and Suwannahong [56] also investigated the use of ozonation for the removal of color from wastewater from a brewery in the Pathum Thani Province of Thailand. Ozonation was applied to an effluent from biological treatment, including upflow anaerobic sludge blanket (UASB) reactors, followed by activated sludge reactors. The biological treatment was effective in COD removal (residual: 57 to 68 mg/L), but color removal was unsatisfactory (residual: 500 color units). This study showed that almost 90% of color could be removed by ozonation with 50 mg/L applied doses and 50 min of contact time, while approximately 50% of COD removal could be achieved at the same time. The color and COD removal improved at higher ozone doses (300 mg/L) with the initial pH of the biologically treated wastewater at 8.4.

The wastewater from fresh-cut fruit and vegetable production can contain foodborne pathogens such as *E. coli* and *Salmonella* spp., as well as residual pesticides. In a pilot study, Nahim-Granados et al. [57] investigated the efficacy of ozonation and O₃/H₂O₂ AOP on the inactivation of *E. coli* O157:H7 and *Salmonella enteritidis* and the degradation of six pesticides (0.1 mg/L each), including thiamethoxam, imidacloprid, simazine, azoxystrobin, terbutryn, and buprofezin in synthetic fresh-cut wastewater. A recirculating semi-batch pilot reactor with a capacity of 20 L, where ozone gas was injected via a diffuser, was used. The applied ozone injection rates ranged from 0.09 to 0.15 g/L/h (1.5 to 2.5 mg/L/min). Ozonation at

pH 6.3 was able to inactivate <5 log of *E. coli* and *S. enteritidis* within 5 min of treatment (i.e., <7.5 mg/L of applied ozone dose), while the degradation of pesticides required much longer exposure time (120 min or 180 mg/L of applied ozone dose) to achieve >80% removal. The addition of H₂O₂ or raising the pH to 11 inhibited the inactivation.

To prevent foodborne outbreaks and maintain regulatory food safety standards, intensive chemical cleaning and sanitization processes are commonplace throughout the food and beverage industry [58–62]. Clean-in-place (CIP) is a commonly used method to clean and sanitize the interior surfaces of pipes, fittings, and equipment within food and beverage processing facilities [63]. Common cleaning chemicals used include sodium hypochlorite, quaternary ammonium compounds, surfactants, and peroxyacetic acid. In addition, ozone is often used as an effective cleaning agent in the beverage industry, including wineries and wine processing [61]. Avila-Sierra et al. [64] reported the use of ozone as a cleaning agent for the CIP system of stainless-steel reactors handling starches in the food and pharmaceutical industries using a simulated bench-scale cleaning device. Heat-treated cornstarch strongly adheres to industrial stainless-steel surfaces and usually requires strong alkaline solutions at high temperatures to remove. Wads of stainless-steel fibers (diameter: 2.0–2.1 cm, width: 0.51 mm, weight: 0.80–0.81 g) were artificially fouled with heat-treated cornstarch gels and were used as a substrate to be cleaned. Ozone gas (21 and 42 g/m³) was injected continuously at a given rate (non-specified) into the cleaning device filled with 1.2 L of 0.60% (*w/w.*) sodium hydroxide solution at variable temperatures (20, 40, and 60 °C). The best result (88% foulant reduction) was obtained when stainless-steel wads were treated with a higher ozone concentration at 60 °C for 120 min, and the ozone clearly improved the cleaning process. COD of the cleaning solution increased with time due to the decontamination, which could be reduced by further ozonation. With this CIP method, the cleaning process and treatment of wastewater can be combined into a single process. Nishijima et al. [65] reported an effective use of ozone as a cleaning agent to remove odorous organic compounds, including *d*-limonene, 1-hexanol, furfural, and 4-vinylguaiaicol from ethylene–polypropylene–diene monomer (EPDM) and silicon rubber gaskets in a CIP system for beverage production line and filling equipment. The authors suggested that, due to ozone's strong ability to degrade a wide range of materials, the gasket materials need to be carefully considered to minimize damage to the gaskets and failures. Gaskets purposely contaminated by the odorous compounds were treated by ozone in a 250 mL glass cylinder where ozone gas (100 mg O₃/L) was added through a diffuser at a flow rate of 50 mL/min (applied ozone injection rate: 25 mg/L/min) at 20 or 70 °C for 60 min with or without 32 mM H₂O₂. Ozonation could substantially improve the *d*-limonene removal from contaminated silicon rubber gaskets very effectively (100% removal within 30 min at 20 °C, applied ozone dose: 750 mg/L) compared with the conventional cleaning method, while it was slightly less effective on EPDM gaskets (86% removal), and the compound persisted for more than 60 min. Similar results were observed with the other odorous compounds. They also found that the molecular ozone pathway was critical for this cleaning process.

3.2. Agriculture and Aquaculture Industry

According to the United States Geological Survey, agriculture is responsible for about 42% of freshwater withdrawal from surface water and aquifers in the US in 2015 [66]. Some of the water used in a variety of agricultural operations, such as building and equipment washing, livestock slaughtering and processing, milking process, and cropland irrigation and tile drainage, becomes wastewater. These wastewaters can contain a variety of different biological and chemical contaminants originating from animal feed, manure, and blood that pose threats to the environment and human health, including pathogenic microorganisms, pesticides, antibiotics, and cleaning agents, as well as suspended solids

and bulk organics [51,67–69]. Ozone could be used to destroy those organic pollutants and disinfect microorganisms in agricultural wastewater. de Souza et al. [70] investigated an ozone-based treatment in a fixed bed reactor containing porous plastic media called “bio-rings” for enhanced gas–liquid transfer to treat and disinfect biologically treated cattle wastewater in an experimental farm at the Federal Rural University of Rio de Janeiro, Brazil. The cattle wastewater was treated in a UASB bioreactor for 7 days prior to the laboratory-scale semi-batch ozonation study. Calculated applied ozone doses ranged from 405 mg/L to 1620 mg/L ($13.52 \text{ mg L}^{-1} \text{ min}^{-1}$, 0.5–2 h treatment). The 2 h ozone treatment could remove color (3010 to 200 units), turbidity (130 to 15 NTU), COD (1100 to 101 mg/L), and BOD₅ (305 to 59 mg/L). The ozone treatment could inactivate up to 99.9% of total and thermotolerant coliforms as well.

Since agricultural wastewaters typically exhibit color derived from biological materials, ozonation has the potential for color removal. Yoon et al. [71] investigated the use of ozonation and O₃/H₂O₂ AOP for the color removal of swine wastewater from a pig farm located in Wonju, Korea. The swine wastewater was first pretreated with biological treatment, followed by precipitation and ultrafiltration (UF) or nanofiltration (NF). The UF and NF permeates were tested for treatability with ozone and O₃/H₂O₂ in a semi-batch laboratory reactor (working volume: 0.75 L). While ozone alone worked better in color removal from NF permeate, the addition of hydrogen peroxide enhanced color removal from UF permeate. More than 90% of initial color (400–450 and 550–600 units) could be removed by ozonation alone, with approximately 100 mg/L of utilized ozone dose, and O₃/H₂O₂ AOP, with approximately 150 mg/L of utilized ozone dose (O₃:H₂O₂ mass ratio: 1:0.7) from NF and UF permeates, respectively. Takashina et al. [72] evaluated the use of ozonation and O₃/UV AOP for the treatment of synthetic coffee wastewater. It is known that coffee production effluent contains high levels of color and caffeine. In this study, the factorial experimental design (three-level central composite face centered) and response surface methodology were utilized to optimize the treatment conditions, including gaseous ozone concentration, caffeine concentration, pH, and reaction time, for effective color and caffeine removal using a semi-batch ozone reactor (working volume: 1 L) with a 125 W mercury vapor UV lamp ($4.6 \times 10^{-7} \text{ Einstein L}^{-1} \text{ s}^{-1}$). Compared with ozonation alone, O₃/UV AOP showed slightly better performance in this study. To achieve the optimum results, the authors recommended pH 9.2, gaseous ozone concentration of 14.7 mg/L, and reaction time of 52 min. Since the gas flow rate to the reactor was not given, the applied ozone doses could not be calculated.

The aquaculture industry is also dependent on the availability of clean water, both freshwater and saltwater. Recirculating aquaculture systems (RASs) offer an attractive alternative to traditional flow-through aquaculture systems. RASs work by treating the wastewater from an aquaculture system and reintroducing it back into the culture waters at fish farms. Existing recirculating systems utilize biological methods to remove constituents that would be harmful to fish in their culture waters, but face multiple problems such as clogged biofilters, long hydraulic retention times, large surface areas, and a long process time [73,74]. For a recirculating aquaculture system to be effective, suspended solids and organic matter must be removed, while oxygen must be added and ammonia, nitrite, pH, and pathogenic bacteria must be controlled. The advantages and challenges of the use of ozone in RAS have been well documented [75,76]. Chen et al. [77] studied the use of ozonation combined with sand pre-filtration, ceramic membrane filtration (pore size: 2 μm), and activated carbon in RASs as an alternative treatment train to remove particulates and organic matter, as well as ammonia-N. The ceramic membranes were coated with titanium dioxide (TiO₂)-based catalysts, namely Ti-Mn/TiO₂/Al₂O₃ and TiO₂/Al₂O₃, to promote the decomposition of ozone and the formation of hydroxyl radicals. In their continuous

flow pilot-scale study, the authors found that membranes coated with Ti-Mn/TiO₂/Al₂O₃ showed the best membrane antifouling performance and COD removal from the saltwater in a 7 m³ aquaculture tank with *Paralichthys lethostigma* (the southern founder). Effective removal of turbidity, nitrite, and ammonia-N was also achieved by this treatment train with an ozone dose of 52 mg/min, which enabled continuous recirculation of treated water. The water recovery was 95.8% after 4 h of operation.

3.3. Textile Industry

The textile industry is another large producer of industrial wastewater, mainly due to the substantial quantity of water needed for the dyeing and finishing process of garments, household fabrics, and other textiles, and is a major point source for pollution in water bodies around the world [78]. The use of dyes, which are chemically complex, diverse, and hard to break down, poses serious health risks to humans and wildlife, with some having been proven to be toxic and carcinogenic [79,80]. These dyes make their way into wastewater from the textile industry easily, with around 10–15% of the dyes used in the manufacturing process failing to bond to the textiles and becoming part of the effluent [81]. Scouring, the process for removing impurities from raw and processed textiles, is another polluting process in the textile industry and leads to the release of impurities such as fats and grease, alongside scouring agents, such as defoamers, and lubricants into the wastewater stream [82]. Other contaminants from this industry that can be found in wastewater streams include metals and plant matter. Typical textile wastewater characteristics include high levels of color density, organic matter, pH, salinity, and turbidity [83]. Hydroxyl radicals can react with many dyes and oxidize most complex organic and inorganic chemicals that may be present in textile wastewater [84]. Additionally, complex aromatic rings and other functional groups, along with the conjugated double bonds of dyes, can be effectively broken down by ozone [85]. Conventional biological wastewater treatment does not completely degrade dyes due to their toxicity, so alternative forms of treatment, such as ozonation, are desired. Several recent studies evaluated the use of ozonation as a pretreatment to various biological treatment processes for textile wastewater, as reviewed below.

Suryawan et al. [86] conducted a bench-scale experiment to assess ozone treatment as a pretreatment for biological wastewater treatment using anoxic–aerobic activated sludge on wastewater from an Endek textile plant in Denpasar, Indonesia. Endek, a traditional Balinese fabric, generates wastewater high in organic matter and contains synthetic and natural dyes, acids, bases, chemicals, and suspended solids during its production. A 3 L ozone batch system with an ozone gas injection rate of 0.05 g/min for 60 min was used. The ozonation alone reduced color from 835 to 463 PtCo and COD from 615 to 395 mg/L. When combined with activated sludge treatment, these values further decreased to 109 PtCo and 145 mg/L, respectively. While ozonation alone had limited impact on BOD₅ and total ammonia (initial concentrations: 151 mg/L and 15.2 mg/L, respectively), the combined treatment improved their removal from 28.6% to 72.6% for BOD₅ and from 17.9% to 73.0% for total ammonia. Similarly, Fu et al. [87] investigated a combined biological wriggle bed (BWB) and ozone biological aerated filter (O₃-BAF) treatment system for COD removal at a textile wastewater treatment plant in Foshan, China. The BWB with an increased air-to-water ratio was upstream of a 550 L O₃-BAF reactor packed with ceramic granular media. The system operated for 19 days with an influent flow rate of 30 L/h and an average COD concentration of 827 mg/L. A sedimentation basin was situated between the BWB and O₃-BAF system. Ozone doses in the wastewater ranged from 75 to 125 mg/L. The study achieved a COD removal efficiency of 90.4%, with an average effluent COD concentration of 86 mg/L. The BWB reactor removed approximately 70% of the COD, while the O₃-BAF

treated recalcitrant pollutants. Increasing ozone doses from 75 mg/L to 125 mg/L on days 4 and 7 led to higher COD levels due to microorganism inactivation, which took 2 days to stabilize after ozone levels were reduced. Weather changes and colder temperatures also negatively impacted effluent quality.

Ozonation was investigated as a pretreatment for textile effluent from an industrial plant in Erode, India, aiming to increase biodegradability and reduce treatment costs [88]. The process was optimized using synthetic effluent with industrial-grade red, yellow, and blue dyes and tested on real textile wastewater (pH 10.6, COD 2754 ± 40 mg/L). Ozonation was performed in a 200 mL batch reactor with an ozone concentration of 80 mg/L and a flow rate of 1 L/min for 30 min. A 1 L sequential batch reactor was used for biological treatment. The optimized conditions from synthetic effluent tests were applied to real textile effluent, resulting in 94.6% color removal and 67.4% COD removal. Subsequent biological treatment in the sequential batch reactor achieved 98.6% total color removal and 91.6% total COD removal. The biodegradability of the effluent improved significantly, with an 81.8% increase in the biodegradability and a 126.2% increase in the specific oxygen uptake rate, likely due to the breakdown of complex compounds by ozonation into simpler, more biodegradable forms. Similar to textile wastewater, Schrank et al. [89] evaluated the effect of ozonation on inorganic and organic constituents at different pH levels in tannery wastewater, settled and decanted at an industrial-scale tannery in Brazil. Using a 2500 mL batch reactor, ozone was bubbled at a rate of $250 \text{ mg O}_3 \text{ L}^{-1} \text{ h}^{-1}$ for 2 or 4 h with continuous stirring at 600 rpm. The wastewater was coagulated with aluminum sulfate, settled for 1 h, and decanted before pH adjustment using sodium hydroxide. pH levels of 3, 5, 7, 9, and 11 were tested. Helium gas and a sodium sulfite solution were added to ensure the destruction of excess ozone. COD removal (initial concentration: 130 mg/L) was 70% at pH 11, 49% at pH 7, and 28% at pH 3. BOD removal (initial concentration: 47 mg/L) was 68% at pH 11, decreasing progressively to 38% at pH 3. Ammonia (initial concentration: 9.5 mg/L) showed the highest removal to 2.3 mg/L at pH 11. Increasing the ozone dosage to 500 mg/L and reaction time to 4 h improved COD and BOD₅ removal by 15%. However, TOC and DOC concentrations changed marginally, indicating incomplete mineralization of oxidized organic compounds.

3.4. Pulp and Paper Industry

The manufacturing of pulp and paper requires significant freshwater for wood chip processing, pulp bleaching, washing, steam production, and cooling [90,91]. Much of the wastewater generated in pulp and paper mills is reused within the plant after proper treatment. The process involves various chemicals like bleaching agents, binders, fillers, acids/bases, and dyes, which are discharged into wastewater. Bleaching processes release hemicellulose and lignin, complex natural organic compounds, resulting in dark-colored wastewater known as black liquor [92]. Lignin, in particular, is highly recalcitrant and resistant to biological degradation. Pulp mill wastewater also contains toxic and recalcitrant substances such as complex resins and fatty acids [93]. Ozone has been proposed to degrade these recalcitrant organics and enhance the biodegradability of wastewater for subsequent biological treatment [93,94], as discussed by Rice [18].

Shahzad Munir et al. [95] compared the effectiveness of ozonation and a combined O₃/UV AOP process for COD removal and color removal of industrial wastewater from the pulp and paper industry. This wastewater contains lignin, chlorinated organic compounds, cyanide, polyphenols, and other aromatics, resulting in high COD, color, turbidity, toxicity, and varying levels of pH. Conventional biological methods are less effective at degrading pollutants due to the presence of highly recalcitrant lignin. The study found that the O₃/UV AOP was more effective than ozonation alone at reducing COD and color, with a

56% reduction in COD and 71% reduction in color at an ozone dosage of 0.2 mg/mL for 3 h. Mainardis et al. [96] conducted a pilot study of the treatment of pulp and paper wastewater using ozonation, with the aim of finding a feasible substitute for conventional tertiary physicochemical treatment. Four different process streams were analyzed: process water, consisting of the excess water that is removed from cellulose fibers, which is high in volume but low in COD; bleaching water, which is an effluent of the cellulose cleaning and washing process and has a high COD concentration; and wastewater final wastewater streams before and after secondary biological treatment. With a 400 L ozonation system with venturi injection and an ozone dosage up to 600 mg O₃/L, it was found that ozonation was most effective after biological treatment where up to 81% of COD was removed, followed by process water with 60% COD removal, then before biological treatment where the mean removal was 46%, and lastly, bleaching water with only 28% COD removal. Economic analysis found that an ozone dosage of 100 mg/L would effectively provide the same result as conventional physicochemical treatment but save hundreds of thousands of dollars per year.

The presence of compounds in pulp and paper mill sludge, which is a result of an activated sludge process for the treatment of a mill's wastewater, contributes to its toxicity and creates environmental concerns if discharged without treatment. This sludge is typically sent to a landfill or incinerated, and its disposal can account for more than half of the total cost of a mill's wastewater treatment [97]. Gupta et al. [98] investigated the degradation of absorbable organic halides (AOX), extractable organic halogens (EOX), and chlorophenols in the sludge of a pulp and paper facility in India by ozonation as a pretreatment step to the activated sludge process. The AOX and EOX concentrations in the sludge were found to be 1980 ± 42 and 599 ± 19 mg/kg, respectively. Ten chlorophenols were found to be present as well. The reduction of AOX and EOX compounds was 23 ± 2 and 26% with ozone treatment at an ozone dosage of 45.3 ± 2.1 O₃/g, whereas chloride content in the aqueous phase increased from 683 ± 8 to 694 ± 7 mg/L. Chlorophenols were also degraded during ozonation, ranging from 19–68% removal. The use of ozonation before biological treatment resulted in higher overall degradation among the chlorinated compounds in comparison to a controlled non-ozonated sample. Combining ozonation and biological treatment resulted in AOX, EOX, and chlorophenol removal of 80.1%, 81.2%, and 79.9%, respectively.

3.5. Oil and Gas Industry

Wastewater effluents from the oil and gas industry can contain diverse constituents such as hydrocarbons, grease, heavy metals, hydrogen sulfide, ammonia, and phenols, making them toxic, high in COD and BOD, and potentially hazardous to public and environmental health. Sources of wastewater include refineries, extraction sites, and injection sites within industry. According to a recent EPA report on on-site wastewater treatment technologies in American petroleum refineries, 78% of refineries with available data (129 out of 143 total) employ biological treatment, but only 26% perform additional polishing treatments on their effluent. The report also highlighted a lack of utilization of ozonation and AOPs in wastewater treatment technologies reviewed [99]. In high-salinity wastewaters, such as those encountered in oil and gas operations, ozone solubility and radical-based reaction efficiency may be reduced due to ionic strength effects and radical scavenging. These factors require further investigation to optimize ozone treatment under saline conditions.

Talei et al. [100] investigated the use of the O₃/UV AOP to treat effluents from the Shiraz oil refinery in Iran, achieving 92% COD and 100% sulfide removal under optimal conditions (15 °C, initial pH 9.4, and UV) after 60 and 45 min of ozonation, respectively, at

a dosage of 2335 mg/L. The treated water met quality standards for recycling in various refinery units, such as cooling towers and boilers. Chen et al. [101] investigated ozone treatment of heavy oil refinery wastewater using activated carbon-supported manganese oxides (MnO_x/GAC) as a catalyst. The study optimized conditions, including temperature, pH, and treatment time, achieving the highest COD and TOC removal at 60 °C and pH 6.0, with further improvement observed with extended reaction times. Significant removal efficiencies were also observed at the original pH of 7.4, with optimal conditions identified as 60 °C, 80 min, and pH 7.4, resulting in 51% COD and 47% TOC removal. Phenol concentration was reduced by 71% to 30.5 mg/L after 80 min of treatment.

Boczka and Fernandes [102] investigated the treatment of effluent from a petroleum bitumen production plant in Poland using ozonation, H_2O_2 , and $\text{O}_3/\text{H}_2\text{O}_2$ AOP. They evaluated COD and BOD_5 degradation, sulfide oxidation, biotoxicity, BOD_5/COD ratio changes, and the degradation of volatile organic compounds (VOCs), volatile sulfur compounds (VSCs), and volatile nitrogen compounds (VNCs). Optimal parameters for organic degradation were defined by the oxidant to COD ratio (w/w) of 0.34 for ozonation, 0.49 for $\text{O}_3/\text{H}_2\text{O}_2$ at 25 °C, and 0.45 for H_2O_2 at 40 °C. The $\text{O}_3/\text{H}_2\text{O}_2$ AOP achieved the highest COD and BOD_5 reduction (43% and 34%, respectively) at 25 °C and an oxidant to COD ratio of 0.49. BOD_5/COD increased significantly by 16% and 26% with $\text{O}_3/\text{H}_2\text{O}_2$ treatment. Ozonation at a ratio of 0.34 and 25 °C was most effective in reducing biotoxicity. Hydrogen sulfide was effectively oxidized in all processes. VOCs removal was most effective with ozonation at a ratio of 0.34 and 25 °C, whereas H_2O_2 struggled with VOC degradation. The $\text{O}_3/\text{H}_2\text{O}_2$ AOP at a ratio of 1.02 and 40 °C exhibited the highest efficiency, achieving >99% total VSCs degradation, with ozonation proving more effective in degrading VNCs. The H_2O_2 process was the least expensive (USD 72 per batch), while the $\text{O}_3/\text{H}_2\text{O}_2$ AOP was the most expensive (USD 402.3 per batch).

Corrêa et al. [103] investigated the degradation of contaminants and ecotoxicity of wastewater from petroleum refineries with the use of $\text{O}_3/\text{UV}/\text{TiO}_2$ and biological remediation by macroalgae (*Ulva* spp.). The Lumistox test and *Poecilia vivipara* test were performed as toxicity tests with the bacterium *Vibrio fischeri* and the fish *Poecilia vivipara* for the raw and treated water from the treatment of $\text{O}_3/\text{UV}/\text{TiO}_2$ and *Ulva* spp. Treatment by $\text{O}_3/\text{UV}/\text{TiO}_2$ for 5 and 60 min resulted in a decrease in phenol, sulfide, COD, oil and grease, and ammonia concentrations of 99.9%, 53.0%, 37.7%, 5.2%, 1.9% and 99.9%, 97.2%, 89.2%, 98.2%, and 15%, respectively. The BOD_5/COD ratio was observed from 0.13 to 0.41 after 5 min, and the highest (0.68) was found after 20 min of treatment. From the toxicity tests, the raw wastewater was very toxic to *V. fischeri* and *P. vivipara* [effective/lethal concentration (E/LC_{50} : <1.55%)], whereas the treated samples had lower toxicity towards bacteria (EC_{50} = 30.3%) but significant toxicity toward the fish species (LC_{50} = 1.9%). The combination of 10 min $\text{O}_3/\text{UV}/\text{TiO}_2$ treatment, followed by biotreatment with microalgae, seemed to be the ideal and most cost-effective treatment method.

Sun et al. [104] investigated the use of microbubble ozonation (MB- O_3) to separate total petroleum hydrocarbons (TPH) and solid particles from petroleum waste sludge. TPH in the sludge inhibits sludge disintegration, and MB- O_3 was employed to enhance ozonation efficiency and sludge decomposition. The sludge composition included total solids (TS) at 20.0 ± 0.9 g/L, volatile solids (VS) at 14.2 ± 0.6 g/L, soluble chemical oxygen demand (SCOD) at 680 ± 73 mg/L, residual TPH at 0.8 ± 0.06 w%, and pH at 6.8 ± 0.1 . Conventional ozonation achieved a maximum solubilization of 22.1%, whereas MB- O_3 improved solubilization to approximately 41.9%. SCOD concentration increased by 390% with MB- O_3 compared to 239% with conventional ozonation. The sludge particle size distribution, initially ranging from 15 to 100 μm , decreased due to ozone oxidation, with the medium diameter decreasing from 38.6 to 17.5 μm with MB- O_3 , indicating disruption of

the water–oil–gel structure. In related research, Sun et al. [104] also evaluated TPH removal from oily sludge using MB-O₃, achieving 70.9% removal at an ozone dosage of 0.27 g/g of TS over 120 min, compared to 36.8% removal with conventional ozonation under similar conditions. The rate constant for MB-O₃ (0.0269 min⁻¹) exceeded that of conventional ozonation (0.0116 min⁻¹) by more than double.

He et al. [105] investigated the remediation of toxic oil sands process-affected water (OSPW) in Alberta, Canada, using ozonation to reduce concentrations of naphthenic acids (NAs) and other dissolved organic compounds. OSPW, which is stored on-site due to the surface-mining oil sands industry's no-release policy, was treated with ozone (O₃-OSPW) and activated charcoal (AC-OSPW). The study compared the toxicity of untreated OSPW to O₃-OSPW and AC-OSPW using fathead minnow (*Pimephales promelas*) embryos as indicators. Untreated OSPW significantly decreased embryo survival rates (43.8 ± 7.1%) compared to tap water controls (97.9 ± 2.1%), while O₃-OSPW (93.8 ± 4.0%) and AC-OSPW (77.1 ± 7.1%) showed improved survival. Embryos exposed to untreated OSPW exhibited higher rates of premature hatching and spontaneous movement, along with increased incidences of hemorrhage (50.0 ± 3.4%), pericardial edema (56.3 ± 7.1%), and spinal malformations (37.5 ± 5.4%). These adverse effects were significantly mitigated in embryos exposed to O₃-OSPW and AC-OSPW. The study concluded that ozonation is a promising method for remediating OSPW and reducing its environmental toxicity.

3.6. Medical and Pharmaceutical Industry

The characterization of wastewater from the medical industry, including hospitals and other healthcare facilities, as well as pharmaceutical manufacturing facilities, differs significantly from other industrial wastewaters discussed in this paper. This type of wastewater contains various emerging contaminants, including antibiotic-resistant bacteria (ARB), antibiotic-resistant genes (ARGs), viruses, pharmaceuticals, personal care products (PPCPs), disinfectants, and blood [106]. The degradation of these contaminants through ozonation and AOPs has been extensively studied [5–7]. Research indicates that oxidative degradation mediated by direct ozone and hydroxyl radicals is highly effective for treating water and wastewater containing pharmaceuticals. These contaminants contribute to high BOD and COD levels, along with toxic recalcitrant organics, viruses, ARB, and ARGs, all of which must be removed before discharge into the environment.

Ferre-Aracil et al. [107] investigated the treatment of wastewater from a hospital in Valencia, Spain, using ozonation and O₃/H₂O₂ AOP, varying the ozone concentration, reaction time, and H₂O₂ dosage, and analyzed the kinetics of ozone consumption to determine reaction rate coefficients with oxidizable organic matter and cytostatic compounds. The study detected four cytostatic compounds: irinotecan, ifosfamide, cyclophosphamide, and capecitabine, with concentrations of 273, 1187, and 1139 ng/L for irinotecan, cyclophosphamide, and capecitabine, respectively. The wastewater was treated with ozone concentrations of 45, 55, and 70 g Nm⁻³ in a 1 L bubble column reactor, with a fixed [O₃]_{sat}:[H₂O₂] molar ratio of 1:1, 1:2, 1:0.5, and 1:3. Cyclophosphamide was not completely removed at low ozone concentrations (45 and 55 g/m³). However, after 10 min of treatment, the elimination rates of cyclophosphamide were 97% and 99% for ozone concentrations of 43.9 and 55.3 g/m³, respectively. Complete removal was achieved by increasing the reaction time to 20 min or by O₃/H₂O₂ AOP. The kinetic rate constant for cyclophosphamide was 33.8 and 35.6 M s⁻¹ in experiments 1 and 3, averaging 34.7 M s⁻¹. The mean value in molar units was 5.3 ± 0.9 mM, with an equivalent ozone demand of 254.4 mg/L. The second-order kinetics for ozone and the reacting species were 8.4 ± 0.8 M s⁻¹, indicating 80% reaction completion within 20 min. For a hydraulic retention time of 30 min and treating 1 m³/h in a 500 L reactor, approximately 6.7 L/min of oxygen is required. Vo et al. [108] studied

the removal of antibiotics from raw hospital wastewater in Ho Chi Minh City, Vietnam, using a sponge MBR combined with ozonation. The antibiotics targeted were norfloxacin, ciprofloxacin, ofloxacin, sulfamethoxazole, erythromycin, tetracycline, and trimethoprim. The MBR operated on an 8 min on/2 min off cycle with hydraulic retention times of 10, 6.7, and 5 h at fluxes of 10, 15, and 20 L/m²/h and a sludge retention time of 20 days. The permeate was treated in a 2 L ozone reactor with a 10 min contact time and an ozone supply of 20–40 mg O₃/h. COD removal efficiencies were 97 ± 3%, 96 ± 2%, and 96 ± 2% at respective fluxes, while NH₄⁺-N removal efficiencies were 92 ± 4%, 94 ± 6%, and 93 ± 3%. Total nitrogen removal efficiencies were 43%, 50%, and 33%, and total phosphorus removal efficiencies were 45 ± 16%, 47 ± 28%, and 41 ± 18%. Sponge-MBR alone achieved antibiotic removal rates of 62–86% (norfloxacin), 14–70% (ciprofloxacin), 68–93% (ofloxacin), 24–60% (erythromycin), and 47–93% (trimethoprim). When combined with ozonation, removal rates were 97 ± 2% (trimethoprim), 92 ± 4% (norfloxacin), 90 ± 1% (erythromycin), 88 ± 4% (ofloxacin), 83 ± 7% (ciprofloxacin), 100% (tetracycline), and 66 ± 1% (sulfamethoxazole). Hansen et al. [109] studied the treatment of biologically treated wastewater from Aarhus University Hospital, Aarhus, Denmark. The study focused on removing pharmaceuticals from the effluent using ozonation, investigating the impact of DOC and pH on ozone lifetime and pharmaceutical removal. Ozone lifetime decreased with increasing pH: at pH 5, 6.25, and 7.00, ozone lifetimes were 3, 2, and 1 min, respectively, with a 10 mg/L ozone dose, reducing to less than 20 s at pH 9. To achieve 90% removal of 33 pharmaceuticals across six effluents with varying DOC levels, ozone doses ranged from 0.50 ± 0.06 mg/mg DOC (sulfadiazine) to 4.7 ± 0.6 mg/mg DOC (diatrizoic acid). Higher ozone doses were necessary for recalcitrant pharmaceuticals, especially at lower wastewater pH, extending ozone lifetime and residence time. Addition of H₂O₂ at 0.1 mg per mg of O₃ reduced ozone lifetimes to 10 and 3 min at pH 5 and 6.25, respectively, without affecting pharmaceutical removal efficiency.

Kist et al. [110] investigated the disinfection and treatment of hospital laundry wastewater from a regional hospital in the state of Rio Grande do Sul, Brazil. The clothes washed contained varying levels of contamination from hospital operations and patient health, and they were cleaned using a combination of chemicals. The study employed catalytic photoozonation with UV, ozonation, TiO₂, and combined treatments of O₃/UV, TiO₂/UV, O₃/TiO₂, and UV/TiO₂/O₃, with a treatment duration of up to 60 min and an ozone generation rate of 5.80 mg O₃/h. The removal efficiencies for COD and BOD₅ were 30%, 20%, 28%, and 30% and 42%, 69%, 40%, and 75% for O₃/UV, TiO₂/UV, O₃/TiO₂, and UV/TiO₂/O₃ treatments, respectively. The highest turbidity removal at 45% was achieved with the UV/TiO₂/O₃ process. *E. coli* and thermotolerant coliform concentrations were reduced to 230 and 500 MPN/100 mL, respectively, after 60 min of treatment with the UV/TiO₂/O₃ process. The study estimated that 20 min of treatment time with the UV/TiO₂/O₃ process is sufficient for the full inactivation of microorganisms.

Several researchers reported the effective ozone-based treatment of hospital wastewater in terms of bulk organics abatement. Arslan et al. [111] investigated the ozonation of raw hospital wastewater from the Hospital of Medicine Faculty of Kocaeli University, Kocaeli, Turkey, using various treatment trains: ozonation, O₃/UV/H₂O₂, and O₃/UV. The study examined factors such as initial pH, reaction time, ozone concentration, and H₂O₂ dosage. Although the specific makeup of the wastewater in terms of PPCPs was not described, the results showed that the O₃/UV/H₂O₂ combination was effective for COD removal. Optimal conditions were identified as pH 6.0, ozone concentration of 10 mg/L, and H₂O₂ dosage of 1.8 mL within 60 min, and pH 8.0, ozone concentration of 4.2 mg/L within 27 min, achieving a 46.3% COD removal. Indah Dianawati et al. [112] investigated the treatment of hospital wastewater from hospitals in Semarang, Indonesia, by ozonation.

After two hours, with varying ozone concentration/dosage of 100, 200, and 300 mg/L, the COD removal efficiencies were 43, 65, and 44%, respectively, and the total dissolved solids (TDS) removal efficiencies were 7.6, 5, and 4.9%, respectively.

Effluent from pharmaceutical manufacturing facilities is characterized by a complex mixture of contaminants, including active pharmaceutical ingredients, byproducts, solvents, reagents, and catalysts. It typically has variable pH, elevated temperatures, high turbidity, and significant organic and inorganic loads [BOD, COD, TOC, TDS, total suspended solids (TSS)]. The effluent may also contain nutrients (nitrogen, phosphorus), toxic substances (heavy metals, toxic organics, endocrine-disrupting compounds), and microbial content, including ARB. Thus, advanced treatment processes are necessary to mitigate these contaminants before discharge or reuse. Gupta et al. [113] investigated a combination of ozonation and biological treatment for pharmaceutical industry effluent in Mysore, India. The pH, COD, BOD, TOC, and BOD/COD ratio of the raw effluent were 6.98, 63,000 mg/L, 7717 mg/L, 24,280 mg/L, and 0.12, respectively. Ozone was dosed at 7 g/h with a concentration of 4% *w/w* for 4 h. Activated sludge was collected and used to acclimate the effluent for the aerobic oxidation process. In the ozone pretreatment, the BOD/COD ratio increased to 0.44, the COD removal efficiency was 41%, and the color was reduced by 33.3%. Both COD and color reached their maximum reduction values at 150 min with no further reduction thereafter. After the full 240 min, the pH value dropped from 7.0 to 5.5. Following ozone pretreatment and 10 days of aerobic biodegradation, a COD reduction efficiency of up to 73% was observed, with a significant increase in color removal efficiency (62%). In comparison, effluent without ozone treatment achieved only 15% color removal. The kinetic rate constant for untreated effluent and ozone-pretreated effluent (150 min ozonation) was found to be 0.04 and 0.12 day⁻¹, respectively. Post-treatment with ozonation resulted in an overall COD removal of 87% and color reduction of 93%. The O₃-aerobic oxidation-O₃ approach proved to be suitable for the treatment of pharmaceutical effluent.

Lester et al. [114] studied the treatment of wastewater from TevaKS, a major pharmaceutical formulation facility in Israel, using biological treatment followed by ozonation. High concentrations of carbamazepine (0.84 ± 0.19 mg/L) and venlafaxine (11 ± 2 mg/L) were found in the wastewater post-biological treatment. Biological treatment alone removed TOC, COD, and BOD₅ by 87%, 84%, and 92%, respectively, but only 5% of carbamazepine and venlafaxine were removed. Ozone treatment (1 L/min, 20 mg/L) significantly reduced carbamazepine by >99% (from 0.83 to 0.001 mg/L) at an O₃/DOC ratio of 0.55 and venlafaxine by 98% (from 11.7 to 0.2 mg/L) at a ratio of 0.87. Lowering pH from 7 to 5 enhanced carbamazepine degradation but reduced venlafaxine degradation. Although DOC and COD remained largely unchanged post-ozonation, BOD increased from 79 to 251 mg/L, indicating improved effluent biodegradability.

Li et al. [115] investigated the ozonation and O₃/H₂O₂ AOP pretreatment of pharmaceutical wastewater from a steroid hydrocortisone factory in Tianjin, China, before biological treatment. The wastewater, characterized by pH 5.76, COD 5280 mg/L, BOD₅ 350 mg/L, TOC 1070 mg/L, and a BOD₅/COD ratio of 0.066, poses challenges for traditional biological treatment due to its toxicity. Testing various conditions, the study found optimal treatment at pH 5.76, ozone dose 218 mg/L, and 90 min reaction time, achieving the highest efficiency. Under these conditions, COD and TOC removal efficiencies reached 94% and 91%, respectively. Further increases in ozone dose showed no additional COD and TOC removal benefits. Introducing H₂O₂ with an optimal H₂O₂/O₃ molar ratio of 0.3 and a 15 min reaction time improved COD removal to 67% compared to 45% with ozone alone under the same conditions. Wajahat et al. [116] assessed the degradation of the fluoroquinolone antibiotic ciprofloxacin in wastewater from a pharmaceutical production plant in Lahore, Pakistan, using ozonation, photolysis, and photocatalysis. The emergence

of fluoroquinolones in wastewater raises concerns about potential antibiotic resistance in microbial species. Pharmaceutical production generates wastewater at multiple stages, often releasing toxic, untreated effluent. The raw wastewater had a pH of 6.87, COD of 603 mg/L, BOD of 116 mg/L, BOD₅/COD ratio of 0.19, and ciprofloxacin concentration of 7.91 mg/L. Ozonation across pH 3 to 10 removed ciprofloxacin by 87.2% to 98.7% after 30 min, with optimal degradation at pH 9 (98.7% removal). Photocatalysis with TiO₂ achieved complete ciprofloxacin removal (100%) at the original pH and a TiO₂ dose of 1000 mg/L. UV/TiO₂ combined treatment proved faster and more effective than UV alone in ciprofloxacin removal.

3.7. Miscellaneous Industry

Wastewater from industrial facilities manufacturing products such as pesticides, cosmetics, cigarettes, latex, and cork, as well as from semiconductors and electroplating industries, can benefit significantly from ozone-based technologies. These effluents can be characterized by high BOD and COD and toxicity due to various natural and synthetic organics. This section reviews recent studies on the treatment of these diverse effluents.

The production of pesticides generates wastewater containing a wide array of organic pollutants, leading to high COD levels and poor biodegradability due to their toxicity, which hampers biological treatment effectiveness. Chen and Sun [117] investigated catalytic ozone oxidation as a treatment method for pesticide production wastewater from a facility in Jiangsu Province, China. They utilized self-made Al₂O₃ as a catalyst, varying ozone dosages and reaction times. Results showed a COD removal of 38% and ammonia nitrogen conversion rate of 47% at pH 8, with ozone dosage of 3000 mg/L, H₂O₂ dosage of 3 mg/L, catalyst dosage of 50 g/L, and a 120 min reaction time. Wiliński et al. [118] explored the oxidation of PPCPs using dissolved ozone flotation (DOF) to improve the performance of dissolved air flotation (DAF) in the treatment of cosmetics wastewater from a factory producing lipsticks, serum, creams, and UV filters in Poland. In the DOF process, soluble substances were oxidized by ozone, causing solid particles to float on the surface of the treated solution. This method, relatively new for industrial wastewater treatment, has previously been applied to livestock and pigment processing wastewaters [40,119]. Aluminum-based coagulants were employed to remove the micropollutants. The raw wastewater contained COD, dissolved COD, TSS, anionic surfactants, and a BOD/COD ratio of 2680 mg/L, 1760 mg/L, 268 mg/L, 260 mg/L, and 0.18, respectively. During the 5 min flotation process, 11 mg/L of ozone was applied. Twelve aluminum-based coagulants were tested for their effectiveness, with Brenntag 6010 and Brenntag 3010 proving to be the most efficient, achieving COD and TSS removal efficiencies of 79% and 95% for DAF pretreatment and 79% and 94% for DOF pretreatment, respectively. Although the DOF process did not exhibit improvements in terms of COD and TSS removal, it helped remove endocrine disruptors via oxidation.

The wastewater from tobacco and cigarette production industries is characterized by high BOD and toxicity attributed to alkaloids, nicotine, and tannins. Traditional onsite anaerobic and aerobic biological processes are commonly used for treatment, but they can increase chromaticity in the effluent due to lignin, nicotine, and carbohydrates. Li et al. [120] investigated the efficacy of ozonation and AOPs such as Fenton and O₃/H₂O₂ on the effluent from a biological treatment plant at a cigarette factory. Their study demonstrated that ozone oxidation effectively reduced COD and chromaticity to meet environmental discharge standards. Compared to the Fenton process and O₃/H₂O₂, ozonation proved to be the most cost-effective treatment method. Hadiyanto et al. [121] studied the treatment of wastewater from a latex production facility in Semarang, Indonesia, characterized by high levels of COD, BOD, nitrogenous compounds, and phosphorus. They explored

various treatments, including UV irradiation, ozonation, and UV/O₃ AOP. The UV/O₃ AOP demonstrated superior performance, achieving 81% COD removal, 70% total nitrogen removal, and 26% phosphorus removal using an ozone dosage of 0.86 mg/L over a 16 min period. The cork production process involves boiling raw cork to disinfect and moisten it, generating substantial wastewater containing tannins, phenolic acids, and other organics, resulting in high COD, color, and toxicity. Santos et al. [122] investigated an integrated treatment approach for cork production wastewater involving UF, ozonation, and biological treatment. Sequentially, pollutants from cork boiling wastewater passed through four UF membranes of varying sizes, yielding four retentates and one permeate. These fractions underwent individual ozonation to assess each membrane's impact on biodegradability and toxicity. The study revealed a correlation between membrane molecular size and organic load, influencing biodegradability, with ozonation effectiveness diminishing as molecular size decreases.

Kim et al. [123] investigated the O₃/H₂O₂ AOP to degrade tetramethylammonium hydroxide (TMAH), a common and problematic chemical in semiconductor wastewater due to its toxicity, which disrupts biological treatment processes and can harm essential microorganisms in activated sludge. H₂O₂, widely used in semiconductor industries for wafer cleaning, was recycled to facilitate this AOP. The study examined TMAH degradation kinetics through ozonation alone, nano-ozonation using a nano-sized bubble generator, O₃/H₂O₂, and nano-ozone/H₂O₂ reactions in a benchtop setup. Nano-ozone bubbles and H₂O₂ were found to significantly enhance TMAH degradation, achieving the highest removal rate of 95%, along with 65% removal of TOC. Cui et al. [124] investigated the treatment of wastewater from an electroplating industrial park in Guangdong province, China, which contained cyanide. Cyanide is commonly used in electroplating processes, resulting in highly toxic wastewater that requires proper treatment to prevent harm to both humans and the environment. Traditional methods like alkaline chlorination oxidation produce toxic intermediates and pose environmental risks. Biological treatment alone struggles with efficient cyanide removal, necessitating alternative approaches. The study compared ozone as a pretreatment before biological processes and as an intermediate between two biological treatment stages. The combination of BAF followed by ozonation and another BAF (BAF1-O₃-BAF2) proved most effective. An ozone dose of 100 mg/L, with hydraulic retention times of 9 h for the first BAF and 6 h for the second, achieved significant removal efficiencies: 99.9% for CN⁻, 84.6% for COD, 98.4% for Cu²⁺, and 95.9% for Ni²⁺.

4. Discussion

Ozone-based technologies have demonstrated effectiveness across a range of industrial wastewater treatment applications. The flexibility of ozone, as a disinfectant, color and odor remover, and oxidant for both biodegradable and recalcitrant compounds, makes it especially attractive in industrial settings with variable wastewater flows and characteristics. Across sectors, innovative approaches have emerged to improve the performance and sustainability of ozone-based wastewater treatment. Hybrid systems combining ozonation with biological treatment, such as biofiltration or MBRs, have demonstrated synergistic effects, improving both removal efficiencies and energy use. Novel processes, such as DOF and catalytic ozonation, and the integration of ozone with nanomaterials or advanced membranes, are also being developed to expand treatment capacity for recalcitrant pollutants. These approaches illustrate how the continued evolution of ozone technologies can support more adaptive and efficient wastewater management strategies in industrial settings. However, cost, energy demand, and process optimization remain key barriers to widespread adoption, particularly in sectors where ozone competes with other chemical

oxidants or physical–chemical treatment technologies. Figure 2 illustrates the various applications of ozone in industrial wastewater treatment, including pretreatment, primary treatment, secondary treatment, tertiary treatment, and disinfection, as well as possible introduction of AOPs and other innovative processes.

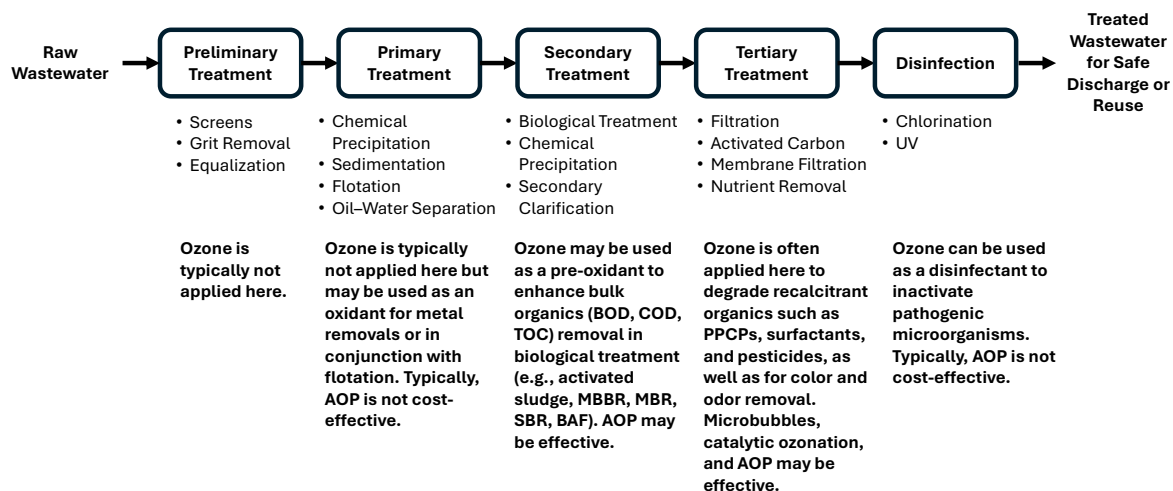


Figure 2. Applications of ozone in industrial wastewater treatment.

The following subsections examine sector-based research trends and explore key economic considerations that influence the practical implementation of ozone technologies in industrial wastewater treatment.

4.1. Sector-Based Research Trends

In the food and beverage sector, ozonation has been shown to efficiently remove color, odor, trace organics, and pathogens, especially when used as a tertiary treatment following biological processes. The intermittent nature of wastewater generation in these industries, particularly from CIP systems, aligns well with the operational characteristics of ozone treatment. Notably, ozone alone often outperforms O_3/H_2O_2 AOPs in these settings, likely due to the scavenging of hydroxyl radicals by background constituents such as chloride, bicarbonate, and natural organic matter. In agriculture and aquaculture, although fewer peer-reviewed studies exist, ozone has been evaluated as a polishing step after biological treatment systems like UASB reactors and MBRs. It is particularly effective in color removal and, in recirculating aquaculture systems, ozonation contributes to ammonia removal through the formation of hypobromous acid. As in the food sector, enhancements from AOPs using hydrogen peroxide or UV were generally modest.

For the textile industry, ozonation has been explored primarily as a pretreatment step to degrade recalcitrant dyes and reduce COD, improving the efficiency of downstream biological treatment. While full-scale implementation remains limited, this approach holds promise for water reuse and near-zero discharge goals. Additionally, although ozone alone is not effective for removing PFAS, recent studies suggest that combining ozone with UV irradiation or alkaline conditions may provide viable treatment pathways. Pulp and paper wastewater, often rich in lignin, dyes, and chlorinated organics, can benefit from ozonation and related AOPs to enhance biodegradability and reduce toxicity. The combination of ozone with UV or hydrogen peroxide has shown potential to improve overall treatment performance and help facilities meet discharge regulations.

In the oil and gas sector, ozonation has achieved high removal efficiencies for hydrocarbons, metals, and other contaminants. Researchers have explored process intensification using hydrogen peroxide, catalysts like MnO_x/GAC , and microbubble injection to further improve ozone transfer and reactivity. These advancements suggest growing potential for

ozone applications in treating complex refinery wastewater and produced water. Pharmaceutical and healthcare wastewaters, which contain persistent micropollutants, have been another important focus. Ozone-based processes, often paired with biological treatment or UV-enhanced AOPs, have been used to degrade compounds like carbamazepine, hydrocortisone, and fluoroquinolones. Studies from Israel, Denmark, China, and Pakistan highlight ozone's versatility in these applications, with performance often improved through the use of adjuncts like TiO₂ under UV light. Table 1 below presents an overview of the reviewed studies on ozone-based industrial wastewater treatment.

Table 1. Summary of recent reviewed studies on ozone-based industrial wastewater treatment.

Industry Sector	Wastewater Characteristics	Wastewater Sub-Type	Treatment Processes	Typical Ozone Dose	Pollutants Targeted	References
Food and beverage	High organic content, various pH, mostly biodegradable, batch production	Tofu production	O ₃ + GAC	16–39 mg/L	COD	[52]
		Cheese	O ₃ /H ₂ O ₂ , O ₃ /Fe ₂ O ₃ -MnO _x	Up to 4.2 g/L	COD, BOD ₅ , TOC, color	[53]
		Confectionery factory	O ₃	Vary	Dye, COD, TOC	[54]
		Soft drink	O ₃ , O ₃ /H ₂ O ₂	433 mg/L	COD, turbidity	[55]
		Brewery	O ₃ + UASB	Up to 300 mg/L	Color, COD	[56]
		Fresh-cut fruits	O ₃ , O ₃ /H ₂ O ₂	7.5 mg/L for disinfection, 180 mg/L for pesticides	<i>E. coli</i> , <i>Salmonella</i> , pesticides	[57]
Agriculture and aquaculture	Organics, pesticides, antibiotics, cleaning agents, suspended solids, mostly biodegradable	Clean-in-place	O ₃	750 mg/L	Odorous organics	[65]
		Swine	UF/NF + O ₃ or O ₃ /H ₂ O ₂	100–150 mg/L	Color	[71]
		Coffee (synthetic)	O ₃ , O ₃ /UV	Vary	Color, caffeine	[72]
		Recirculating aquaculture system	Sand filtration/ceramic membrane + O ₃ , TiO ₂ catalysts	52 mg/L	COD removal, ammonia-N, nitrite, turbidity	[77]
Textile	Dyes, colored, highly recalcitrant, toxic	Textile	O ₃ + anoxic-anaerobic activated sludge	1 g/L	Color, COD, BOD ₅	[86]
		Synthetic dye solutions	O ₃ + BAF	125 mg/L	COD	[87]
		Tannery	O ₃ + bioreactor	80 mg/L	Color, COD, biodegradability	[88]
				200 mg/L	COD, BOD	[89]
Pulp and paper	Organics, hemicellulose, lignin, colored, toxic, and recalcitrant	Pulp and paper effluent	O ₃ , O ₃ /UV	Vary	Color, COD	[95]
			O ₃	Up to 600 mg/L	COD	[96]
		Sludge	O ₃ + activated sludge	45 g/g	AOX, EOX, chlorophenols	[98]
Oil and gas	Hydrocarbons, metals, hydrogen sulfide, ammonia, phenols, high salinity, toxic, and hazardous	Oil refinery effluent	O ₃ /UV	2335 mg/L	COD, H ₂ S	[100]
			O ₃ /MnO _x /GAC	Vary	COD, TOC	[101]
			O ₃ , O ₃ /H ₂ O ₂	Vary	COD, BOD ₅ , H ₂ S, toxicity, biodegradability, VOCs, etc.	[102]
			O ₃ /UV/TiO ₂	Vary	COD, phenol, H ₂ S, oil and grease, ammonia, ecotoxicity	[103]
		Petroleum waste sludge	Microbubble O ₃	Vary	TPH, TSS	[104,125]
	Oil sands process-affected water	O ₃	Vary	Ecotoxicity	[105]	

Table 1. Cont.

Industry Sector	Wastewater Characteristics	Wastewater Sub-Type	Treatment Processes	Typical Ozone Dose	Pollutants Targeted	References	
Medical and Pharmaceutical	Contains various emerging contaminants such as pharmaceuticals, ARB and ARGs, viruses, disinfectants, and high BOD and COD	Hospital effluent	O ₃ , O ₃ /H ₂ O ₂	55 mg/L	Cytostatic compounds (irinotecan, ifosfamide, cyclophosphamide, capecitabine) COD, antibiotics (norfloxacin, ciprofloxacin, ofloxacin, sulfamethoxazole, erythromycin, tetracycline, and trimethoprim)	[107]	
			Sponge MBR + O ₃	3.3 mg/L	pharmaceuticals	[108]	
				O ₃ , O ₃ /H ₂ O ₂	10 mg/L	pharmaceuticals	[109]
				O ₃ , O ₃ /UV/H ₂ O ₂ , O ₃ /UV	4.2 mg/L	COD	[111,112]
		Hospital laundry wastewater	O ₃ , O ₃ /UV, O ₃ /TiO ₂ , O ₃ /TiO ₂ /UV	Vary	COD, BOD ₅ , <i>E. coli</i> , coliform	[110]	
		Pharmaceutical manufacturing	O ₃ + aerobic biological treatment	Vary	BOD, COD, TOC	[113]	
			Biological treatment + O ₃ , O ₃ /H ₂ O ₂ , O ₃ /H ₂ O ₂ , O ₃ , photolysis, UV/TiO ₂	Vary	BOD, COD, TOC, carbamazepine, venlafaxine	[114]	
Miscellaneous	Vary (often recalcitrant and toxic)	Pesticide production	O ₃ , O ₃ /Al ₂ O ₃	3 g/L	COD, ammonia-N	[117]	
		Cosmetics	Dissolved O ₃ flotation	11 mg/L	BOD, COD, TSS, PPCPs	[118]	
		Cigarette	O ₃ , O ₃ /H ₂ O ₂ , Fenton	Vary	COD, color	[120]	
		Latex	O ₃ , O ₃ /UV	Vary	BOD, COD, total N, total P	[121]	
		Cork	UF-O ₃ -biological treatment	Vary	Biodegradability, toxicity	[122]	
		Semiconductor	O ₃ /H ₂ O ₂ , nano O ₃	Vary	TOC, TMAH	[123]	
		Electroplating	BAF-O ₃ -BAF	Vary	Cyanide, COD, metals	[124]	

4.2. Economic Considerations and Future Directions

While ozone treatment technologies offer notable technical advantages, such as high oxidation potential, short reaction times, and the ability to address complex or refractory compounds frequently found in industrial wastewater, their economic feasibility remains a key factor in technology selection and implementation. Capital investments for ozone systems can be significant, particularly when high-capacity ozone generators, oxygen feed systems (e.g., air dryers and purifiers for air-fed ozone generators and liquid oxygen tanks or oxygen concentrators for oxygen-fed generators), and dedicated contact reactors are required. Operational costs are primarily influenced by electricity consumption, system efficiency, maintenance needs, and the quality of feed gas. Readers are encouraged to refer to selected studies for more detailed discussions on ozone system costs and case studies [23,126–128]; however, it should be noted that many of these references are based on municipal applications, which may differ in scope and data availability from industrial contexts.

In some cases, ozone-based treatment can lead to long-term cost savings, especially when improved regulatory compliance, reduced sludge production, or enhanced biodegrad-

ability lowers downstream treatment costs. However, comprehensive cost–benefit analyses remain relatively scarce, particularly for full-scale industrial applications. This gap is partially due to the proprietary or confidential nature of industrial processes and wastewater characteristics, which often limits the sharing of detailed cost and performance data. Unlike municipal wastewater treatment, where public transparency is the norm, industrial applications are typically more constrained in disclosing operational and economic details. As a result, comparing different case studies or drawing generalizable economic conclusions remains difficult.

To support more informed decision-making, future research should focus on standardized and transparent reporting of capital and operating costs, along with life-cycle assessments and return-on-investment analyses under realistic industrial conditions. Refining ozone system design, such as optimizing ozone doses, reactor configurations, and integration with complementary processes, remains a critical area of development, particularly given the diversity of industrial wastewater matrices. Comparative studies involving other AOPs, including Fenton, photo-Fenton, and UV-based systems, are also needed to better understand the context in which ozone provides the most sustainable and cost-effective treatment option. These efforts will help define ozone’s role within the broader industrial water treatment toolbox and guide technology adoption in both regulatory and operational frameworks.

5. Concluding Remarks

Ozonation and ozone-based AOPs have gained global traction in industrial wastewater treatment over the past few decades. This review highlights their proven efficacy across a wide range of sectors, including food and beverage, agriculture, aquaculture, textiles, pulp and paper, oil and gas, pharmaceuticals, pesticide manufacturing, cosmetics, semiconductors, electroplating, and more. As both a strong oxidant and disinfectant, ozone plays a critical role in removing contaminants and inactivating pathogens. Many industrial effluents contain complex and recalcitrant compounds, both synthetic (e.g., pharmaceuticals, pesticides) and natural (e.g., tannins, lignin). Ozonation as a pretreatment step can significantly enhance the biodegradability of these wastewaters, facilitating more effective downstream biological processes such as activated sludge. When combined with hydrogen peroxide, UV irradiation, or catalysts like TiO_2 , ozone-based AOPs become even more effective at breaking down persistent organics. However, complete removal of bulk organics (e.g., COD, TOC) is often not achievable through ozonation alone. For cost-effective and robust treatment, integrating ozone with biological processes remains essential. Looking ahead, future research should focus on addressing emerging contaminants such as microplastics and PFAS, scaling up ozone-based treatment for less-studied sectors like conventional oil and gas and the growing hydrogen and carbon capture industries, and exploring reuse pathways to support circular water systems.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Activated carbon/charcoal
Al ₂ O ₃	Aluminum oxide
AOP	Advanced oxidation process
AOX	Absorbable organic halides
ARB	Antibiotic resistant bacteria
ARG	Antibiotic resistance gene
As(III)	Arsenic(III), Arsenite
As(V)	Arsenic(V), Arsenate
BAF	Biological aerated filter
BOD	Biochemical oxygen demand
BOD ₅	5-Day BOD
BWB	Biological wriggle bed
CIP	Clean-in-place
ClO ₄ [−]	Perchlorate
CN [−]	Cyanide
COD	Chemical oxygen demand
DAF	Dissolved air flotation
DOC	Dissolved organic carbon
DOF	Dissolved ozone flotation
EC ₅₀	Half maximal effective concentration
EOX	Extractable organic halogens
EPA	Environmental Protection Agency
Fe(II)	Iron(II), Ferric iron
Fe(III)	Iron(III), Ferrous iron
FTU	Formazin nephelometric unit
GAC	Granular activated carbon
HCO [−]	Bicarbonate
HO•	Hydroxyl radical
HS [−]	Bisulfide
H ₂ O ₂	Hydrogen peroxide
H ₂ S	Hydrogen sulfide
LC ₅₀	Lethal concentration 50
MBR	Membrane bioreactor
MBs	Microbubbles
MnO _x	Manganese oxides
Mn(II)	Manganese(II)
Mn(IV)	Manganese(IV)
NAs	Naphthenic acids
NH ₃	Ammonia
NH ₄ ⁺	Ammonium
NF	Nanofiltration
NTU	Nephelometric turbidity unit
N ₂	Nitrogen

OSPW	Oil sands process-affected water
O ₂	Oxygen
O ₃	Ozone
PAC	Powdered activated carbon
PFAS	Per- and polyfluoroalkyl substances
PFOS	Perfluorooctanesulfonic acid
PPCPs	Pharmaceuticals and personal care products
PtCo	Platinum cobalt
RAS	Recirculating aquaculture system
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SCOD	Soluble chemical oxygen demand
SO ₄ ²⁻	Sulfate
SeO ₄ ²⁻	Selenate
TDS	Total dissolved solids
TiO ₂	Titanium dioxide
TMAH	Tetramethylammonium hydroxide
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
TS	Total solids
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
UF	Ultrafiltration
UV	Ultraviolet
VNCs	Volatile nitrogen compounds
VOCs	Volatile organic compounds
VSCs	Volatile sulfur compounds
VS	Volatile solids

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