RESEARCH PAPER

Application of Transition Metal-Based Nanocatalysts in Advanced Oxidation Processes for Removal of Reactive Textile Dyes

Himanshu Rajput[1], Professor Anil Kumar[2]
[1]Research Scholar. Bhagwant Global University, Kotdwar. Email: rajputhimanshu096@gmail.com
[2]Research Division. Department of Chemistry, Sahu Jain Collage Najibabad. Email: anil21.1747@yahoo.com

Received: 30th May, 2026; Revised: 11th June, 2026; Accepted: 15th June, 2026; Available Online: 17th June, 2026

ABSTRACT

Water shortage has become an international issue due to the rise of both industry and population. There is a lack of treatment for most wastewaters containing dyes, despite the fact that the textile sector is the world's second biggest. When combined with fresh water, carcinogenic chemical molecules known as dyes pose a threat to aquatic life and human health. In order to maintain a clean and green atmosphere, it is a tough effort to remove harmful colours from textile effluent. As a result, the researcher is trying to track down the most up-to-date information on AOPs. While there are a number of treatments available, the most of them are prohibitively costly and provide only partial relief from the condition. One use of this biological process is the purification of water. Nevertheless, it generates a substantial quantity of sludge, which in turn increases the expenses connected with managing and disposing of it. The increased removal efficiency of AOPs makes them a popular choice for sustainable wastewater cleanup. This paper thoroughly examines the mechanism and describes the latest developments in the use of several AOPs to the treatment of textile wastewater. The review draws attention to both the existing literature and new developments in the treatment of textile wastewater utilising a variety of catalysts. Additionally, it delves into the upcoming obstacles and possible remedies for putting AOPs into practice for treating textile wastewater.

Keywords: Advanced oxidation process, Hybrid treatment, Water pollution

How to cite this article: Rajput H, Kumar A. Application of Transition Metal-Based Nanocatalysts in Advanced Oxidation Processes for Removal of Reactive Textile Dyes. Int J Drug Deliv Technol. 2026;16(60s):1064-1073. DOI: 10.25258/ijddt.16.60s.117

INTRODUCTION

Industrialisation and population growth cause pollution and water constraint. Pesticides, dyes, heavy metals, and other industrial contaminants may be removed using established methods. Standard biological treatment fails to remove hazardous pollutants such drugs, hormones, pharmaceuticals, disinfectants, antibiotics, byproducts, artificial sweeteners, etc. The water would become harmful to aquatic life and people, making remediation harder[1]. Enhanced removal requires energy-efficient treatment methods. Ponds, attached growth, activated sludge, membrane filtration, coagulation-flocculation, sequencing batch reactors, adsorption, and other conventional methods have been used to remove colour, salts, COD, and other inorganic contaminants. Some were used largely little, others huge. Additionally, modified conventional wastewater treatment methods were shown to be effective. Removing these pollutants from industrial or real wastewater is difficult. As demonstrated in Table 1, several industries' effluents have been removed using traditional and innovative methods[2].

Table 1. Industrial wastewater treatment using conventional technology.

Waste water Type	Treatment Method	Targeted Contaminants Removed	Catalyst / Technique Used	Removal Efficiency	Working Conditions
Industrial Wastewater	Adsorption	Heavy metals	PAMAM/ TiO_2 hydroxide	Over 95.9 % removal	60 minutes
Municipal Wastewater	MBR coupled with ozonation, AFF, FAB, CW, EBR, and SBR	Effluents, organic pollutants	Membrane Bioreactor (MBR) with ozonation	More than 90% treatment efficiency	Heterotrophic bacteria activity involved
Paper and Pulp Industry	MBR coupled ozonation	Colour and COD	Ozonation	85% removal after	3 hours treatment time

Waste water				3 hours	
Textile Waste water	Ozonation / Electroflocculation	Colour and COD	Clay-supported TiO_2/ZnO nanocatalyst	More than 95% removal	60 minutes
Tannery Waste water	Electrocoagulation and Photoreaction	Chromium (Cr) and COD	UVC-assisted electrocoagulation	Cr = 98.27 %, UVC Cr = 99.52 %, COD = 98.52 %	Voltage: 2.5 V; wavelength: 185/254 nm; current: 100–600 µA; reaction time: 10–30 min

Standard bacteria and antibiotic genes were used to remove drugs from local wastewater in a research. Local treatment methods may eliminate infections and antibiotic genes, according to this study. Advanced aerobic treatment (ATS), septic treatment systems (STS) alone and with constructed wetlands (WET), and solid municipal waste treatment facilities were examined[3]. Procedure ATS and (STS+WET) effluent quality were compared to MTP. The current study found that MTP and ATS methods eliminated CECs better than STS. Adding a WET procedure fixed this. The method does not eliminate unwanted compounds.

Hospital wastewater was treated with seven conventional methods before discharge into sewage treatment plant [4]: constructed wetland (CW), submerged aerated fixed film (SAFF) reactor, extended aeration (EA), membrane bioreactor (MBR), eco-bio reactor (EBR), fluidised aerobic bed reactor (FAB), and pharmaceuticals (furosemide, carbamazepine, erythromycin, simvastatin, diazepam, and ibupro

This research addressed standard treatment constraints and suggested coupling for better removal. Complex pollutants may be difficult to remove using conventional methods. Thus, this strategy eliminates drugs best. Safely disposing of hospital effluent is difficult. Ozone and peroxone AOPs addressed this issue. As indicated in Table 1, only CW and MBR eliminated pharmaceuticals and particular pollutants from secondary and tertiary treatment stages of the seven standard treatment methods.

Treatment of paper and pulp industry wastewater has been accomplished using simple and UV ozonation. The authors found that UV-ozonation cleared better than ozonation alone. AOPs can remove over 95% colour and COD from textile wastewater in 60 min, unlike other industries. Table 1[5] shows that AOPs remove more quickly than traditional approaches.

Toxic pollutants in waste water are highest in textile industry. Textile industries use the most water because to complex organic and inorganic contaminants such heavy metals, dyes, inorganic salts, designers, detergents, bleaching, stabilising agents, etc. AOPs in textile wastewater treatment are the topic of this study.

More than 38% of Pakistan's employment and 65% of exports come from the textile industry. The textile industry generates 17–20% of industrial pollution during dyeing and finishing, according to the World Bank. Table 2: Major Pakistani industrial wastewater outputs Major textile industry characteristics compared to NEQS[6].

Pretreatment, printing, finishing, and dying are typical textile industry procedures in printing and dyeing. Since these activities continually produce wastewater with complex organic pollutants such inorganic salts, colours, chemicals, viruses, bacteria, and microorganisms, pollutant water is inorganic and organic. Treatment of such water is necessary[7].

Table 2 Typical textile effluent characteristics

Parameters	**Diamond Fabrics Ltd.**	**Sadiqqusons Dyeing and Printing Industries (Pvt.) Ltd.**	**Sapphire Finishing Mills Ltd.**	**US Apparel & Textile (Pvt.) Ltd.**	**NEQS**
Temperature (°C)	32–40	32–40	45–59	41–51	25–30
pH	12–14	5.5–7.5	11–13	11–13	6–9
Wastewater Flow (m^3/hr)	71–96	61–75	131–150	31–65	1000–18,000
COD (mg/L)	1000–18,000	330–600	1400–2000	1200–2100	150
TSS (mg/L)	200–600	150–400	300–800	500–790	200
BOD_5 (mg/L)	350–550	90–200	590–800	600–900	60–80
Colour	1 ppm to <15 TCU	1 ppm to <15 TCU	1 ppm to <15 TCU	1 ppm to <15 TCU	<15 TCU
Turbidity (NTU)	90	80	100	0.79	5
BOD_5/COD Ratio	0.281	0.344	0.291	0.45	0.40

For years, researchers have sought cost-effective and energy-efficient industrial wastewater treatment methods. The finest wastewater cleanup choices include physical, chemical, and biological approaches. Specific restrictions are in Table S1[8]. Most of the methods above are expensive, time-consuming, and unsuitable for bulk-scale treatment due to inherent failures like adsorbent regeneration, membrane replacement's high operational cost in membrane filtration technologies, and precipitation methods' sludge handling issues. Additionally, aerobic/anaerobic biological techniques have operational constraints, expense, and inefficient removal of pollutants in Table S1 at high concentrations[9]. Chemical degradation methods like oxidation involve powerful oxidants as ozone, oxygen, air, NaOCl, H2O2. Biological approaches for sludge processing and disposal are expensive, time-consuming, and inefficient. Thus, a more sophisticated treatment is needed to remove pollutants faster. Table 3 shows most traditional procedures are costly. Coagulation/Flocculation systems remove 43% of textile effluent, however AOPs boost removal effectiveness from 43% to 98% under actual conditions. Combining coagulation/flocculation with catalytic ozonation reduces operating costs from 1.51 to 1.41 \$/m3[10].

The biological processes estimated in Table 3 take too long to remove enough. However, bio Table adsorbents of bacteria and algae are too sensitive to heat and need a culture and environment to grow and manage, making the process more delicate and costly. Avoid this strategy for large-scale application.

As shown in Fig. 1(a), photocatalysis, photochemical Fenton, photo Fenton, electrochemical, ozonation, ultrasound, and other AOP research have been published. Few research coupled and compared the effects of various AOPs on actual textile or industrial wastewater treatment and the gaps, according to the literature. Fig. 1(b) lists AOP articles from the previous two decades. AOPs grew from 2020 to 2024[11]. The major emphasis is on removing heavy metals and synthetic colours from wastewater, and few articles or papers have been published on treating textile wastewater using various AOPs and analysing their pros and cons. To the author's knowledge, few research have compared industrial and lab-scale AOP approaches. This study discusses notable AOP uses in textile industry. Textile companies and organisations seeking sophisticated treatment procedures lack information. This analysis examines the effects of various AOPs on industrial wastewater, compares approaches, and finds gaps and optimal alternatives for cost-effective and energy-efficient wastewater remediation[12].

Table 3 Comparison of AOPs to different wastewater treatment methods..

Wastewater Type	Treatment Method	Catalyst / Microorganism	Target Contaminant	Removal Efficiency	Operating Conditions	Cost
Textile Wastewater	Adsorption	Bentonite Clay / TiO_2 / ZnO	Textile dyes and COD	95%	Time = 120 min	2.986 USD kg^{-1}
Textile Wastewater	Coagulation/Flocculation	PACL	Colour and COD	43.1%	Time = 60 min	0.974 $\$/m^3$
Textile Wastewater	Coagulation and Flocculation	PACL	Colour and suspended solids	33.1%	Time = 60 min	1.37 $\$/m^3$
Textile Wastewater	Catalytic Ozonation	PACL	Colour and COD	94%	Time = 60 min	1.51 $\$/m^3$
Textile Wastewater	Coagulation/Flocculation + Catalytic Ozonation	PACL	Textile dyes and COD	98%	Time = 30 min	1.41 $\$/m^3$
Textile Wastewater	Ozonation/Electroflocculation	Clay/TiO_2/ZnO	COD and Colour	COD = 97.86%, Colour = 97.90%	Time = 60 min	0.34 $\$/m^3$
Textile Wastewater	Biological Treatment	Bjerkandera adusta	Malachite Green Dye	90%	Time = 96 h	0.50 $\$/m^3$
Textile Wastewater	Biological Treatment	Chlorella vulgaris	Orange 2RL Dye	88%	Time = 7 days	0.45 $\$/m^3$
Textile Wastewater	Biological Treatment	Halomonas bacteria	Reactive Black 5 Dye	87%	Time = 5 days	0.40 $\$/m^3$
Textile Wastewater	Biological Treatment	Lactobacillus delbrueckii	Reactive Red 152 Dye	85%	Time = 5 days	0.42 $\$/m^3$
Textile Wastewater	Membrane Bioreactor (MBR)	MBR System	Colour removal	30% colour retention	Retention time > 1 h	0.95 $\$/m^3$
Textile Wastewater	Anaerobic–Anoxic–Aerobic + MBR + NF/RO	Combined MBR and NF/RO filtration	Textile effluents	98.3% / 97.2%	Flux = 3.4–4.4 L m^2/hr	1.85 $\$/m^3$
Industrial Wastewater	Persulfate Oxidation	Bisphenol A / Persulfate (PS)	Organic pollutants	78%–86% and 100%	Time > 1 h 30 min	0.4 $\$/m^3$

ADVANCED OXIDATION PROCESS

AOPs were suggested for potable water treatment in the 1980s. Oxidation mechanisms like AOPs produce enough highly reactive hydroxyl radicals (OH•) to purify water. This notion altered reactive sulphate radical oxidative reactions. Common radicals like chlorine and ozone disinfected and decontaminated. The initial use of AOPs is wastewater organic/inorganic pollutant removal. Hydroxyl radicals, a strong oxidising agent, are expected to degrade industrial pollutants into less harmful soluble and even non-toxic byproducts when these AOPs Fig. 1(a) are used for wastewater treatment, providing an ultimate or alternative wastewater remediation solution. The oxidising potential of reactive species appears in Table 4[13].

AOPs are used to treat agrochemical, distillery, oilfield, paper and pulp, textile, hazardous effluent, metal-plating wastes, abattoir wastes, hospital wastes, pathogens and pharmaceuticals, persistent dyes, and heavy metals like arsenic (As) and chromium (cd) from water. AOPs may be categorised by mechanism of free and transitory hydroxyl radical production. Synergistic treatments may dramatically decrease cost, operation time, and removal efficiency. AOPs operate synergistically with free radicals more reactive than O3 •H2O2 (peroxide) decreases treatment plant time, cost, and capacity. Most other methods create secondary pollutants following pollutant breakdown. AOPs can remove most of these from textile waste water without secondary pollution[14].

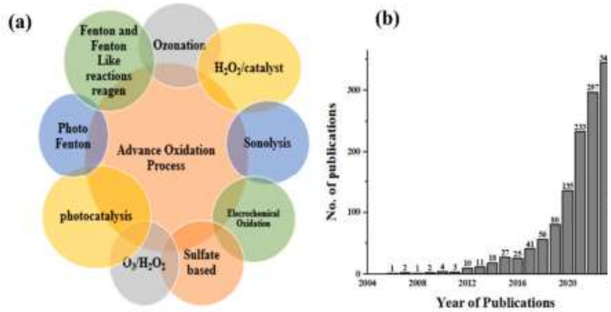

Fig. 1. (a). AOPs are categorised by reactive species OH. c). Papers assessing AOP methods for textile waste water treatment in the previous 20 years.

Table 4 Some Common Oxidisers' Oxidisability

Oxidising Agent	Electrochemical Oxidation Potential (V)
Atomic Oxygen	2.42
Hydroxyl Radical (•OH)	2.80
Ozone (O_3)	2.08
Hydrogen Peroxide (H_2O_2)	1.78
Molecular Oxygen (O_2)	1.23
Hydrogen Dioxide	1.46
Superoxide Radical Anion	0.93

AOPs strength and weakness

The most common tertiary wastewater treatment methods are amine-oxidation processes (AOPs), which employ in-situ produced radicals like hydroxyl (•OH) or sulphate (•SO_4–) to remove organic contaminants from aqueous medium (•OH/H_2O = +2.80 V). •OH-based AOPs have a remarkable oxidation potential just slightly lower than fluorine (+2.87 V). Due to their efficacy in degrading most harmful pollutants, (•SO_4–) radical-based AOPs may have risen. This is because sulphate radicals have a lifespan of 30-40 µs, compared to 20 ns for hydroxyl radicals. AOPs' potential to augment biological processes or replace established therapies has increased public attention [15].

Naturally disinfecting AOPs need no chemicals or catalysts. This prevents dangerous derivatives. AOPs are advanced mineralising and water-recycling pollution-controlling chemicals that may enhance biological processes. Advanced oxidation methods may breakdown chemicals that electrochemical treatment cannot, making them ideal for textile wastewater treatment. Studies show that AOPs increase the biodegradability and reduce the toxicity of mineralization-resistant compounds. AOPs are "green" because in situ hydroxyl radicals mineralise organics. This radical can mineralise most organic wastes and nutrients due to its high standard redox potential. These findings demonstrate that AOPs are intriguing novel therapeutic techniques that might replace established treatments [16].

It is the finest chemical oxidant for chemical oxidation because it reacts fast with most organics and has a radical oxidation potential of 2.80 V vs. hydrogen (H_2) electrode. Depending on the pollutant, full oxidation produces H_2O, CO_2, O_2, and various mineral acids.

Ozone (O_3) based AOPs

Several O_3-based medicines use ozone, a potent oxidiser. Ozoneation of inorganic and organic contaminants uses hydroxyl radical-based processes and molecular ozone (ozonolysis). These responses vary on time, pH, pollutant type, and other conditions. When molecular O_3 dominates at low pH, organic materials are more sensitive to its electrophilic assault. High pH levels (>8) produce hydroxyl anion or radicals (HO^-), which deconstruct O_3 into radicals (HO_2• and O_2•-) and create •OH, degrading contaminants [17]. They are AOPs because they include hydroxyl radicals. Ozone at 0.5 mg/min removed reactive black 5 from wastewater with 35% COD and 40% TOC in 30 min. The pH-dependent mechanism prevented satisfactory clearance. Increase reaction time to remove COD over 50%. Table 4 shows that another investigation found that 2 h removed reactive black 5 from aqueous solution at 94%. The ozonation process alone has been used to degrade real textile effluents, removing more than 90% of colour and COD at optimised conditions of 2 g/h ozone dose, 170 mg/L initial COD concentration, and basic pH = 9. Time and cost would be a concern, but the process is suitable for large-scale commercial use

O_3/catalyst-based AOPs

Catalytic ozonation may be heterogeneous or homogeneous. Most catalytic ozonation uses homogeneous and heterogeneous catalysis. The catalyst, usually a homogenous transition metal cation like Mn^{2+}, Zn^{2+}, Cr^{3+}, Fe^{2+}, or Ni^{2+}, forms the •OH radical from O_3 breakdown. simultaneous liquid dissolution of O_3 and transition metal cations. Fig. 2 shows that indirect O_3 degradation on the metal pollutant's complex structure explained metal cations and catalytic activity. The bulk-dissolved electro-potential transition metal cations attract impurities, generating a transitory complex. Adsorption of O_3 molecules may cause complicated self-decomposition. Direct contact of the cation with the O_3 molecule was thought to start a chain of processes that led to O_3 self-decomposition via metal cations. The reactive red dye was treated with Fe (III) in water. 40% of the colour was eliminated at pH 3 and 100 mg/l, but not enough after 30 min. Heterogeneous catalytic ozonation uses solid catalysts. In this system, the catalyst's sorption capability is crucial, and at least one reagent must be adsorbed on its surface. To start catalysis, O_3 is adsorbed on the catalyst or sorbent surface, and the adsorbate is deposited on the nanocatalyst pores. On the support, the heterogenic catalyst contains natural minerals, metals, metallic oxides, and carbon[18]. Metallic and metal oxide catalytic activity rely largely on sportive characteristics relative to catalyst active centers on Lewis acid oxides. Because of their ion exchange capacities, redials (OH) cover oxide surfaces and are absorbed into centers. Catalytic activity for metals on catalyst support has two pathways. Organic molecules adsorb on the catalyst's active site and are oxidised by ozone or •OH. The second is electron transport via reduction or oxidation of metal sites on the supporting material to decompose O3.

Fe degraded reactive red with 40% COD elimination, while nZVI on a heterogeneous catalytic surface removed more than 87%. Heterogeneous catalyst (nZVI/Alg) removed 100% colour and 98% COD from reactive red 195 in 30 and 90 min, respectively. Heterogeneous catalytic ozonation removed more quickly than homogeneous because to its sorption capacity, porosity, and rapid hydroxyl (OH) formation (Fig. 2) [19].

Copper(II)-doped carbon dots for textile wastewater treatment Heterogeneous ozonation for actual and synthetic wastewater Organics removal exceeding 98% in 60 min at pH 7 and 1.98 g/L ozone. So heterogeneous catalytic ozonation removes more than homogeneous [60]. The graphene/α-MnO2 nanocrystals hybrid aerogel effectively removed Rhodamine, with almost 100% colour removal and over 89% COD elimination in 15 min using 0.035 g/L ozone dosage and 50 mg/L dye concentration. Nano sorbent base on graphene has higher sorption capacity, surface area, and porosity. Table 5.

Table 5 Ozonation and Catalytic Ozonation using AOPs.

Pollutant / Dye	Catalyst / Treatment System	Removal Mechanism	Removal Efficiency	Operating Conditions
Reactive Black 5	Ozonation / Catalytic Ozonation	Reactions involving O_3 and ·OH radicals	COD = 35%, TOC = 40%	Dye concentration = 0.5 g/L; Catalyst dose = 0.5 g/L; Time = 30 min
Reactive Black 5	O_3 and ·OH oxidation	O_3 and hydroxyl radical reaction	Colour = 96.7%, COD = 77.5%	Dye concentration = 40 mg/L; Reaction rate = 1.1 mg/min; Time = 2 h
Reactive Yellow 84 (CI)	Catalytic Ozonation	O_3 and ·OH interaction	COD = 60%	Time = 60 min; Dye concentration = 9.1 mg/L
Reactive Red 2	Ozonation	O_3 and ·OH reactions	Colour removal > 90%	pH = 4/7/10; O_3 flow = 500 mL/min; Dye concentration = 40 mg/L
Textile Effluent	Catalytic Ozonation	Reactions involving O_3 and ·OH radicals	Colour = 97%, COD = 81%	O_3 = 2 g/h; COD = 172 mg/L; pH = 9
Reactive Red 195	nZVI–Alg / Ozonation	O_3 and ·OH interaction	Colour = 100% after 30 min; COD = 98% after 90 min	Dye concentration = 25 mg/L; Catalyst dosage = 50 g/L
Reactive Red 120	Fe(III) / Ozonation	O_3 and ·OH reaction	Dye removal = 40%	Co = 0.556 mg; pH = 3; Time = 30 min
Textile Effluent	Fe(II), nZVI / Ozonation	π–π interaction, O_3 and ·OH reaction	87% removal	Time = 40 min; O_3 flow = 0.2 mg/min; Catalyst dose = 0.7 g/L
Rhodamine B	Graphene/αMnO_2 Nanocrystal Hybrid Aerogel (GMA)	O_3 and ·OH interaction	COD = 89.02%; Colour = 100%	Time = 15 min; Dye concentration = 50 mg/L; O_3 = 0.035 g/L
Real Textile Effluent	Copper(II)-Doped Carbon Dots	O_3–O_2 interaction and ·OH reaction	Colour = 99.8%	Time = 60 min; O_3 concentration = 1.98 g/L; pH = 7
Real Textile Effluent	g-C_3N_4/Al_2O_3 / Ozonation	O_3 oxidation and hydroxyl radical reaction	High colour and COD removal	O_3 flow = 1.5 L/min; pH = 7.1; Catalyst dose = 0.5 g/L

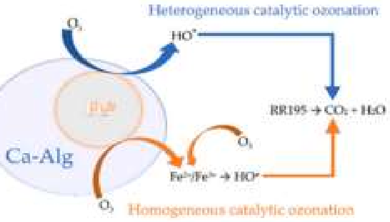

Fig. 2. The suggested process for homogeneous and heterogeneous catalytic ozonation does not need CY-licensed 04 open access..

O3/H2O2 based AOPs

Ozone is very selective for saturated carboxylic acid or inactive aromatic organic pollutants since it requires a lot of energy to create a substantial dosage. Ozone (O3) is unstable and needs a costly mixing equipment to maintain. Peroxone and catalysts speed up the reaction by creating extremely energetic hydroxyl radicals, making the method practical compared to simple ozonation.

Fast production of extremely energetic hydroxyl radicals (•OH) promotes O3 oxidation of organics by attacking bonds like aromatic rings under H2O2. H2O2 dissociation yields hydro peroxide ion, which attacks O3 and forms OH• radicals. A typical peroxon mechanism is given below:

$$H_2O_2 + 2\,O_3 \longrightarrow 3\,O_2 + 2\,OH\bullet$$

Compared to other AOPs, pH is crucial for process efficiency. Alkaline O3 solutions with H2O2 (hydrogen peroxide) generate OH• hydroxyl radicals quickly. At 2.7 g/h ozone, 7.5 mM/L H2O2, 0.3 g/L dye, and pH 8.7, Congo red was eliminated. Over 90% of colour was removed in an hour. Peroxone removed many textile colours, as illustrated in Table 6[20].

The peroxone procedure eliminated reactive Red 198 in one hour at 0.25 g/h O3, 0.03 mol/L H2O2, 200 mg/L dye, and pH 6–10. This approach is advantageous since the peroxone procedure does not need UV radiation or other light sources for murky waters.

Table 6 Using AOPs in peroxone.

Pollutant / Dye	Treatment Approach	Removal Mechanism	Removal Efficiency	Operating Conditions

Six Reactive Dyestuffs	O_3/H_2O_2 Advanced Oxidation Process	O_2 and ·OH radical reactions	Complete colour removal	Ozone dosage = 0.25 g/h; H_2O_2 = 0.03 mol/L
Reactive Red 198	O_3/H_2O_2 Process	O_2 and ·OH radical oxidation	Complete colour removal	Ozone dosage = 0.25 g/h; H_2O_2 = 0.03 mol/L
Reactive Red 198	O_3/H_2O_2 Process	O_2 and ·OH radical oxidation	COD removal = 55%	Ozone dosage = 0.25 g/h; H_2O_2 = 0.03 mol/L; pH = 6–10; Dye concentration = 200 mg/L
Reactive Dye Solution	O_3/H_2O_2 Advanced Oxidation	O_2 and ·OH radical interaction	High colour and COD removal	pH = 8.7; Ozone dosage = 2.7 g/h; H_2O_2 = 7.50 mM/L; Dye concentration = 0.3 g/L
Reactive Dye Solution	O_3/H_2O_2 Process	O_2 and ·OH radical oxidation	Efficient degradation of dyes	Ozone dosage = 2.7 g/h; H_2O_2 = 7.50 mM/L; Dye concentration = 0.3 g/L; pH = 8.7

UV/O3, UV, H2O2, UV/H2O2 based AOPs

Most photochemical (UV/O3) reactions involve chemical molecules being electronically excited by UV or light energy. Common photolysis radiation is 200–400 nm in the UV range. Photosensitive compounds like dyes absorb light and become excited. This may cause bond breakage and deterioration. UV light (hv) combines with strong oxidisers to form free radicals photochemically. Radicals have low UV absorption and good dye removal effectiveness. The literature focuses on photo-assisted catalytic ozonation with and without UV irradiation. Both catalytic ozonation scenarios consumed (OH) hydroxyl radicals quickly. Forming the •OH radical in photocatalytic and catalytic ozonation is not the sole method to comprehend these processes, hence a more basic explanation is needed. Recently, O3 self-decomposition was suggested to create hydroxyl (•OH), which drives catalytic ozonation. UV irradiation ($\lambda < 300$ nm) converts dissolved O3 to O2 (atomic oxygen), which subsequently forms reactive species (HO·) via H2O2. O3 has a molar extinction value of 3300 M−1 cm−1 at 254 nm, the same wavelength as H 2 O 2. Cage recombination produces a little quantity of H2O2, which weakly generates HO radical[21].

Energy-intensive UV-irradiation and O3 production restrict its use in bulk or full-scale operation. H2O2./UV under UV-C:25 W, H2O2 concentration of 50 mM, initial TOC and COD of 336 mg/L and 1476 mg/L at pH= 10 treated raw textile wastewater with 14% TOC and 2% COD [84]. When treating Acetate and polyester fibre dyeing wastewater with ozone, colour and COD removal efficiency increased to above 90%. UV-C:5 W, Fe catalyst: 200 mg, H_2O_2 = 0.4 M. In another investigation, UV, H2O2, and UV/H2O2 dye removal efficiency were examined singly and in combination. For total dye degradation, UV light in quartz tubes with H2O2 as a bleaching agent worked well. For colour removal, yellow Procion dye was 70% removed in 3 h. •H2O2's hydroxyl radicals kill germs and illness better than UV alternatives.•This approach is not suited for big commercial UV removal because H2O2 and UV take too long to remove. However, using ultraviolet radiation alone does not remove efficiently. Using UV with the photocatalyst increases activity and removal efficiency. According to Table 7.

Table 7 Photochemical or UV/O3 AOP application

Pollutant / Wastewater	**Treatment Method**	**Removal Efficiency**	**Operating Conditions**
Untreated Textile Effluent	UV/H_2O_2	COD = 2%, TOC = 14%	UV-C = 25 W; H_2O_2 = 50 mM; TOC = 336 mg/L; COD = 1476 mg/L; pH = 10
Chemical Waste from Dyeing Acetate and Polyester Fibres	UV/O_3	Colour = 93%; COD = 94%	pH = 9; O_3 dose = 2 g/h; UV source = 15 W
C.I. Reactive Red 2	UV/O_3	Colour = 75%	pH = 7; O_3 = 500 mL/min; Dye concentration = 20 mg/L; UV-A = 8 W
Actual Textile Effluent	$TiO_2/O_3/UV$	90% degradation	pH = 8; Time = 60 min
Untreated Textile Effluent	UV Treatment	COD = 66%; Colour = 73.7%	Time = 30 min; Catalyst dose = 10 g/L; pH = 8
Raw Textile Wastewater	Water Treatment Process	COD = 48.1%; Colour = 58%	Catalyst loading = 10 g/L·h; Time = 30 min; pH = 4
Raw Textile Wastewater	O_3/H_2O_2	Colour = 69.7%; COD = 66.5%	pH = 8; Catalyst loading = 10 g/L·h; Time = 30 min
Raw Textile Wastewater	$UV/H_2O_2/O_3$	Colour = 76.7%; COD = 89.2%	pH = 8; Catalyst loading = 10 g/L·h; Time = 30 min
Procion Yellow H-4 Dye	H_2O_2/UV Treatment	Colour removal = 70%; Shade reduction = 30%	Time = 3–6 h

Fenton- based AOPs

Multiple chemical reactions may create this transient species. Usually, H2O2 is used as an oxidiser, although sometimes O3 and air are.

The Fenton's reaction is the interaction of ferrous iron Fe2+ with hydrogen peroxide (H2O2). Fenton's reagent, soluble Fe(II) salt and H2O2, abates organics in this method. This chemical AOP class is crucial. This approach was initially used in 1984 to destroy and oxidise using Fenton and H2O2. Fe (II) salts catalyse H2O2 decomposition via radical and chain mechanisms. The catalytic oxidation and coagulative capabilities of Fenton reagents are commonly utilised to destroy and oxidise reactive pigments. Organic pollutant degradation is inexpensive, easy, and effective via the Fenton process. For substantial COD reduction, this procedure may produce H2O2 without activation energy, making it extremely effective[22].

$$Fe^{2+} + H_2O_2 \longrightarrow OH + HO^{\cdot} + Fe^{3+} \quad K_1 = 70\ M^{-1}\ s^{-1}$$

$$Fe3+ + H2O2 \longrightarrow HO2\cdot + H+ + Fe2+ \quad K2 = 1{\cdot}0 \times 106\ M-1\ s-1$$

$$Fe2+ + HO2\cdot \longrightarrow HO2- + Fe3\ K23 = 1{\cdot}3 \times 106\ M-1\ s-1$$

$$Fe3+ + HO2\cdot \longrightarrow H+ + Fe2+ + O2\ K4 = 1{\cdot}2 \times 106\ M-1\ s-1$$

$$H2O2 + \cdot OH \longrightarrow H2O + HO2\cdot\ K5 = 2{\cdot}7 \times 107\ M-1\ s-1$$

Some H2O2 values increased •OH species formation. Although optimal H2O2 levels might boost response rates or other processes (parasite). The deteriorating efficiency reduced because H2O2 engaged in free radicals produced fewer oxidising HO2• radicals. Two Fenton processes: homogenous and heterogeneous The homogeneous one is investigated for pesticides, herbicides, organic compounds, and effluent water. The technique has several water and wastewater treatment benefits. It uses cheap chemicals and no energy and is simple to use. Acidification at pH 2-4 before treatment, iron sludge generation, neutralisation, and after treatment are drawbacks. In situ environmental treatment is limited by Fe(OH)3 sludge buildup at the conclusion of the procedure. Fenton-like reagents (Fe-CNTs) removed over 90% COD and colour from textile wastewater at pH3 in 30 min with 0.1 ml/lit HO2. Treatment with Fe-CNT removed almost 40% of TOC from actual effluents, showing that they are tougher to decompose than synthetic ones.

Uneven Fenton process: To circumvent the constraints of the homogeneous Fenton technique, heterogeneous catalysts are intensively studied for Fenton-like reactions in diverse pH ranges. Fig. 3 shows how iron salts or species immobilised or dissolved in Nanocatalyst holes generate rapid hydroxyl radicals via H2O2. This approach prevents iron (Fe (III) ions) from leaking into H2O and precipitating Fe (OH)3. Reactive species (OH) free radicals from the redox pair Fe2+/Fe3+ reduce contaminants. Cheap, facile separation and spent catalyst recovery, and sustained catalytic activity throughout repeated operation make this procedure superior to traditional treatment techniques. Several nanomaterials showed promising results due to their sorption capabilities, large surface area, tiny size, and porosity. The procedure is straightforward to deploy in pilot or full-scale facilities and done at ambient temperature and pressure. One drawback of Fentonlike reactions is their restricted pH range. Industrial effluent is usually basic, while the Fenton process requires 2–4 pH. Manpower and chemicals are needed to acidify sample water and neutralise treated water before disposal. Fe 2+ reagents are used in huge numbers to cleanse textile effluent. After adding FeSO4 (ferrous salt), a lot of Feloaded (iron) sludge may have been produced that required treatment and disposal. Fe2+ is underutilised in processed sample. Residual Fe2+ may raise raw water Fe levels over threshold, causing rejection. [23] Thus, residual iron removal from wastewater increases operational expenses.

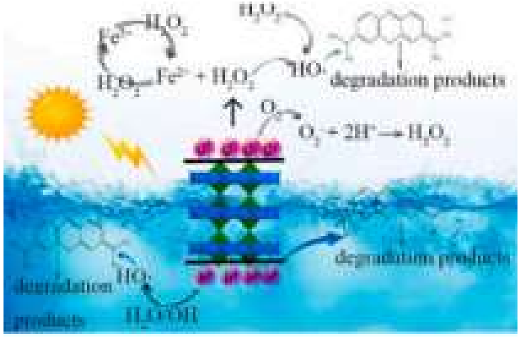

Fig. 3. Schematic photograph Fenton-like reactions licensed CY-04 no permission needed open access.

Photocatalysis

TiO2, a photo-excited semiconductor with a high band gap of 3.2 eV, divided water (H2O) into hydrogen (H2) and oxygen (O2) in a standard electrochemical cell (Fig. 4). Variations of this technology have led to the creation of a novel AOP process, usually based on photocatalyst and semiconductor (ZnO, TiO2) photocatalysis, for energy and environmental applications to degrade RB4 in textile effluent.

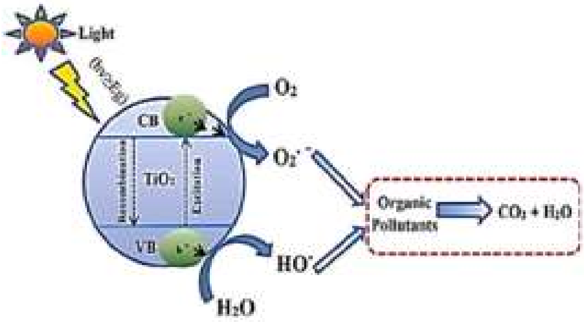

Fig. 4. Photocatalysis Mechanism Creative Commons Attribution License Permission-Free CY-04

When a photocatalyst (ZnO, TiO2) is exposed to ultra-band gap energy (hʋ > Eg) light (hv). This mechanism excites an electron in the valence band into the conduction band, creating a photo-generated (h+) hole in the outermost band. In photocatalytic pollutant elimination under wet circumstances, couples e−/h+ moved to the semiconductor surface and engaged in reduction processes involving reactive hydroxyl radicals (•OH) and superoxide ion radicals (•O2 −). Photo-generated (h+) oxidants directly destroy organic pollutants dependent on oxidation conditions and Nanocatalyst. Without hole scavengers or electrons, photo-induced electrons readily recombined with h+. The scavenger must lower recombination charge for best efficiency. Titania is a typical photocatalyst [24]. The equations below describe UV reactions.

$$\begin{aligned}
&TiO_2 + h\nu \longrightarrow h^+ + e^-.\\
&h^+ + H_2O \longrightarrow OH^- + H^+.\\
&h^+ + OH^- \longrightarrow \cdot OH.\\
&2e^- + 2H^+ + O_2 \longrightarrow H_2O_2.\\
&e^- + H_2O_2 \longrightarrow \cdot OH + OH.\\
&\text{Organics} + \cdot OH + O_2 \longrightarrow H_2O + CO_2 + \text{others.}
\end{aligned}$$

Nano-anatase titania totally destroyed anthraquinone dye when irradiated. Titania-H2O2 synergy may boost photocatalytic activity. Hydrogen peroxide (H2O2) also optimises solar dye degradation. This makes the offerings viable and cheap.

ZnO semiconductors have been shown to remove Methylene Blue from water. Furthermore, the reactions may lower COD and remove colour. This shows partial oxidation of dissolved organic materials. Table 8 shows that photocatalysts, air, water, and UV light may be needed for oxidation.

Photocatalysis degrades industrial effluents that mineralise chemicals. This work used ZnO and Nb2O5 on zeolite (clay) and activated carbon to photodegrade textile colours. First-order kinetics showed that ZnO/NaX removed 98% dye at 10 mg/L.

Table 8 AOPs use Fenton, Photo Fenton, and Electro Fenton

Pollutant / Wastewater	Treatment Process	Catalyst / Reagent	Removal Efficiency	Operating Conditions
Textile Effluent	Fenton Process	$FeSO_4$ / H_2O_2	Colour = 98%	H_2O_2 = 0.1 mL/L; pH = 3; Time = 30 min
Textile Effluent	Fenton Process	$FeSO_4$ / H_2O_2	COD = 85%	$FeSO_4$ = 1.2 g/L; H_2O_2 = 0.6 mL/L; pH = 3
Reactive Yellow 84	Fenton Oxidation	Fe^{2+} / H_2O_2	Colour removal = 85%	pH = 3; H_2O_2 = 250 mg/L; Fe^{2+} = 25 mg/L
Reactive Blue 4	Nano-TiO_2 Photocatalysis	TiO_2 Nanocatalyst	>90% degradation	pH = 6; Time = 40 min; UV Lamp = 125 W; Agitation = 500 rpm; TiO_2 = 1 g/L
Textile Dye	ZnO Photocatalysis	ZnO Nanocatalyst	High dye degradation	Dye concentration = 60 ppm; Time = 60 min; UV Light = 125 W; Agitation = 250 rpm; pH = 6
Organic Dyes in Textile Effluent	Photocatalysis	Semiconductor Catalyst	90% degradation	pH = 8; Time = 60 min
Nylon 5 Textile Dye	ZnO Photocatalysis	ZnO	98% degradation	Time = 60 min
Methylene Blue (MB) and Rhodamine B (RB)	Photo-Fenton Oxidation	Fe/Mn Catalyst	Colour change = 93%	Sunlight irradiation; Time = 40 min
Methylene Blue (MB)	Fenton Catalytic Process	Fe(BDC)	>99% degradation	Time = 60 min
Textile Effluent	Photo-Fenton and Fe-CNT Fenton	Fe-CNT / H_2O_2	TOC > 40%	UV-C Lamp = 4 W; Fe^{2+} = 1 mM; H_2O_2 = 10 mM; Dye = 0.02 mM; pH = 3; Catalyst dose = 200 mg
Reactive Blue 4	Electro-Fenton Process	Fe^{2+} / H_2O_2	TOC > 50%	pH = 3; Current density = 100–200 mA; Dye concentration = 231 mg/L
Acid Orange 7	Electro-Fenton Process	Carbon Felt Electrodes	TOC = 92%	Anode/Cathode = Carbon Felt; Current = 0.3 A; pH = 3; Dye = 0.1 mM; Fe^{3+} = 0.1 mM
Real Textile Wastewater	Electro-Fenton Process	mZVI	TOC = 92.44%; Colour = 82.84%	pH = 3; Voltage = 5.0 V; mZVI dose = 1.0 g/L
Rhodamine B	Electro-Fenton Process	$MnFe_2O_4$-GO	Colour = 97.51%	Electro-Fenton conditions

Electrochemical AOPs

Electric current-driven electrochemical AOPs create reactive radical species (HO•) and oxidise and breakdown pollutants to less hazardous chemicals. EAOPs use indirect and direct oxidation to transport electrons. When contaminants adsorb on the anode, direct oxidation occurs. In liquid electrolyte, oxidants lose electrons to indirectly oxidise pollutants into smaller products. In situ, aqueous anions react with the aluminium anode to produce reactive O2 species. Due to its direct and green electrochemical generation of HO•, anode oxidation was intensively explored. High-voltage anodes with high reactive oxygen evolution immediately form free radicals via anodic oxidation of H2O at the surface. Heterogeneous reactive molecular oxygen species oxidise organics in the anode (M(HO•)) to create water, carbon dioxide, and inorganic ions [25]. Greenness and the (e) electron prime reagent make this approach advantageous. The procedure is straightforward to manage, automatable, chemical-free, and produces no sludge. EAOPs use more energy and transfer less mass than Fentonlike reactions. The anode surface may also produce hazardous substances and provide a poisoning danger at low potential. Ti/RuO2-IrO2 anode and DSA were utilised to remove Rhodamine B at room temperature with 0.1 mol/L electrolyte, 0.05 mol/L sodium sulphate in NaCl electrolyte, 50 mg/L dye concertation, and 40 mA/cm2 current intensity. Nearly 100% colour removal was accomplished. Table 9 shows that Ti/TiOx-RuOx electrodes with 5 mA/cm current intensity at room temperature removed 98% COD and 100% colour from genuine effluents. It seems that the technique works equally effectively for actual and synthetic effluents. However, genuine systems get little attention.

Table 9. Electrochemical processes with AOP.

Pollutant / Wastewater	Process	Electrode / Catalyst	Removal Efficiency	Experimental Conditions

Real Textile Wastewater	Electrochemical Treatment	Electrochemical Electrode	COD removal from 58,000 mg/L	Current intensity = 5 mA/cm²
Rhodamine B	Electrochemical Oxidation	Ti/RuO_2–IrO_2 DSA Anode	Dye degradation = 98%	Electrolyte = 5 mmol/L NaCl + 0.1 mol/L NaOH; Dye = 50 mg/L; Current = 40 mA/cm²; Temperature = 25–35 °C
Rhodamine B	Electrochemical Oxidation	Hexagonal Electrochemical Anode	100% degradation	Electrolyte = 5 mmol/L NaCl + 0.1 mol/L Na_2SO_4; Dye = 50 mg/L; Temperature = 25 °C; Current = 20–40 mA/cm²
Rhodamine B	Electrochemical Oxidation	SnO_2 Electrochemical Anode	100% degradation	Electrolyte = 5 mmol/L NaCl + 0.1 mol/L Na_2SO_4; Dye = 50 mg/L; Current = 40 mA/cm²; Temperature = 25–35 °C
Natural Textile Wastewater	Electrochemical Oxidation	Ti/TiOx–RuOx Anode	Colour = 100%; COD = 560 mg/L	Current = 5 mA/cm²
Coca-Cola Wastewater	Electrochemical Treatment	Electrochemical Electrode	95% degradation	Standard electrochemical conditions
Textile Wastewater	Electrochemical Redox Ozonation	Aluminium Anode and Cathode	Colour removal >96%	Combined electrochemical–ozonation process
Textile Wastewater	Electrochemical Catalytic Oxidation	Aluminium Electrodes	Approximately 97% degradation	Oxygen catalytic electrochemical process

CONCLUSIONS

This review reveals that AOPs are cheaper and more efficient than standard treatment methods. This research also compares effective AOP uses in pharmaceutical, paper & pulp, and textile sectors. The rise in published papers in the study shows increased interest in using AOPs in wastewater cleanup for environmental protection. By making reactive species generation inexpensive and energy-intensive, heterogeneous catalysts improve it. Practical application of AOPs may reduce costs, particularly for physicochemical or UV-assisted treatments that intensely modify pollutant structures. The procedures were mostly used for synthetic dye wastewater cleanup or effluent removal, not genuine effluents. More research is required to identify chemical intermediates, rate expression developments, and many factors. Energy and economic features of various AOPs and the treatment process's energy and power requirements should be studied further than other treatment techniques. More small or pilot-plant size investigations with genuine textile effluent should identify scale-up parameters.

FUTURE CHALLENGES AND SOLUTIONS

Reusability study

Reusability is a key indicator of catalyst stability and sustainability. This allows the catalyst to be employed in quantity for real-world applications. Reusability studies suggest the procedure is practical and profitable. In practice, a catalyst must be thermally or chemically stable in wastewater. Unfortunately, few nanocatalyst studies in AOPs have examined reusability. Pharmaceutical, municipal, chemical, textile, and industrial wastewater are treated most. Type-specific ingredient compositions impact catalyst reusability. Thus, catalyst reusability must be studied in more severe settings (actual wastewater). In AOPs, free hydroxyl radicals (OH) from various processes may react non-selectively with diverse molecules in wastewater [113]. Thus, catalyst reusability must be tested in actual settings. To improve catalyst reusability, use appropriate recovery procedures [4]. Additionally, catalyst stability or reusability should be tested under varying pH, temperature, agitation speed, and time intervals.

Treatment cost

Development of low-cost, high-performance catalysts is in great demand. Most studies do not provide catalytic-based AOP treatment costs. Several studies estimated energy, operational, and chemical expenses, but not catalyst production costs. Aqueous system analysis employing targeted contaminants as typical of entire effluent was used to estimate costs in several studies. Actual wastewater concentration depends on wastewater type (pharmaceutical, textile, chemical, solid municipal, biochemical, etc.). Due to composition and COD loading differences, cost estimates in aqueous solutions may not accurately reflect actual wastewater. The data above suggest that wastewater cost estimate should be comparable to traditional wastewater treatment prices. To ensure sustainability, researchers will concentrate on cheap catalyst production!

Metal leaching

Extending the catalyst toxicological studies in the environment is crucial. Certain catalysts may include environmentally hazardous components. The environmental impact and leaching of harmful elements in the external environment must be studied. Future challenges include cleaning complicated effluent from textile and pharmaceutical sectors using meta-organic frameworks (MOFs). MOFs are employed for aqueous solutions, although lab-scale wastewater treatment has not been done. AOPs generate OH, which leaches metal ions from MOFs and degrades the catalyst. The literature revealed that zero-valent iron (nZVI), activated carbons-coated with chitosan-based activated carbon (AC/CH-nZVI), and nZVI/AC-nZVI as Fenton-like catalyst removed chemical oxygen requirement and colour from melanoid in synthetic wastewater [114]. Leaching is 77% complete. As leach-out increased, wastewater catalyst performance declined. Iron-on AC-nZVI catalyst coating on chitosan reduces metal leaching. Due to weak interactions that cause metal leaching in wastewater matrixes, metal loading on the catalyst surface promotes reversible physical adsorption. Metal chemisorption on supports is more stable and useful under practical settings.

REFERENCES

[1]. Raashid M, Kazmi M, Ikhlaq A, Iqbal T, Sulaiman M, Shakeel A. Degradation of aqueous confidor® pesticide by simultaneous tio2 photocatalysis and fe-zeolite catalytic ozonation. Water 2021;vol. 13(23).

[2]. Dinari A, Mahmoudi J. Response surface methodology analysis of the photodegradation of methyl orange dye using synthesized TiO2/Bentonite/ZnO composites. Adv Environ Technol 2022;vol. 8(1):31–46.

[3]. Jamil T, et al. Treatment of textile wastewater by a novel clay/TiO2/ZnO-based catalyst, applying a synergic catalytic ozonation–electroflocculation process. Catalysts 2023;vol. 13(9).

[4]. Adane T, Hailegiorgis SM, Alemayehu E. Acid-activated bentonite blended with sugarcane bagasse ash as low-cost adsorbents for removal of reactive red 198 dyes. Water Reuse 2022;vol. 12(2):175–90.

[5]. Jamil T, et al. Bentonite-clay/CNT-based nano adsorbent for textile wastewater treatment: optimization of process parameters. Water 2023;vol. 15(18)

[6]. Urbina-Suarez NA, Machuca-Martínez F, Barajas-Solano AF. Advanced oxidation processes and biotechnological alternatives for the treatment of tannery wastewater. Molecules 2021;vol. 26(11).

[7]. Slama HBen, et al. Diversity of synthetic dyes from textile industries, discharge impacts and treatment methods. Appl Sci 2021;vol. 11(14):1–21.

[8]. Javeed T, et al. Application of advanced oxidation processes for the treatment of color and chemical oxygen demand of pulp and paper wastewater. Water 2023;vol. 15(7).

[9]. Rizvi OS, et al. Application of poly aluminum chloride and alum as catalyst in catalytic ozonation process after coagulation for the treatment of textile wastewater. J Environ Manag 2022;vol. 323:115977.

[10]. Castillo-Suárez LA, Sierra-Sánchez AG, Linares-Hernández I, Martínez-Miranda V, Teutli-Sequeira EA. A Critical Review of Textile Industry Wastewater: Green Technologies for the Removal of Indigo Dyes. Springer Berlin Heidelberg; 2023.

[11]. Akbal F. J Environ Chem Eng Treat Text Ind Wastewater Electro-Fenton Process Using Graph Electrodes batch Contin mode 2021;vol. 9(September 2020).

[12]. Faghihinezhad M, Baghdadi M, Shahin MS, Torabian A. Catalytic ozonation of real textile wastewater by magnetic oxidized g-C3N4 modified with Al2O3 nanoparticles as a novel catalyst. Sep Purif Technol 2022;vol. 283:120208

[13]. Kanafin YN, Satayeva A, Abdirova P, Inglezakis VJ, Arkhangelsky E, Poulopoulos SG. Membrane bioreactor and advanced oxidation processes for combined treatment of synthetic wastewater containing naproxen, bisphenol A, and sulfamethoxazole. J Water Process Eng 2023;vol. 55:104250.

[14]. Cardoso RMF, Cardoso IMF, da Silva LP, da Silva JCGE. Copper(II)-doped carbon dots as catalyst for ozone degradation of textile dyes. Nanomaterials 2022;vol. 12(7).

[15]. Ghime D, Ghosh P. 19 - Fenton and Fenton-like processes for improving the dewaterability of refractory organic compounds. In: Pal K, Banerjee I, Sarkar P, Bit A, Kim D, Anis A, Maji S, editors. in Food, Medical, and Environmental Applications of Polysaccharides Elsevier; 2021. p. 555–80.

[16]. Zaki SI, Hodhod OA, Eid MF. Evaluating the effect of using nano bentonite on strength and durability of concrete. Nano Hybrids Compos 2022;vol. 36(January):125–41.

[17]. Masood Z, Ikhlaq A, Farooq U, Qi F, Javed F, Aziz HA. Removal of anti-biotics from veterinary pharmaceutical wastewater using combined electroflocculation and FeZn loaded zeolite 5A based catalytic ozonation process. J Water Process Eng 2022;vol. 49(May):103039.

[18]. Kurian M. Advanced oxidation processes and nanomaterials -a review. Clean Eng Technol 2021;vol. 2(March):100090.

[19]. Pereira CAA, Nava MR, Walter JB, Scherer CE, Dominique Kupfer Dalfovo A, Barreto-Rodrigues M. Application of zero valent iron (ZVI) immobilized in CaAlginate beads for C.I. Reactive Red 195 catalytic degradation in an air lift reactor operated with ozone. J Hazard Mater 2021;vol. 401:123275.

[20]. Ayoub M. Fenton process for the treatment of wastewater effluent from the edible oil industry. Water Sci Technol 2022;vol. 86(6):1388–401.

[21]. Anil G, Scaria J, Nidheesh PV. Removal of synthetic dye from aqueous solution using MnFe2O4-GO catalyzed heterogeneous electro-Fenton process. Water 2022;vol. 14(20)

[22]. Shokri A, Fard MS. A critical review in Fenton-like approach for the removal of pollutants in the aqueous environment. Environ Chall 2022;vol. 7:100534.

[23]. Goren AY, Recepoğlu YK, Edebali Ö, Sahin C, Genisoglu M, Okten HE. Electrochemical degradation of methylene blue by a flexible graphite electrode: techno-economic evaluation. ACS Omega 2022;vol. 7(36):32640–52.

[24]. Anil G, Scaria J, Nidheesh PV. Removal of synthetic dye from aqueous solution using MnFe2O4-GO catalyzed heterogeneous electro-fenton process. Water 2022;vol. 14(20):1–19.

[25]. Xue W, Hong X, Du Y, Chen B. Electro-Fenton mineralization of real textile wastewater by micron-sized ZVI powder anode. Water Sci Technol 2023;vol. 87(4):924–37