



Application of advanced oxidation processes for remediation of rubber industry wastewater: a comprehensive review

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Received: 16 December 2025 / Accepted: 26 April 2026 / Published online: 7 May 2026
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Abstract

Rubber is an industrial material valued worldwide for its remarkable elasticity and versatility. It has become an essential material among the several various sectors, contributing to technological progress and improving the quality of everyday life. In the twenty-first century, increasing global awareness over rubber pollution has highlighted the significant attention towards the ecological footprint and sustainability challenges associated with rubber materials. The manufacturing of rubber is known to produce effluents that are difficult to treat with existing technologies. These effluents are known to have a high chemical oxygen demand (COD) and biological oxygen demand (BOD) alongside organic toxic pollutants. However, the new advanced oxidation processes (AOPs) for treating such wastewater have shown promise alongside AOPs that produce high amounts of hydroxyl radicals. This paper analyzes other prominent techniques such as Fenton and photo-Fenton, photocatalysis, ozonation, and electrochemical oxidation, aimed at treating rubber industry effluents. These techniques are found to be highly effective against resistant pollutants and aid in increasing biodegradation efficiency. The Fenton processes, alongside AOP technologies, pose some operational challenges and are not advanced enough to have cost-effective and efficient solutions. The combination of AOPs with biological processes and other recent studies have been shown to be effective, but more research needs to be done on their economic viability. We have also emphasized the important role of hybrid synergistic systems and AI in improving the effectiveness of AOPs for achieving better waste management practices in the rubber industry.

Responsible Editor: Weiming Zhang

Highlights

- Rubber industry wastewater as a potential renewable resource.
- The application of AOP techniques in Rubber Industry wastewater remediation.
- The application of AOP systems in wastewater treatment and its effectiveness.

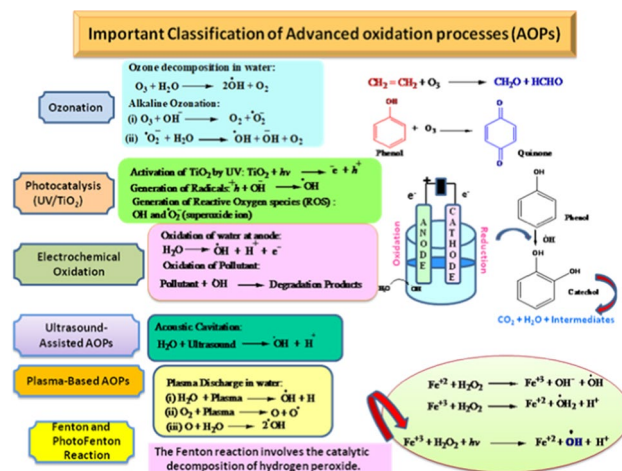
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Graphical abstract

Classification of advanced oxidation process (AOPs) based on reactive mechanism



Keywords Rubber industry wastewater · Advanced oxidation processes (AOPs) · Photocatalysis · Ozonation · Electrochemical oxidation · Biological oxygen demand (BOD)

Introduction

Rubber is a key industry, which comprises the production, processing, and transformation of rubber into products of all kinds. Natural rubber is obtained from the latex of *Hevea brasiliensis* (a tree primarily grown in tropical regions) (Cao et al. 2025). It can be broadly divided into three categories, natural rubbers, synthetic rubbers, and rubber products (Candau and Maspoch 2025; Berladir et al. 2025). The natural rubber industry involves harvesting of latex from rubber trees, mainly found in tropical regions (like Thailand, Indonesia, and India), where the latex is processed into raw rubber, used in products ranging from tyres and footwear to medical goods (Beswick 2002; Marisetti et al. 2025). The synthetic rubber industry produces rubber by the use of petroleum chemicals as raw materials. These industries produce various types of rubber such as styrene butadiene rubber (SBR), polybutadiene rubber (BR), and chloroprene rubber (CR). These various types of rubber are used in automotive components, tire industrial products, and belt manufacturing; are preferred for their low heat buildup, oil-resistant articles, valued for weatherproofing, and resistance to chemicals; and have been trying to secure enough market venue (Rachmat et al. 2025; Aguilar-Bolados et al. 2025; Parthasarathy et al. 2025). All three streams are overlapping and collectively solve the global demand for rubber-based applications (Pathiraja et al. 2025; Aguilar-Bolados et al. 2025). Like other resource industries, the rubber industry can be conceptualized through the analysis of upstream,

midstream, and downstream activities (Ali et al. 2021; Sharib and Halog 2017). The upstream part covers the cultivation and harvesting of raw materials. In the case of rubber production, this includes the growth of rubber trees and latex extraction to produce natural rubber (Santana and Utrera-Barrios 2025; Pinitjitsamuta and Doungmanee 2024). It does not include the manufacturing of petrochemicals, which are the feedstock for synthetic rubber and are derived from oil and gas (Adak et al. 2025). The midstream specializes in the refining of these raw products. In the case of natural rubber, the coagulating and drying latex into slabs or blocks (Santana and Utrera-Barrios 2025; Pinitjitsamuta and Doungmanee 2024). For the synthetic rubber sequence, it consists of a series of complex chemical courses in which polymerization reactions are carried out to create different synthetic rubbers such as SBR, NBR (Adak et al. 2025; Joshi 2025). This step also includes the mixing and preparing of rubber formulations for various end uses. The downstream includes converting the processed rubber to end products (Santana and Utrera-Barrios 2025; Pinitjitsamuta and Doungmanee 2024; Joshi 2025). The downstream sector in the condoms and gloves industry encompasses the final stages of production, packaging, marketing, and distribution of these goods to individual consumers, businesses, or medical facilities (Birnbach et al. 2020). In the downstream stage, raw latex or synthetic materials are turned into finished products. These three segments constitute a value chain that encompasses the whole of the global rubber industry. The rubber business plays a vital role in the global

economy. Rubber is an important material for the end-use consumer and used for making other items like tires, hoses, toys, belts, gloves, condoms, and molded products. These products are used in different daily life applications (Pinitjitsamuta and Doungmanee 2024; Joshi 2025; Birnbach et al. 2020). For example, gloves use in the medical, industrial, household and there are different types of gloves, for example surgical gloves, medical gloves, examination gloves, heavy-duty industrial nitrile gloves, food-handling nitrile gloves, and disposable gloves. Similarly, the condoms are processed for safe sex and contraceptive use, sometimes used with added lubricants, flavors, or coatings (Pinitjitsamuta and Doungmanee 2024; Joshi 2025; Birnbach et al. 2020; Bashpa et al. 2025; Low et al. 2025). In recent years (during the COVID-19), the demand for products like latex and nitrile gloves has increased. This has put pressure on the consumption of raw materials and on the environment, highlighting the importance of adopting more sustainable production practices (Burelo et al. 2025; Cruz-Morales et al. 2023). Nevertheless, the raw rubber processing generates a large amount of wastewater that contains a high amount of both organic and inorganic contaminants. It also contains high levels of chemical and biological oxygen demand (COD and BOD) as well as significant amounts of suspended particles (oil and hazardous organic substances, phenols, polycyclic aromatic hydrocarbons, and leftover latex), which are characteristics of rubber manufacturing effluents (Ho et al. 2023; Hadiyanto et al. 2020; Abazari et al. 2021). The materials of both industries take decades to decompose, adding to plastic pollution and landfill waste (Bashpa et al. 2024; Tsunekawa and Todo 2018). Using non-biodegradable materials, chemical waste, and improper disposal all lead to a severe environmental burden in the condom and gloves industry (Pinitjitsamuta and Doungmanee 2024; Joshi 2025; Birnbach et al. 2020; Bashpa et al. 2025; Low et al. 2025). This can be extremely risky since, if released into the environment untreated, these contaminants provide serious risks to aquatic systems as well as people (Nabeel). As global pollution continues to increase, a wide range of treatment methods including coagulation, adsorption, aerobic processes, membrane separation, ion exchange, sorption, sonolysis, ozonation, photocatalysis, electrocatalysis, electro-Fenton, and photo-Fenton have been developed to improve wastewater purification (Nabeel et al. 2025a; Deb et al. 2023; García-Espinoza et al. 2025). Similarly, the common treatment such as biological methods like anaerobic digestion, aerobic processes, and facultative pond systems is also used, but they often lead to the generation of secondary pollutants or sludges (Li and Koenig 2005). Moreover, studies applying the effluent of natural rubber processing indicate that special additives (accelerators and stabilizers) will still be contained in

the wastewater. For instance, the thiuram accelerators (a class of chemical compounds commonly used as accelerators and vulcanization agents in the rubber industry) are readily determined. TMTD was recently reported as an emerging pollutant with ecotoxicity and potential hazards of accumulation in rubber wastewater (Zhu et al. 2022). Other sulfur-based accelerators described as contaminants include 2-mercaptobenzothiazole (2-MBT). This benzothiazole accelerator was enriched for a bacterial consortium with high capacity to biodegrade 2-MBT in rubber effluent on the basis of potential adverse health effects (Krainera et al. 2020). Dithiocarbamate accelerators ZDEC (zinc diethyldithiocarbamate) and ZDBC (zinc dibenzylthiocarbamate) are also commonly used in vulcanization, and although direct aqueous-phase measurements are scarce, as they must be geometrically constrained to the rubber formulation, dithiocarbamate residues have been detected (1.3–14 µg/g) in the wastewater. Similarly, the phenolic antioxidants and stabilizers (BHT, BHA, 6-PPD) are incorporated into the rubber; a comprehensive recent overview report confirmed that these phenolic additives and their transformation products are environmental contaminants of emerging concern (Xu et al. 2022).

The treatment of this waste water can be done through different processes (coagulation, adsorption, aerobic process, membrane separation, ion exchange, sedimentation, sorption). The main reason for this failure of traditional approaches is due to the following reason. (a) Variety of pollutants: The wastewater from rubber industry contains a large amount of complex and recalcitrant organic pollutants like phenols, aromatic hydrocarbons, and rubber supernatants. The other pollutants are resistant to conventional treatment and require more intense and sophisticated methods (Nabeel et al. 2025c; Zahmatkesh et al. 2022). (b) Environmental and health risks: wastewater generated by rubber processing, if not treated or properly treated, can have a serious impact on the ecosystem, causing water pollution, aquatic toxicity, and bioaccumulation of toxic compounds in the food chain. This endangers public health and biodiversity (Ho et al. 2023). (c) Regulatory pressure: growing worldwide environmental regulations are pressuring industries to adopt advanced technologies to comply with discharge limits of COD, BOD. Noncompliance may incur punitive measures, suspension of operation, or reputational risk (Mokhtar et al. 2024; Ahmad et al. 2024a). (d) Conventional methods are not enough: bioprocesses are often ineffective for treatment of non-biodegradable compounds, on the other hand physicochemical methods, which could efficiently reduce the mass of waste, typically causes the generation of huge amount of sludge and other by products leading to additional treatment and disposal issues. These disadvantages demand for alternate solutions (Wimalaweera et al. 2024; Ibrahim et al. 2025). Table 1 provides a brief

Table 1 Remediation of rubber industry wastewater through different processes

Treatment method	Description	Techniques	References
Mechanical methods	Solids are removed from waste water by physical separation	Screening, sedimentation, adsorption	(Mohammadi et al. 2010; Ullah et al. 2025b)
Chemical methods	Neutralization chemical reactions to eliminate contaminants	Neutralization, precipitation, Fenton's reagent	(Agustina et al. 2017)
Biological methods	Microbial use to decay organic matter	Aerobic and anaerobic processes, bacterial consortia	(Pillai and Girish 2014)
Advanced treatment	Advanced methods to achieve efficient decontamination	Membrane filtration, ozonation	(Mohammadi et al. 2010; Agustina et al. 2017; Ahmad et al. 2025a)
Combined approaches	Combination of multiple methods for best possible performance	Mechanical + chemical + biological processes + green synthesis	(Qasim et al. 2026; Arif et al. 2025; Ullah et al. 2025a)

overview of those methods, along with reputable references. Figure 1 represent the major countries involve in field of driving research in rubber wastewater treatment and current trends in managing rubber industry wastewater (Ullah et al. 2023). In recent years, advanced oxidation processes (AOPs) have emerged as promising technologies for the contaminants commonly found in rubber sector. Advanced Oxidation Processes (AOPs) are considered suitable alternatives due to their generation of highly reactive radicals to attain complete mineralization of persistent pollutants. These processes are characterized by the actual replacement of organic pollutants into benign end products like carbon dioxide and water, not requiring numerous chemical additives (Nabeel et al. 2025c).

Inspired by interesting results of AOPs for the degradation of rubber pollutants, this review aims to provide a comprehensive overview of the application of AOPs in the rubber industry. Hence, in this review, critical advancements pertaining to the performance of AOPs for the treatment of rubber industry wastewater are holistically highlighted. First, it describes the efficiency of individual AOPs, followed by recent progress and operational challenges. It also describes the combination of AOPs with conventional approaches in the development of sustainable, hybrid treatment systems. The aim is to provide an overall perception of how AOPs can overcome the drawbacks of current treatment methods, and promote supra-environmental sustainability in the rubber field. The international trend towards sustainability in industry highlights the demand for cleaner and more efficient wastewater treatment technologies. AOPs support these objectives due to their low environmental footprint and potential for resource recovery (Qasim et al. 2026; Sanongarj et al. 2025; Yin et al. 2026). This review covers and highlights their classification, reaction mechanisms, pollutant-targeting pathways, hybrid and integrated AOP configurations (chemical reactions of singlet oxygen ($^1\text{O}_2$) with one of the major target pollutants of rubber industry wastewater, chemical structure of 6-PPD and its oxidation product 6-PPD-quinone, hypothetical major degradation pathway of

6-PPD-quinone, case studies of application of AOP techniques in treating rubber industry wastewater). We have also highlighted the significance of hybrid synergistic systems and artificial intelligence (AI) in enhancing the efficiency of AOPs (innovations in AOPs technologies, process modeling, and artificial intelligence, conceptual framework illustrating AI integration within AOP-based wastewater treatment and the mapping of AOP techniques to corresponding AI models). Special attention is given to the limitations and disadvantages associated with advanced oxidation processes. Collectively, this work aims to guide researchers, with ideas to construct new materials and elaborate their multifunctional applications, as well as policymakers, toward sustainable wastewater for the rubber industry. Figure 2 illustrates an overview of the major processes within the rubber processing industry, covering both the production of Standard Malaysian Rubber (SMR) and the treatment of its wastewater. The information presented is based on direct observations made during a scientific visit (To Tuaran Crumb Sdn. Bhd) conducted by the Sono-Photochemistry Research Group (SPRG), Faculty of Science and Technology (FST), Universiti Malaysia Sabah (UMS). These industrial-scale observations provide meaningful and scientific insight into the real challenges encountered in rubber processing and the strategies used to address them. This information strengthens the review by giving young researchers a clearer picture of how the rubber industry operates in practice and supporting/guiding future research in rubber science and wastewater treatment.

Characteristics of rubber industry wastewater

The rubber industry produces large volumes of wastewater containing various toxic pollutants. Due to its possible environmental effects and treatment processes that are challenging, its management is crucial. A detailed examination follows (Fig. 3). There are the following characteristics of the rubber industry. (a) Types of pollutants: phenols: as one of the important pollutants in rubber wastewater, phenols

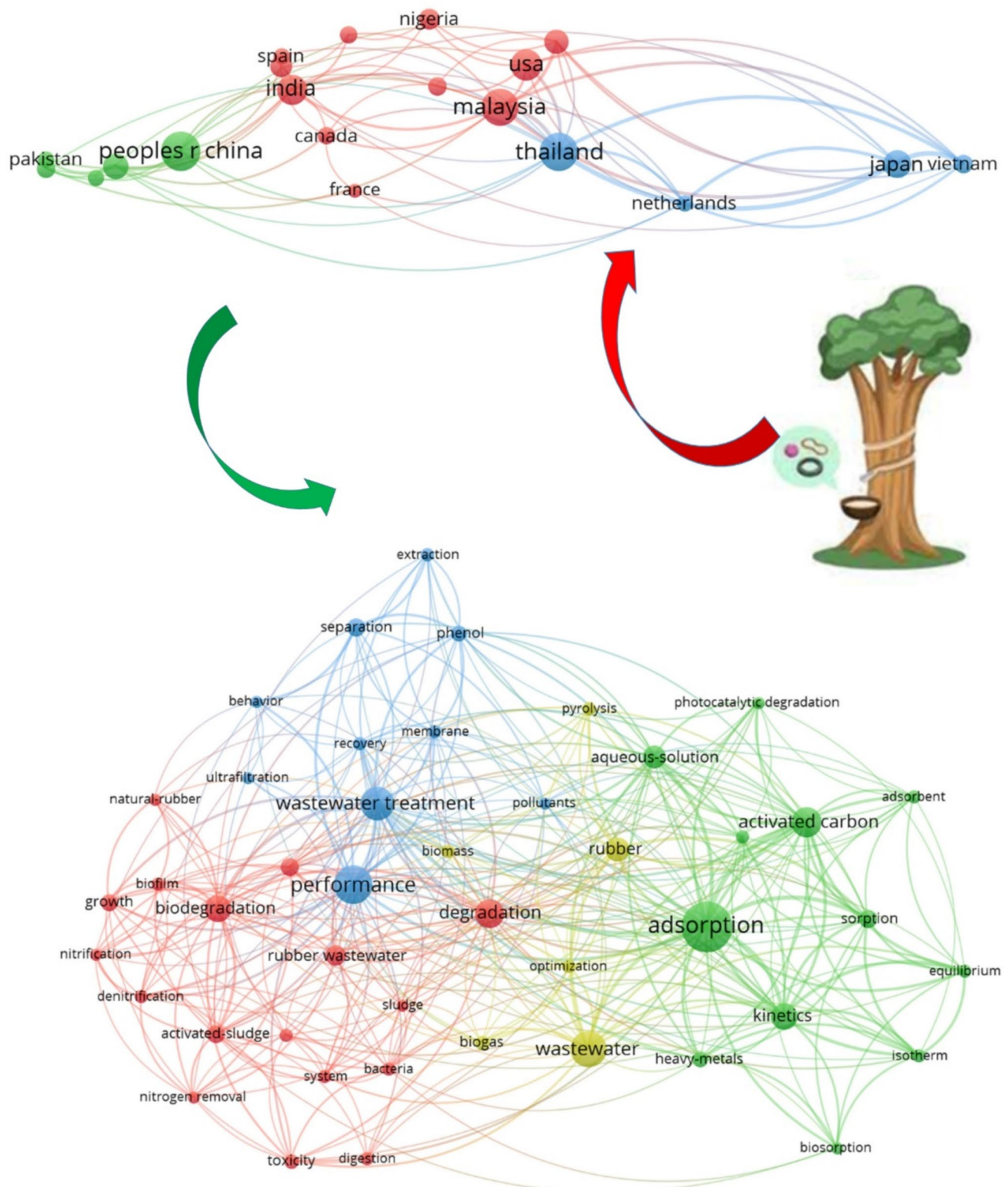


Fig. 1 Leading countries in rubber wastewater treatment research and emerging trends in rubber industry wastewater management (reprinted with permission, Copyright 2023, Springer Nature) (Ullah et al. 2023)

Fig. 2 The schematic diagram represents the different processes in the rubber industry for the production of SMR and the anaerobic process used for wastewater treatment (a scientific trip arranged by the Sono-photochemistry Research Group (SRG), Faculty of Science and Technology (FST), Universiti Malaysia Sabah (UMS) to Tuaran Crumb Sdn. Bhd.)



are produced in the vulcanization process and other related production processes, and these toxic compounds can bioaccumulate and harm aquatic life (Van Der Meer 1944). (b) Volatile organic compounds (VOCs): VOCs, including benzene and toluene, are substances that easily evaporate into the atmosphere, thus causing pollution. They are bio and can threaten human health and ecosystems if left untreated (Huang et al. 2022). (c) Suspended solids: large quantities of rubber particles and other suspended solids are released in rubber manufacturing. These solids lead to increased water turbidity, reduced light penetration, and inhibit aquatic plant growth. (d) High COD and BOD: the wastewater produced by industries involved in rubber manufacturing has high COD and BOD levels because of organic and inorganic pollutants. A high COD/BOD ratio represents slow biodegradability, which makes its treatment more challenging (Ho et al. 2023). Due to the complexity of rubber wastewater and its being influenced by surrounding environmental conditions, it is difficult to treat effectively. A primary example of persistence to breakdown is phenols and volatile organics, which do not undergo biological degradation processes. This requires advanced treatment (Massoudinejad et al. 2015; Ahmad et al. 2023). Moreover, toxic contaminants such as

heavy metals, ammonia, and sulfur compounds hinder the growth and efficiency of microorganisms in the biological treatment processes. Treatment of such complex mixtures of organic-inorganic and particulate pollutants is very complicated and often requires a multi-stage approach involving physicochemical pre-treatment followed by biological treatment, increasing operational costs (Ho et al. 2023). Deposit of pollutants into public waters may be subject to strict parameters in many countries to protect public health and the environment; violations can entail significant penalties, regulatory action, and reputational damage for a company. If these wastewater is not treated well, it can lead to eutrophication, reduction in biodiversity, and contamination of drinking water, necessitating stricter treatments (Wijerathna et al. 2023). New technologies provide tools to address these problems at a limited scale. Anaerobic digestion, constructed wetlands, and oxidation processes are some techniques that have been found to be effective in treating rubber wastewater. The integration of these innovative technologies into the existing treatment systems can improve sustainability and efficiency (Ho et al. 2023; Ahmad et al. 2025a). The treatment of wastewater is important for

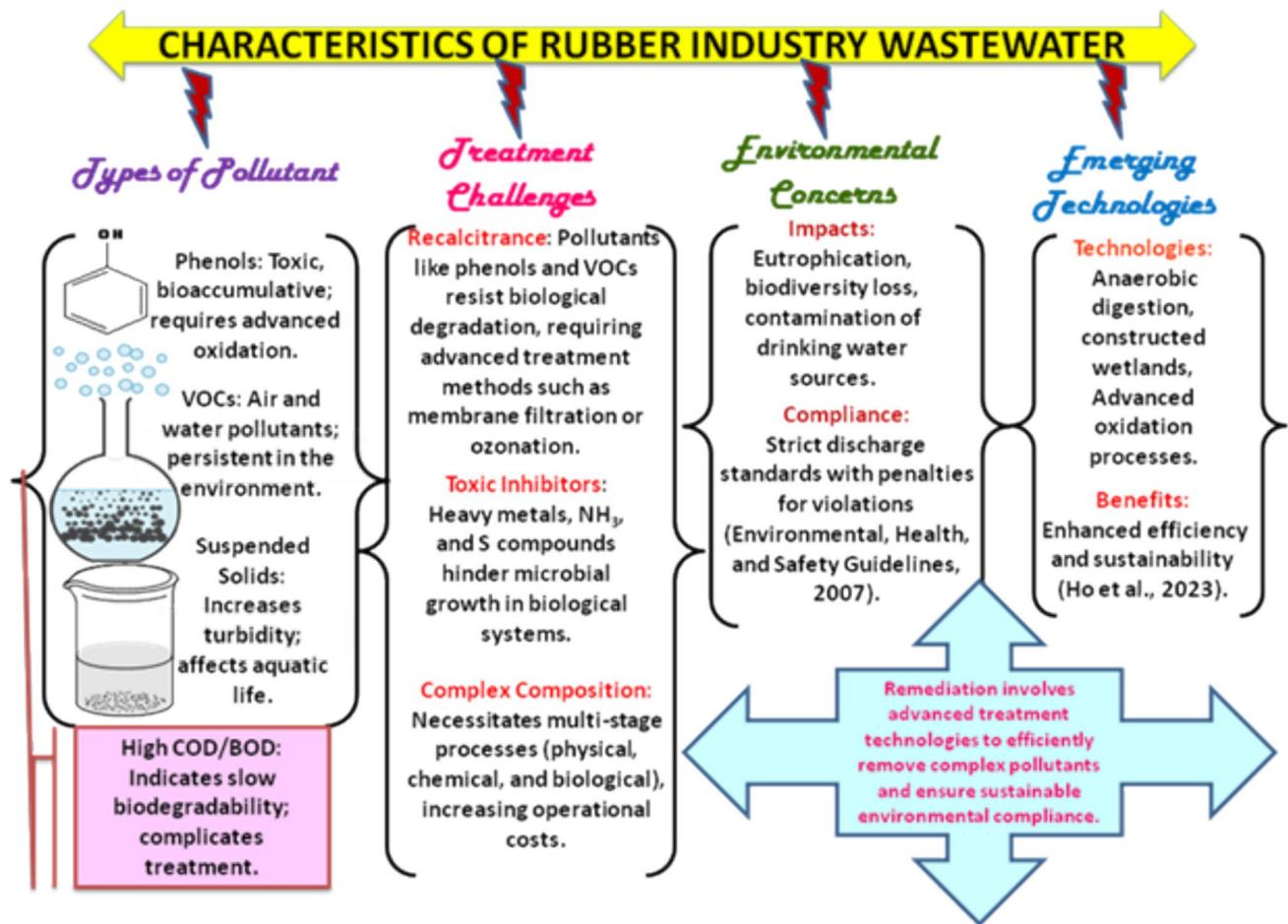


Fig. 3 Significant characteristics, challenges, and emerging solutions for rubber industry wastewater treatment

the progressive management of the environment to greatly reduce pollution emissions due to the rubber industry.

Advanced oxidation processes (AOPs)

Advanced oxidation processes (AOPs) involve a wide range of processes, such as Fenton's process, photocatalysis, ozonation, and electrochemical oxidation, each with specific advantages and disadvantages depending on the composition of the effluent (Nabeel et al. 2025c). Compared to traditional methods, AOPs have several advantages: High Efficiencies: Pollutants such as recalcitrant and toxic compounds can be degraded into non-toxic by products (Ahmad et al. 2024b; Zahmatkesh et al. 2022). Scalability and flexibility: AOPs can be designed to treat wastewater with different properties. Integration potential: AOPs can be successfully integrated with other methods (biological treatment) to improve total treatment efficiency. Advanced oxidation processes (AOPs) refer to a series of chemical treatment procedures intended to remove organic contaminants from water and wastewater (Joseph et al. 2026; Arif

et al. 2026). AOPs accomplish this by producing highly reactive species, mainly hydroxyl radicals ($\bullet\text{OH}$) and singlet oxygen ($^1\text{O}_2$), which partition and degrade complex pollutants into simpler and less harmful products such as carbon dioxide and water (Fig. 4) (Glaze et al. 1987; Khan et al. 2025). Hydroxyl radicals are one of the most powerful oxidizing agents that can be used to treat water, capable of quickly and effectively breaking down organic materials with larger structures into smaller, less harmful molecules, often to the point of complete mineralization to carbon dioxide and water (Arif et al. 2026; Shamim et al. 2026). Advanced oxidation process (AOP) oxidants act on organic pollutants by producing hydroxyl radical ($\bullet\text{OH}$), singlet oxygen ($^1\text{O}_2$), superoxide anion ($\text{O}_2^{\bullet-}$), and other reactive oxygen species (ROS). These species oxidize pollutants, cleaving them into smaller, less toxic and biodegradable compounds. Singlet oxygen generation $^1\text{O}_2$ can be produced via a photochemical reaction, ozonation, redox processes or as a direct reaction between different reactants. Singlet oxygen oxidizes some types of organic compounds specifically and can oxidize aromatic rings found

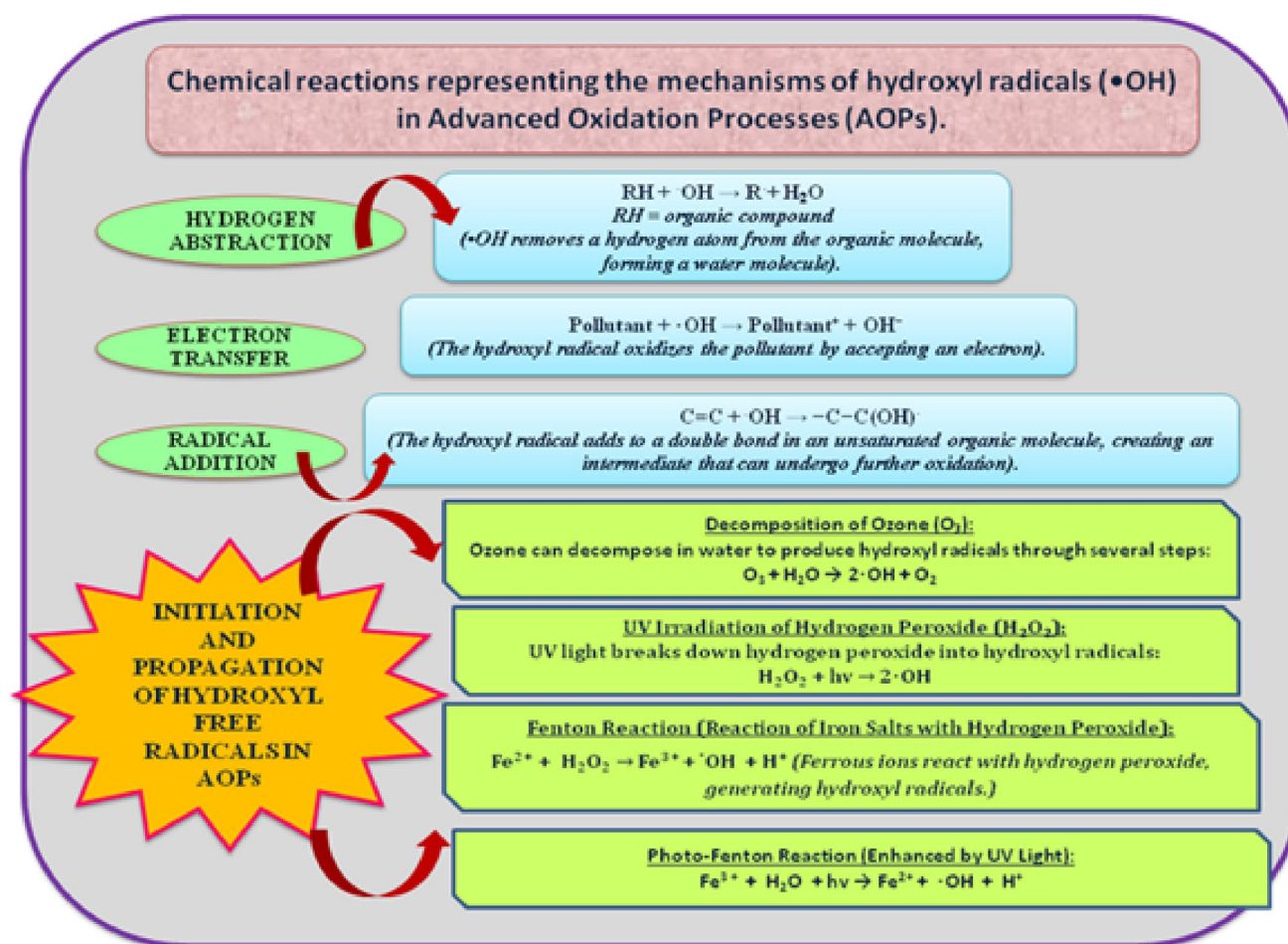


Fig. 4 Important chemical reactions generating hydroxyl radicals in advanced oxidation processes (AOPs)

in compounds from wastewater generated from the rubber industry which are normally electron rich (Nabeel et al. 2025a; Kerboua 2025). The combination of singlet oxygen with the traditional AOP methods enhances the oxidative capacity of the treatment process. These new advanced oxidation processes (AOPs) have advantages over the conventional wastewater treatment methods. They are widely applied for persistent organic pollutants treatment, including pesticides, phenols, and pharmaceuticals (Esplugas et al. 2007; Arif et al. 2026). One of the most important advantages is that they can reach total mineralization, or convert toxic contaminants into harmless products such as carbon dioxide and water. For example, AOPs generate little or no sludge and waste, thus leading to minimal or no secondary pollution. This flexibility enables their combination with alternative treatment methods including biological and physico-chemical processes, improving overall treatment efficiency and sustainability (Kerboua 2025; Silva 2025).

Classification and reaction mechanism of advanced oxidation processes (AOPs)

As highly effective and innovative techniques, advanced oxidation processes (AOPs) are widely employed for the treatment of industrial wastewater. They employ the generation of reactive oxygen species (ROS), including hydroxyl radicals ($\cdot\text{OH}$) and singlet oxygen ($^1\text{O}_2$), to degrade pollutants to less harmful biocompatible by-products (Nabeel et al. 2025a; Kerboua 2025). The main advantage of AOPs is their capacity to oxidatively degrade a variety of organic as well as inorganic pollutants, destroying only hardly degradable compounds. Advanced oxidation processes (AOPs) present unique advantages in the treatment of rubber wastewater. They can also degrade complex hydrocarbons and oxidize sulfur and nitrogen containing compounds and mineralize dyes, and even help to remove heavy metals via the oxidation-precipitation mechanism. Figure 5 shows the classification of Advanced oxidation processes (AOPs).

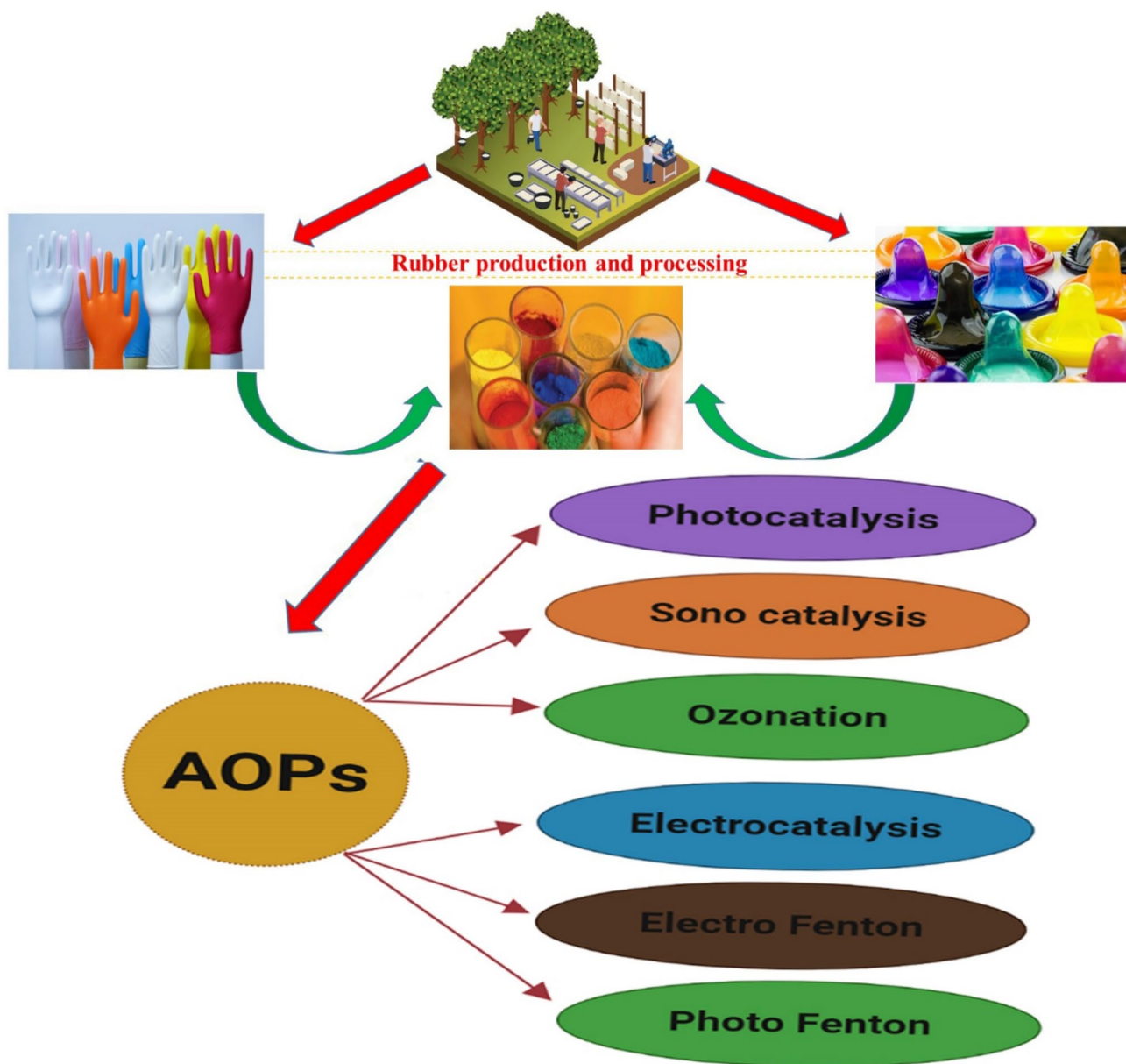


Fig. 5 Classification of advanced oxidation processes (AOPs)

Based on their versatility, they can be grouped with other treatment processes to improve the overall efficiency and sustainability of treatment processes. Examining how AOPs are classified and the reaction mechanisms specific to individual AOPs helps industry formulate specific solutions for each different effluent release from rubber manufacturing. There are following classification of advanced oxidation processes. (a) Photo-Fenton; In both Fenton and photo-Fenton systems, hydrogen peroxide (H_2O_2) reacts with ferrous ions (Fe^{2+}) to generate highly reactive hydroxyl radicals. By means of UV or visible light, the photo-Fenton process facilitates this reaction

(Pignatello et al. 2006). The photo-Fenton process improves the Fenton reaction by driving the photo reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) by light (UV or visible), maintaining of the catalytic cycle and enhancing hydroxyl radical generation. These techniques can be used for the removal of dyes, pharmaceuticals, and industrial contaminants. They are simply made, inexpensive, and active in acidic pH. (b) Ozonation employs ozone (O_3), which breaks down to hydroxyl radicals in the presence of specific conditions like basic pH or UV irradiation in water. Ozone reacts with organic pollutants at their double bonds and with the aromatic systems. Ozone breaks down

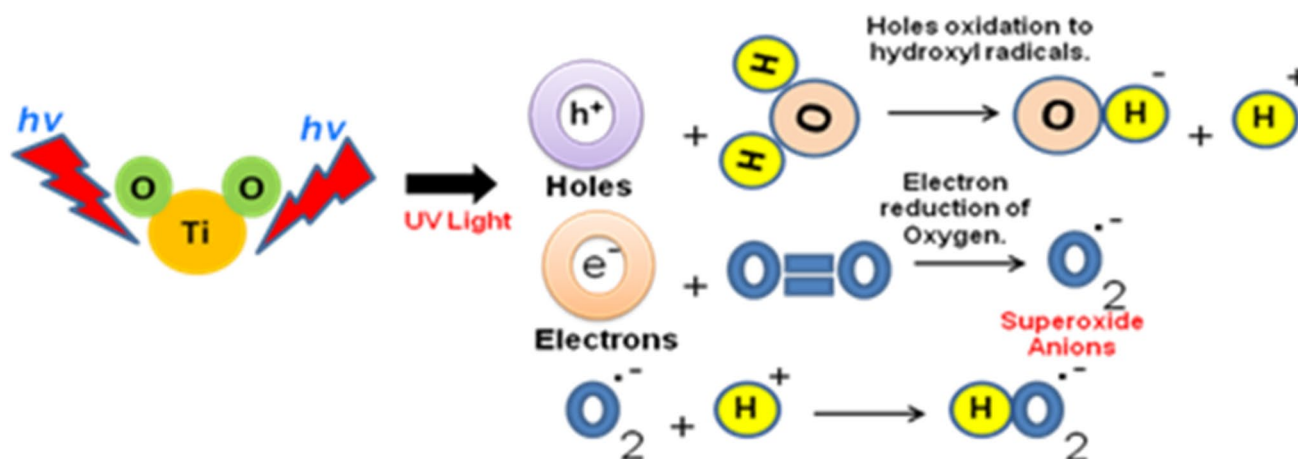


Fig. 6 Photocatalytic reaction sequence of TiO_2

more quickly in the presence of UV light to form hydroxyl radicals. This process is efficient for degrading refractory organics, disinfecting, and color removal (Beltran 2003). Take it for its rapid kinetic response and high oxidation power. (c) Photocatalysis (UV/TiO_2) is based on titanium dioxide (TiO_2) creating electron hole pairs after UV light radiation (Fig. 6), which leads to the hydroxyl radical production for pollutant oxidation (Fujishima and Zhang 2006, Affandi et al. 2025). This process has been proposed to remove pharmaceutical residues, pesticides, organic dyes, providing mild operational conditions with catalysts that are often reusable. Phenol accounts for a significant portion of the pollution present in wastewater from the rubber industry due to cleavage that occurs during the processing and vulcanization steps. Semiconductors, in particular titanium dioxide (TiO_2) and zinc oxide (ZnO), allow photocatalytic degradation of phenol into by-products that are less toxic, such as carbon dioxide (CO_2) and water (H_2O).

AOPs function by generating highly reactive radical species that can rapidly degrade a variety of organic pollutants. These reactive radical species are generated by different mechanisms depending on the types involved in AOPs as shown in Fig. 7. In this figure, the oxidation of phenol ($\text{C}_6\text{H}_5\text{OH}$) by hydroxyl radicals ($\cdot\text{OH}$) occurs. Hydroxyl radicals attack the aromatic ring of phenol, resulting in the formation of hydroxylated intermediates that continue to degrade. (Intermediates also include catechol, hydroquinone, or resorcinol). The hydroxylated intermediates are subjected to oxidative ring cleavage and decompose into smaller organic acids (formic acid, acetic acid) that mineralize further to CO_2 and H_2O (Devipriya and Yesodharan 2010). Similarly, in electrochemical oxidation, the hydroxyl radicals are generated from water oxidation at the anode surface in electrochemical reactions (Moreira et al. 2017). Organic pollutants (R) adsorbed on

the surface of the anode react directly with the generated hydroxyl radicals, resulting in partial or total mineralization, and it has been successfully used for a range of targets, including phenols, cyanides and other industrial products, with advantages such as compact systems, use of limited chemical compounds, and the overall eco-friendliness of the treatment process itself.

Singlet oxygen ($^1\text{O}_2$) is also a strong oxidant and plays an important role in the degradation of organic pollutants in rubber industry wastewater. AOPs are one of the most appealing alternative solutions for microbial resistance in recent years, and singlet oxygen ($^1\text{O}_2$) has unique advantages in its applications. It has advantageous features like selective reactivity that can reduce, hinder, finalize the degradation of organic species that may be resistant to other oxidants like hydroxyl radicals (Nidheesh et al. 2025; Sun et al. 2019). This selectivity renders singlet oxygen especially capable of the treatment of complex wastewater with recalcitrant pollutants. In contrast, the reactions of singlet oxygen may generate fewer toxic by-products, depending on the reaction conditions, and consequently the treatment process is potentially safer and more environmentally friendly. Also, hydrogel-mediated singlet oxygen generation is compatible with solar-induced AOPs, which can be one of the most feasible energy-efficient pollutant elimination processes. Photosensitizers can utilize sunlight to create singlet oxygen, which alleviates the need for external energy sources and lowers the cost of operation. The match with sunlight strengthens its prospects for sustainable water and wastewater treatment technologies (Nidheesh et al. 2025; Sun et al. 2019; Yan et al. 2024). Here we describe how $^1\text{O}_2$ interacts with specific pollutants and detail its reaction mechanism. The reaction mechanisms of pollutant degradation by $^1\text{O}_2$ include multiple pathways (Fig. 8).

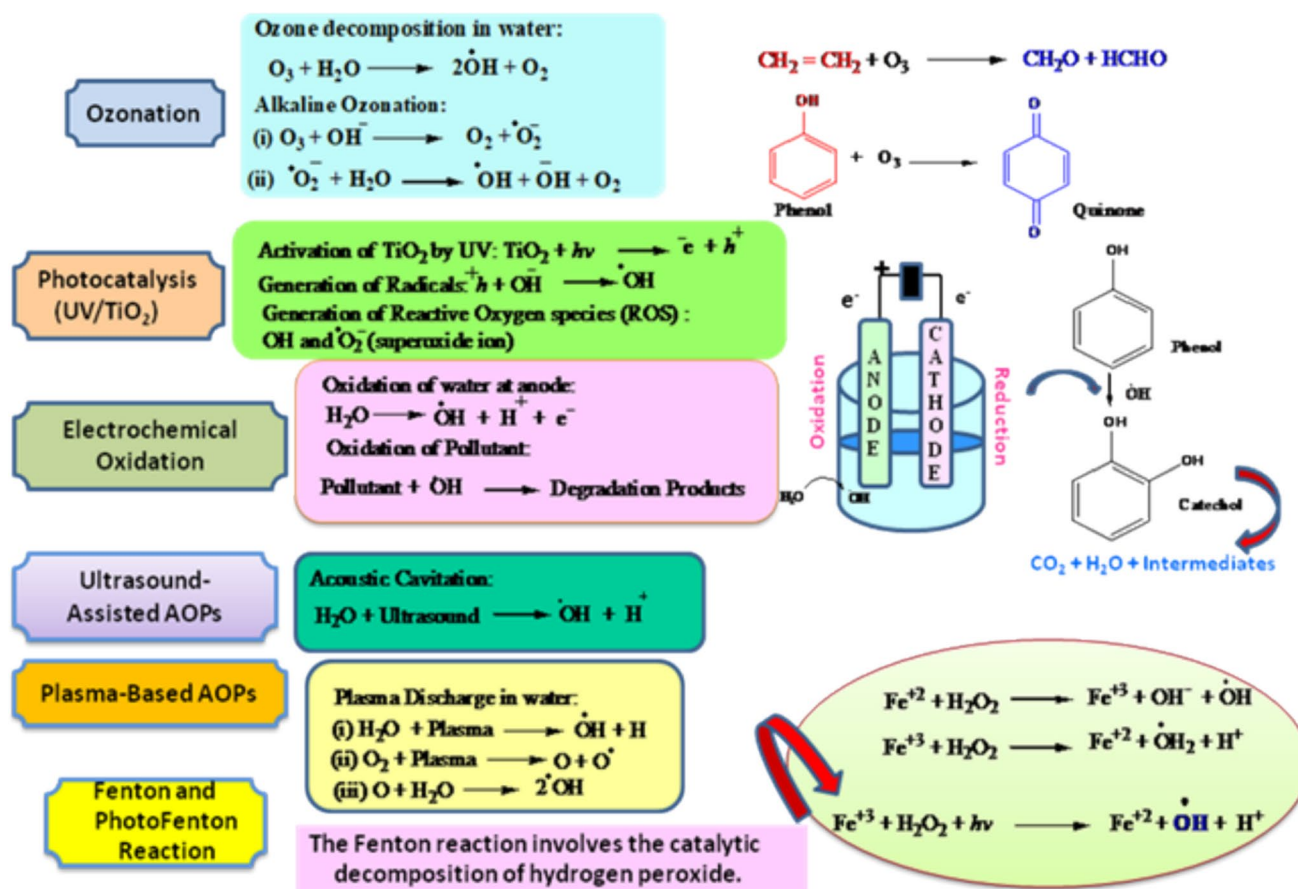


Fig. 7 Based on the reactive mechanism, classification of advanced oxidation processes (AOPs)

In AOPs, singlet oxygen serves as a flexible oxidation route, allowing for the destruction of diverse pollutants via electrophilic addition, electron transfer, and oxidation of heteroatoms. These reactions produce less toxic and more biodegradable products, which improve the effectiveness of wastewater treatment processes. Utilizing the unique reactivity of $^1\text{O}_2$ enables factories to mitigate intricate effluents containing unsaturated hydrocarbons, phenols, heteroatom containing compounds. Ultrasound assisted processes during which hydroxyl radicals are generated by acoustic cavitation (Lei et al. 2023; Yan et al. 2024; Xiong et al. 2018) and plasma based AOPs, where discharge of plasma in water generates radicals and other reactive species are among other emerging AOP (Ma et al. 2020). Hybrid treatment approaches combine different reaction pathways to improve treatment efficiency include O_3/UV or Fenton/photo-Fenton processes (or their combination) which work together to improve pollutant removal (trichloroacetic acid (TCA) and other environmentally hazardous halogenated organic compounds.). The wastewater treatment capabilities of microalgae, including the capability of complete mineralization, adaptability to various contaminants, and reduced secondary

pollution, demonstrate their promise in water and wastewater treatment (Xiong et al. 2018; Nie et al. 2021). These barriers still do exist around cost and operational complexities they are being addressed, with regular advancements in the space making AOPs more accessible and efficient.

Advanced oxidation processes (AOPs) for rubber industry wastewater

rubber industry wastewater is characterized by high concentrations of persistent organic pollutants, phenols, volatile organic compounds (VOCs), and high COD. In this respect, these types of systems were found to be very promising in decomposing complex pollutants into simple, biocompatible and less harmful compounds (Agustina et al. 2017; Masoudinejad et al. 2015). A more specific discussion of their application can be found below. AOPs like Fenton reactions and photocatalysis are able to efficiently degrade phenolic compounds that are commonly found in such effluent. In a similar work, the degradation of phenol using an ozone-activated carbon system was investigated, and the O_3/AC system removed about 26% and 30% higher total organic

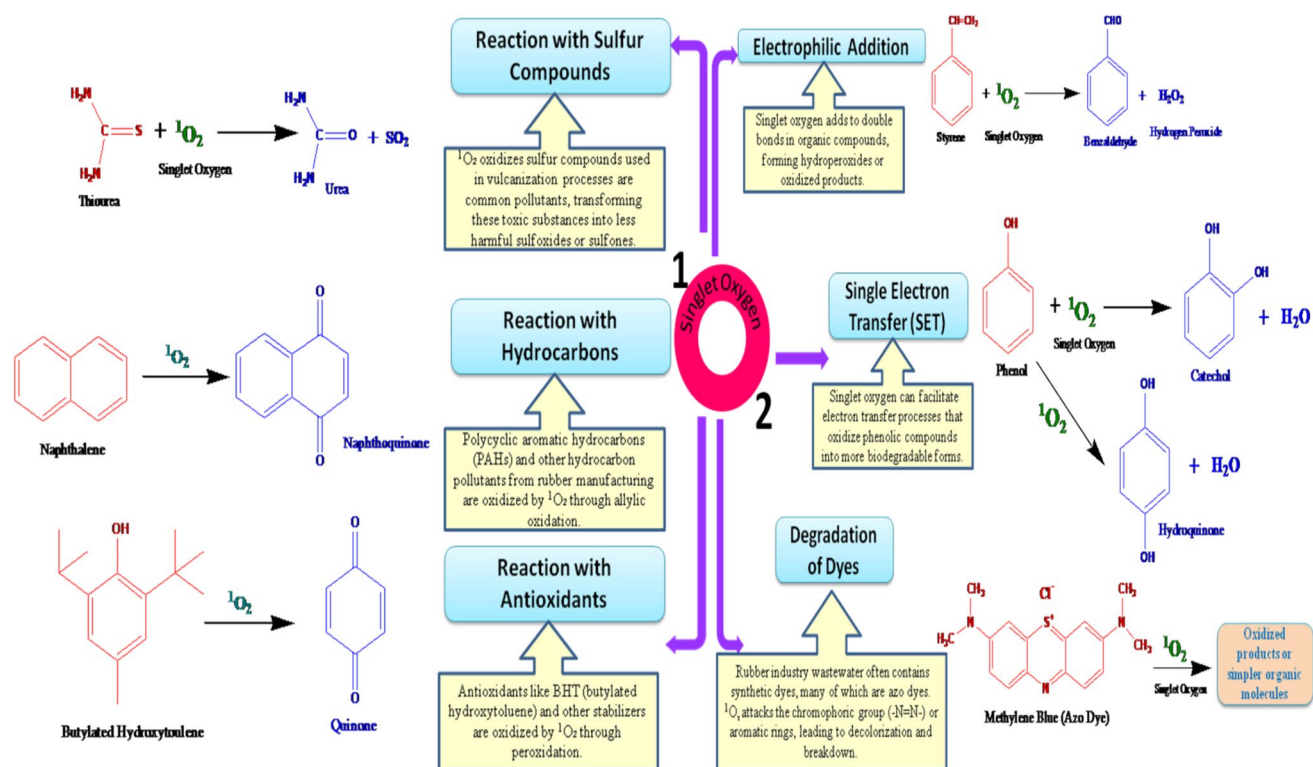


Fig. 8 Chemical reactions of singlet oxygen ($^1\text{O}_2$) with one of the major target pollutants of rubber industry wastewater

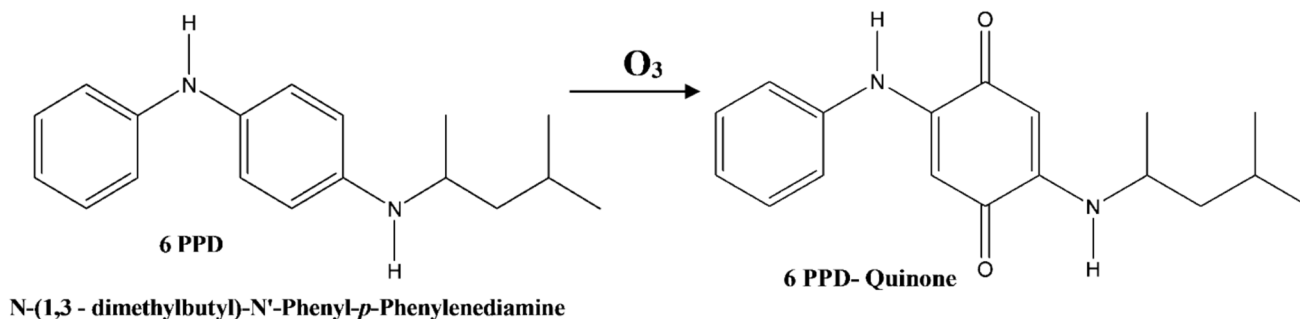
carbon (TOC) than the individual AC and O_3 treatments, respectively (Xiong et al. 2020). The photo-Fenton degradation of aqueous phenol under visible light irradiation could achieve effective degradation of phenol, demonstrating the potential of photo-Fenton catalysts for wastewater treatment (Phan et al. 2021). According to studies, Fenton reactions can remove phenols at up to 90% efficiency in ideal circumstances. The alternative wastewater treatment methods can handle waste from the rubber industry, as volatile organic compounds (VOCs) have been shown to be efficiently removed by ozonation and plasma-based AOPs, in which the compounds break down into environmentally benign by-products like carbon dioxide (CO_2) and water (H_2O). In particular, ozone-based methods stand out for high reaction kinetics and high efficiency. In addition, AOPs significantly reduce COD and BOD, enabling more effective treatment of wastewater by subsequent biological processes. AOPs have been proven to be a powerful tool for removing organic pollutants from rubber wastewater compared with commonly used treatment techniques, where COD removal efficiencies reach only about 75% *in vitro*; therefore, AOPs can be a valuable option for solving issues related to industrial wastewater toxicities (Esplugas et al. 2007). Table 2 compares various AOPs for treating rubber industry wastewater and this comparison helps identify which AOPs are most suitable for specific treatment objectives.

This comparison focuses on their behavior, cost-efficiency, operating cost, reaction time, and environmental impact.

The application of hybrid systems such as the combination of advanced oxidation processes (AOPs) with biological treatment has generated great feasibility to make the processes less expensive and more effective. The pre-treatment of wastewater with AOPs is effective to reduce its toxicity, improving the efficiency of subsequent biological processes. Moreover, innovations like solar-assisted photocatalysis and energy recovery in electrochemical processes are enhancing the energy cost-efficiency for large-scale applications (Pignatello et al. 2006). Customisation is also required as the choice of AOPs will depend on specific wastewater characteristics. For instance, the Fenton and photo-Fenton processes are more effective in treating rubber industry effluents characterized by high phenolic content, while ozonation would be more appropriate for effluents that are mainly polluted by volatile organic compounds (VOCs) (Massoudinejad et al. 2015; Agustina et al. 2017). Rubber industry wastewater can be effectively treated with AOPs due to its complexity and difficulty in biodegradation. The ability to choose appropriate operational parameters to enhance the efficiency through optimization ensures compliance without hindrance to the environment. A few representative examples can be highlighted, such as N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), the most common

Table 2 Comparative study for treating rubber industry wastewater using AOPs methods

Criteria	Fenton/photo Fenton reactions	Ozonation	Photocatalysis (UV/TiO ₂)	Electrochemical oxidation
Efficiency	High for phenols, volatile organic compounds (VOCs), and chemical oxygen demand (COD) removal	Good for VOCs and medium for COD	High efficiency for persistent organics and dyes	Very effective for phenols and dye
Operational conditions	Acidic pH (~3), medium temperature	Wide pH spectrum, more effective when alkaline	Efficient, but requires UV light; effectiveness can vary based on intensity	Variable energy demand and neutral to alkaline pH
Energy demand	Moderate (Fenton requires no additional energy)	Medium energy for ozone generation	High for UV energy-intensive	High for electrochemical equipment
Formation of by-product	Iron sludge at Fenton, not in Photo-Fenton	Low, mainly oxygen	Minimal, no toxic residues	Saline water chlorinated by-products potential
Scalability	Allows scaling for medium scale operations	Scalable; broadly deployed	Limitation based on intensity requirements for UV	Very scalable but energy intensive

**Fig. 9** Chemical structure of 6-PPD and its oxidation product 6-PPD-quinone

antioxidants and antiozonants widely utilized in the rubber industry (Fig. 9). Ground-level ozone, or tropospheric ozone (O₃), interacts with elastomers and causes ozone cracking. Antiozonants like 6PPD can reduce or inhibit the thermal oxidation of polymers by transforming hydroperoxide groups into non-radical products.

The release of 6PPD and its breakdown and oxidation products to the environment is primarily attributed to emissions from rubber manufacturing processes, activities at reconstruction sites, and the leaching of tire materials. When rubbers and rubber particles are released to ambient air and to waste water, it is extremely concerning, as they contain a range of chemicals that can negatively impact human and animal health, and damage our natural ecosystems. The complexity of rubber leachate chemistry makes toxicological assessment of such contamination challenging. The phenomenon known as “urban runoff mortality syndrome (URMS)” has recently been linked to 6PPD, particularly its newly identified oxidation derivative, 6PPD-quinone, which was detected in urban

waters exposed to storm water runoff. 6PPD quinone was found to be highly toxic to coho salmon (Kryuchkov et al. 2023; Zhang et al. 2025). Figure 9 shows the chemical structure of 6-PPD and its oxidation product 6-PPD-quinone. 6-PPD-quinone (6PPD-Q) is a toxic transformation product derived from the tire antiozonant 6-PPD. Its degradation is an integral part of cleaning environmental toxins, particularly in aquatic systems. The degradation mechanisms include various ROS, such as singlet oxygen and hydroxyl radicals. The degradation of 6PPD-quinone (6PPD-quinone) by the application of advanced oxidation processes (AOPs) is a mainstay of environmental chemistry research, being a focus of growing interest on the fate of tire additive residues. Figure 10 is the idealized representations of the possible degradation mechanisms of 6PPDQ. The proposed degradation pathway of 6PPD-Q by AOPs should be further validated by chemical reaction and experimental studies to guarantee the accurate and complete mineralization of 6PPD-Q.

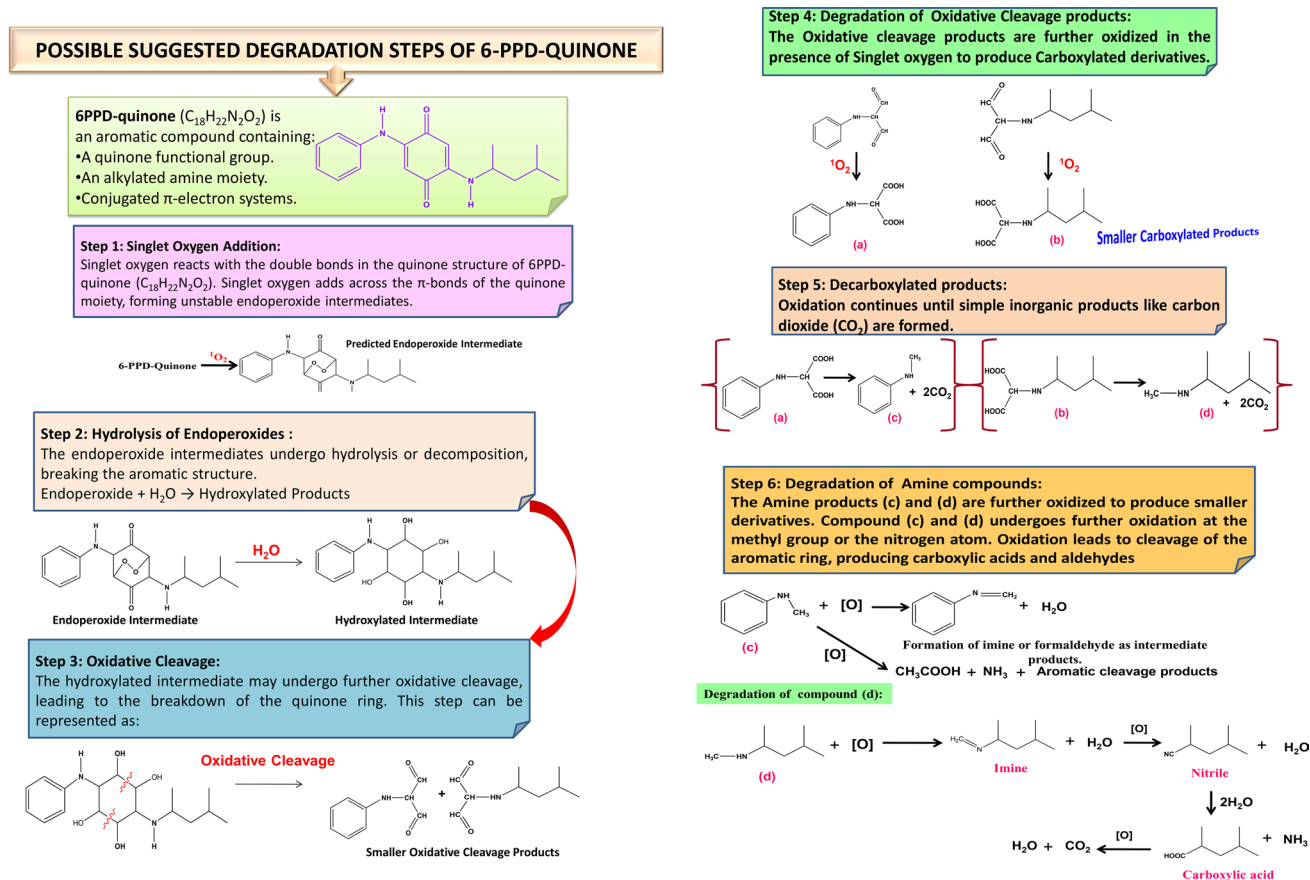


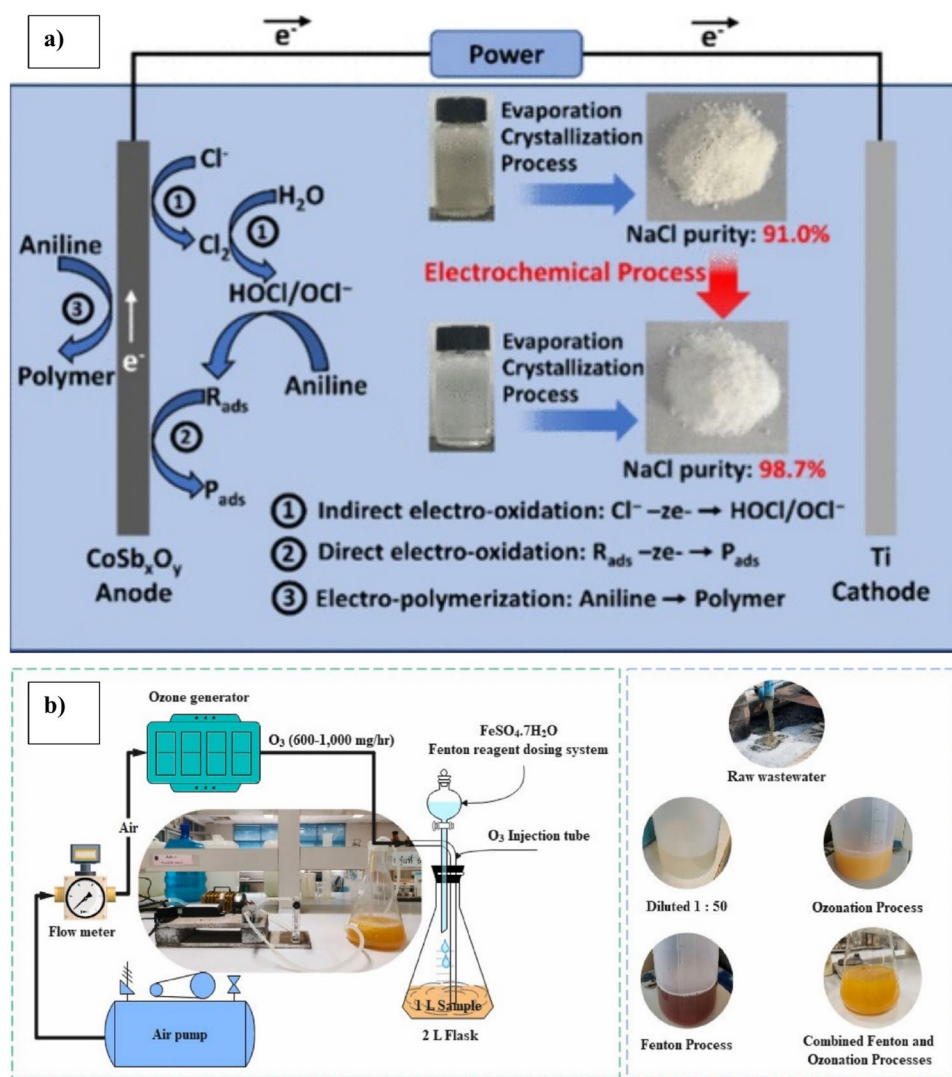
Fig. 10 Hypothetical major degradation pathway of 6-PPD-quinone

Case studies of treating rubber industry wastewater by of AOP

A specifically targeted treatment process is needed to treat rubber industry wastewater, which has been demonstrated by some case studies pertaining to the effectiveness of AOPs. Some of the processes are described here with their efficiency. (a) Electrochemical oxidation: moreover, regarding the simultaneous treatment of the electro-Fenton rubber wastewater and electricity generation in a microbial fuel cell, a study showed that it was feasible to efficiently remove the organic component in the wastewater and produce power. Such an approach implies the potential of energetically favorable treatment strategies (Selvaraj et al. 2020). A recent reported study on zero-liquid-discharge (ZLD) systems demonstrated that treating concentrated saline wastewater from the rubber-antioxidant industry (the electrochemical process effectively removes organic pollutants, mainly aniline), as shown in Fig. 11a. This process takes place by indirect oxidation (Chloride ions at the anode form $HOCl/OCl^-$, which oxidizes aniline), direct oxidation (Adsorbed pollutants can also be directly oxidized), and electro-polymerization (aniline can undergo

electro-polymerization, forming a solid polymer) resulting in significantly improved salt purity during ZLD recovery. Continuous operation achieved COD removal of 71% in 300 h (low treatment cost $\$1.06/m^3$). The purity of the recovered salt increased to between 91.0 and 98.7%, meeting the first-grade industrial salt standard and supporting the practical implementation of zero liquid discharge (ZLD) systems (Liu et al. 2025). Energy efficiency continues to be a major goal, and developments such as solar-assisted UV-driven processes and energy recovery techniques in electrochemical systems will aid in operating cost reduction. However, scalability is a major concern and moving from lab-scale to field applications requires consideration of maintenance, economy of scale, and adaptation to different compositions of wastewater. Such cases emphasize the efficacy and versatility of different AOPs in treating rubber industry effluents. Successful large-scale implementation, however, requires site-specific adaptations, technology optimization, and rigorous economic feasibility studies (Ullah et al. 2023; Zhang et al. 2025; Tin et al. 2025). (b) Ozonation and UV/O_3 processes: treatment of rubber wastewater using UV, ozone, and UV/ozone combinations showed that the

Fig. 11 **a** Efficient treatment of rubber wastewater by electrochemical oxidation (zero liquid discharge) (reprinted with permission, Copyright 2025, American Chemical Society) (Liu et al. 2025). **b** Schematic diagram for the hybrid processes for rubber wastewater treatment (reprinted with permission, Copyright 2025, Elsevier) (Sanongarj et al. 2025)



UV/ozone combination was the most efficient technique on account of its higher reaction rate constant. The mixture enhanced pollutant degradation of the wastewater (Hadiyanto et al. 2020). A separate study explored the treatment of natural rubber industry wastewater, using a combination of physicochemical and ozonation processes. Ozonation as a post-treatment process subsequent to physicochemical processes was the focus of this study and was utilized to evaluate its efficacy (Massoudinejad et al. 2015). (c) Fenton and photo-Fenton processes: the treatment of rubber industry wastewater was studied by using Fenton's reagent and the adsorption of activated carbon. Optimization of Fenton reagent molar ratios (pH, reaction time) for chemical oxygen demand (COD) degradation. Meanwhile, in the study by Agustina et al., the combination of Fenton reagent and activated carbon reduced the COD to 71 mg/L, which is already below the environmental quality standards in Indonesia (Agustina et al. 2017). Figure 11b illustrates the schematic of the

combined processes used for rubber wastewater treatment, and in this setup, 1 L of the prepared wastewater was placed into a 2-L flask. Fenton reagents were added at the specified dosage rates, and the ozone was supplied from an ozone generator. Air was supplied to the generator via a pump equipped with a flow meter, allowing precise control of the ozone dose by adjusting the airflow. After each predetermined contact period, the treated water samples were collected for subsequent quality analysis (Sanongarj et al. 2025).

Advanced Oxidation Processes for Rubber Industry Wastewater Treatment give insightful trends on the hybrid approaches which achieved better performance than the independent processes because the combined method can have detected both degradable and non-degradable contaminants (Ullah et al. 2023). Table 3 presents a collection of studies highlighting the performance of different AOP techniques, their effectiveness in treating rubber industry wastewater.

Table 3 The reported applications of AOPs for treating rubber industry wastewaters

Case study	Location	Objectives	AOP process used	Pollutants treated	Results	Reference
Treatment of rubber wastewater using UV, ozone, and UV/ozone combinations	Thailand	Examine the efficiency of UV, ozone, and their combination on treating rubber wastewater	UV, Ozone, UV/Ozone	VOCs, COD	UV/ozone obtained the highest pollutant removal efficiency in relation to other technologies	(Hadiyanto et al. 2020)
Physicochemical and ozonation treatment of natural rubber industry wastewater	Malaysia	Investigate combined ozonation and physicochemical treatments of rubber processing wastewater	Physical–chemical methods, ozonation	COD, Color, phenolic compounds	Reduction of COD and color by 85%; wastewater with enhanced quality for reuse	(Massoudinejad et al. 2015)
Application of mechanical technologies in water treatment wastewater	Worldwide research	Application of AOPs in decolorization and detoxification	Various AOPs	Color, toxic organics	Good removal of hard pollutants; useful results for treating rubber wastewater	(Azbar et al. 2005)
A review of the treatment of rubber industry wastewater: recent advances and future prospects global	Worldwide research	Investigate the hybrid methods of AOPs	AOPs, Hybrid treatments	COD, VOCs, Phenolic compounds	Focus on the advantages of hybrid AOP-biological systems	(Ho et al. 2023)
Advanced oxidation processes for water and wastewater treatment	Global (review)	Summarised several AOPs for treatment of industrial wastewater and operational parameters	Ozonation, photocatalysis	Others COD, VOCs, persistent pollutants	Emphasized energy-efficient AOP designs and scaling potential to industry	(Hübner et al. 2024)

Remediation using hybrid integrated AOP approaches and their advantages

Hybrid advanced oxidation processes (AOPs) combine multiple oxidation techniques to boost pollutant removal efficiency. The inherent synergism of hybrid and integrated systems corresponds to the coupling of AOP processes with biological, physical, or chemical treatments, for enhancing the efficiency of wastewater treatment, lowering the cost, and improving pollutants removal efficiency. The complementary processes for these systems overcome the technical drawbacks of AOPs, such as energy-intensive operation, non-complete mineralization, and secondary sludge generation. For instance, the recent approaches that combine AOPs and biological treatments promote the AOPs' decomposition of toxic or non-biodegradable pollutants into simpler, biodegradable intermediates that microorganisms can further degrade. These techniques have been widely investigated, and common combinations in engineered systems are ozonation-activated sludge, Fenton-anaerobic digestion, and UV/H₂O₂-membrane bioreactors (MBR). Ozone pre-treatment followed by biological activated sludge treatment demonstrated an increase in removal of chemical oxygen demand (COD) from rubber industry wastewater due to degradation of difficult-to-degrade organics (Rizzo et al. 2019). Moreover, the combination of AOPs with physical treatments such as adsorption or filtration can also improve the efficiency of treatment by removing suspended solids, reducing the turbidity of secondarily polluted water, and thus enhancing the penetration of light, which benefits UV/H₂O₂ combined with ultrafiltration membranes to treat textile wastewater (Miklos et al. 2018a). AOPs remove dissolved organics, while coagulation with alum or ferric chloride or similar chemical treatment is often used with AOPs to remove suspended solids. An example of this success is the combination of Fenton oxidation and coagulation-flocculation, which has been shown to effectively remove heavy metals and persistent organic pollutants from industrial wastewater while reducing treatment time and sludge generation (Gillpavas et al. 2017). By combining the strengths of each treatment method, these integrated systems offer a greater comprehensive and effective way of treating wastewater. The combination of AOPs with biological, physical or chemical treatments is an innovative strategy to effectively mitigate the respective limitations of stand-alone AOPs. It is the only efficient step to the operation to improve some advantages insofar as treatment efficiency and performed in the same line of there for a broader target of pollutants with increasing of total organic carbon (TOC) removal and beyond with-about (COD) and biological oxygen demand (BOD) reduction (Asheghmoalla and Mehrvar 2024). A

recently reported hybrid system utilized a PVDF-based membrane embedded with a MoS₂/WO₃ photocatalyst, acting as a dual-function (synthetic system) for the removal and degradation of rubber wastewater pollutants. The setup begins with a feed tank that holds the polluted water inside and it is attached to a pump that pushes this water into the membrane module (membrane illuminated by a visible light lamp). Pressure gauges help regulate the flow as well as the pressure during this treatment operation. Clean water that passes through the membrane is collected in a permeate tank, and the resulting modified membrane showed outstanding performance (high photocatalytic degradation and strong self-cleaning behavior). The membrane exhibited an initial permeate flux of 100.66 L·m⁻²·h⁻¹, achieving removal efficiencies of 98.77% for COD, 94.30% for TDS, and 96.66% for NH₃-N. The membrane also maintained stable performance over 10 h of continuous filtration under illumination, indicating reliable long-term usability (Kusworo et al. 2023). Overall, this reported study highlights the strong potential of synergetic approaches to treat heavily polluted natural rubber wastewater as shown in Fig. 12. Furthermore, hybrid systems can be more economical, since they allow for energy and chemical consumption reduction as pollutant breakdown in sequential treatment steps is optimised. Generally speaking, biologicals after AOP pre-treatment are cheaper, and improve the complete cost effectiveness of the system (Asheghmoalla and Mehrvar 2024; Deng and Zhao 2015). A second prominent advantage is the lower sludge production, wherein the combined physical and chemical methods with AOPs can minimize sludge production compared to these processes when used alone such as coagulation or Fenton oxidation (Asheghmoalla and Mehrvar 2024; Deng and Zhao 2015).

Table 4 shows key examples of industrial applications of hybrid systems, combining advanced oxidation processes with other treatment technologies, to improve wastewater treatment efficiency.

Additionally, hybrid systems provide greater stability in processes, since hybrid treatment relies on a multi stepped treatment process which makes it more robust to variations in wastewater composition. This enhanced biodegradability leads to a higher bio-mass production in a two-step biological method however AOPs will serve as a treatment method to remove toxic compounds and improve biodegradability of the treated wastewater prior to biological treatment (Kasprzyk-Hordern et al. 2003; Qasim et al. 2026). Overall, hybrid systems combining AOPs with various treatment technologies offer a more sustainable and adaptable approach for treating complex industrial effluent, including rubber wastewater. Continued exploration of process optimization, reactor design, and energy efficiency will only add to the efficacy and

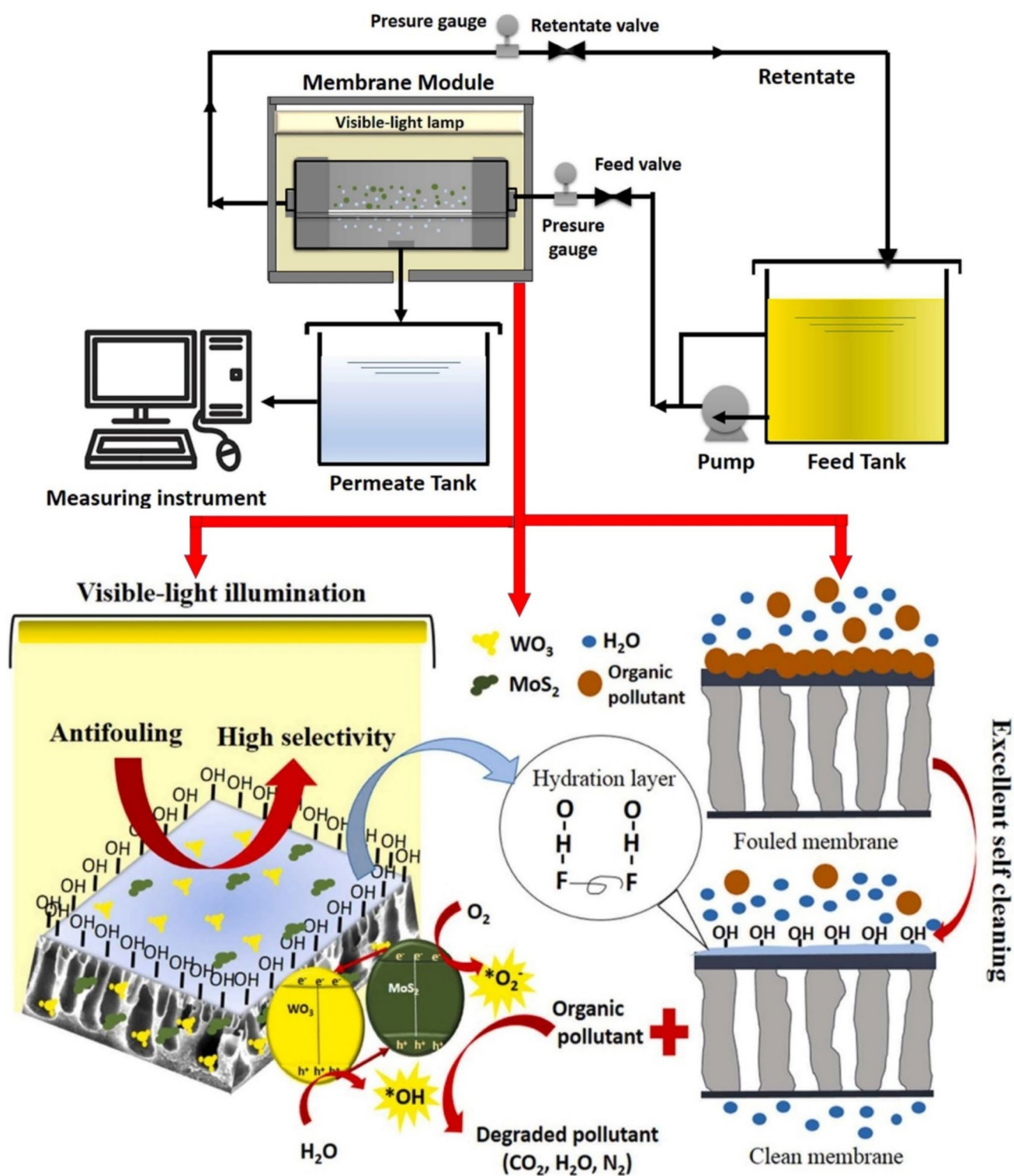


Fig. 12 Schematic of a visible-light-driven photocatalytic membrane filtration system and its self-cleaning performance for pollutant-burdened natural rubber wastewater treatment (reprinted with permission, Copyright 2023, Elsevier) (Kusworo et al. 2023)

Table 4 Important hybrid systems applied in treating wastewater

Hybrid system	Application	Results	References
Ozonation + biological activated sludge	Pulp and paper mill effluent treatment	80% COD reduction and lignin derivatives removal	(Kasprzyk-Hordern et al. 2003)
UV/H ₂ O ₂ + membrane bioreactor (MBR)	Pharmaceutical wastewater treatment	High elimination of pharmaceutical contaminants, meeting the release parameters	(Rizzo et al. 2019)
Activated carbon + Fenton	Rubber industry wastewater	Removal of COD, suspended solids, organic pollutants, improved biodegradability and efficiency	(Agustina et al. 2017)
Ozonation + sequential batch reactor	Textile wastewater treatment	98.6% color removal and 91.6% COD removal with improved biodegradability	(Mohan and Oke 2022)

scalability of these systems to meet the needs of larger scale applications.

Innovations in AOPs technologies, process modeling, and artificial intelligence (AI)

Progress on AOPs has recently been oriented towards efficiency, costs, and expanding pollutants that can be treated. Among them, the Electro-Fenton process is an attractive innovation that integrates electrochemical oxidation and the conventional Fenton reaction to produce hydroxyl radicals ($\bullet\text{OH}$) for the degradation of contaminants. Recent advances in this regard include carbon-based electrodes and electrocatalysis that improve electron transfer and minimize energy consumption (Guo et al. 2024). The photocatalytic systems, especially those operating in the ultraviolet (UV) region, have been optimized with novel visible-light-active photocatalysts and composite systems, commonly between TiO₂. Recent adverts include photocatalytic membranes, where photocatalysts are encapsulated into filtration systems to enable in-situ contaminant removal (Zhang et al. 2023). Nanomaterials are also another important kind of innovation in ozone-based AOPs. Ozone reactivity and efficacy can be increased with the use of nanostructured catalysts like graphene and metal oxides, which can promote the degradation of persistent organic pollutants (Merchant et al. 2024; Cardoso et al. 2021). Recent advancements are also seen in the Sono-Fenton process which integrates sonication with Fenton chemistry. Recently low-frequency ultrasound has been employed to enhance cavitation and radical generation, increasing the global performance of the process (Serna-Carrizales et al. 2024). Hybrid AOPs, in particular combinations of ozone, hydrogen peroxide, and UV light, have been proven effective in breaking down a diverse range of contaminants, including pharmaceuticals and endocrine-disrupting compounds. To reduce the formation of harmful by-products, researchers have developed hybrid systems to

accelerate pollutant degradation (Cao et al. 2023; Fedorov et al. 2022). To generate more hydroxyl radicals for electrochemical AOPs (E-AOPs), new electrode materials have been explored, including boron-doped diamond electrodes, which are more sustainable alternatives to post-treatment wastewater treatment (Ganiyu et al. 2021). Also, biological-AOP hybrid systems, combining biological treatments with AOPs, have proved to be a complementary and promising solution. AOPs are employed to minimize the toxicity in a pre-treatment before biological approaches that can further degrade residual contaminants (Ponnusami et al. 2023). Lastly, the invention of electro-ozonation systems that generate ozone in situ through electrochemical cells has enabled researchers to design more effective reactors with low-cost, long-life materials, facilitating the use of on-site ozone generation for wastewater treatment (Das et al. 2024). These advancements collectively reflect the evolution and optimization of AOPs, rendering them more effective, economically feasible, and increasingly applicable to diverse environmental issues. Artificial Intelligence (AI) is emerging as an incredibly effective tool to optimize AOPs. Using historical data (Alsabt et al. 2024) to leverage ML (machine learning) algorithms for the prediction of optimal conditions for treatment (pH, dosage, and retention time), moreover, this predictive capability allows the design of treatment processes to be more efficient and tailored to specific treatment scenarios, reducing the risk of trial-and-error experiments and lowering operational costs. Process simulation tools such as MATLAB, Aspen Plus, and COMSOL Multiphysics are being employed to simulate reactor behavior, which optimizes design while reducing the need for expensive pilot-scale experiments (Serna-Carrizales et al. 2024). Through predictive modeling, real-time monitoring, and control systems are progressively becoming part of AOPs (Akintola 2024). The Internet of Things (IoT) offers real-time data collection from AOP reactors (chemical oxygen demand (COD), total organic carbon (TOC) and turbidity), which plays

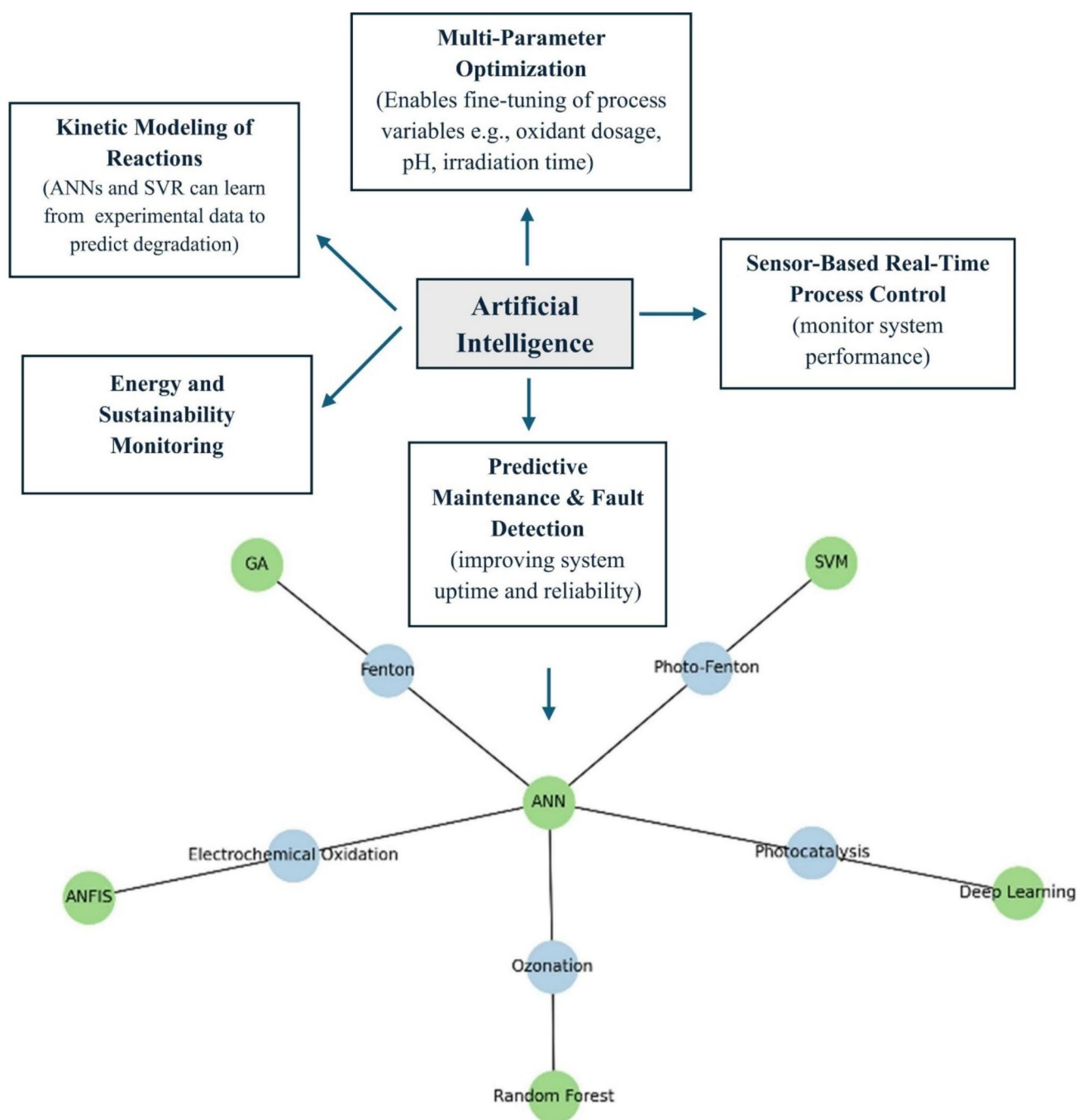


Fig. 13 A conceptual framework illustrating artificial intelligence (AI) integration within AOP-based wastewater treatment and the mapping of AOP techniques with suitable AI models (reprinted with permission, Copyright 2025, Elsevier) (Reyhan 2025)

an important role in real-time dynamic adjustments of the process (Aghasadeghi et al. 2018). Artificial intelligence (AI) has strengthened the optimization of AOP-based treatment, and a recently reported paper in the literature highlights how AI supports process optimization (kinetic modeling, pollutant degradation prediction, and real-time operational control). A conceptual framework depicting

the integration of AI into AOP-based treatment is shown in Fig. 13. The efficiency is further improved with the intelligent use of AI-driven automation, which automatically adjusts operational parameters to real-time data (Nagpal et al. 2024). Furthermore, artificial intelligence (AI) is employed for predictive maintenance, wherein AI systems predict potential failures and optimize system maintenance

schedules to reduce downtime and ensure continuous operation (Vicente et al. 2024).

Disadvantages of AOPs for rubber sector effluent treatment

AOPs are novel technologies and have a great potential for the degradation of complex pollutants in the rubber industry wastewater via the generation of highly reactive radicals (hydroxyl radicals ($\bullet\text{OH}$)) (Sanongarj et al. 2025; Wang and Xu 2012). While such methods have been found to be effective, several challenges hinder their large-scale industrial implementation. One of the most limiting factors is the high operational cost, which is mainly caused by energy-consuming processes like UV/ H_2O_2 , UV/ O_3 and electrochemical oxidation systems that are based on energy demand systems like UV lamps and ozone generators (Nabeel et al. 2025a; Ahmad et al. 2025b). Miklos et al. indicated that the energy consumption is responsible for more than 60% of total operating costs in UV-based AOPs. Another challenge is the continuous need for hydrogen peroxide (H_2O_2), which has a limited shelf life. Moreover, the employment of expensive reagents like ozone, and catalysts including TiO_2 increases costs as well. Fenton-based approaches need to introduce chemical agents in constant quantities, such as iron salts and pH-modifying substances, increasing economic expenditures (Miklos et al. 2018a; Ali et al. 2023). Moreover, expensive H_2O_2 and ozone reagents and catalysts, such as TiO_2 , further add to the costs. Processes based on Fenton also require the continuous addition of chemicals such as iron salts and pH-adjusting agents, which increases operating costs, and the generation of secondary pollutants can be another limitation (Zheng et al. 2013; Agabo-García et al. 2023). Fenton oxidation generates large amounts of iron-based sludge that demand safe disposal, whereas ozonation may lead to the formation of cancer-inducing by-products such as bromates. According to Von Gunten et al., the optimization of process parameters is crucial to minimize the formation of by-products during ozonation (Von Gunten 2003). Scalability and industrial feasibility also present challenges. Full-scale implementation must overcome several challenges that are not as apparent at the laboratory scale, such as the design of reactors with precise parameters, online monitoring of the process, and the need to have uniform UV irradiation (Visan et al. 2019). This emphasizes the importance of kinetic modeling for the scale-up photocatalytic reactor design. Furthermore, most existing AOP systems focus on batch processes that are not suitable for continuous treatment of industrial wastewater (Russo 2021; Braham and Harris 2009). The modular designs of these reactors make them more scalable, but that comes at a high up-front cost to the companies. The AOPs' efficiency is highly dependent on wastewater characteristics. High COD,

turbidity, and suspended solids can limit the penetration of UV and generation of radicals, thus decreasing the treatment efficiency. The conventional Fenton process has major limitations. Also, the pH sensitivity of many AOPs results in processes such as Fenton's demanding low pH (pH 2–4), requiring that acids be added to alkaline wastewater while increasing costs as well as producing additional sludge. It produces $\bullet\text{OH}$ only under very acidic conditions. It can harm aquatic systems that can lead to iron sludge formation, making large-scale use costly. The reaction is also slowed by the sluggish conversion (Fe^{3+} to Fe^{2+}), and reducing degradation (Khan et al. 2024). Rizzo et al. emphasized the influence of the components of the wastewater matrix on the efficiency of AOPs. Although they are effective, there are many limitations associated with these techniques that prevent their widespread adoption such as (i) high energy consumption, (ii) chemical costs, (iii) secondary pollution issues, (iv) scalability, and (v) sensitivity to wastewater characteristics. In the future, evaluation of solar-driven AOPs, combination of AOPs with biological or membrane systems, reactor design optimization, and catalytic degradation and process enhancement to minimize reactant consumption are key topics of research in developing future energy-efficient AOPs (Rizzo et al. 2019). These advances may render AOPs more economically favorable and sustainable for large-scale industrial use.

Future road of AOPs for the treatment of the rubber industry wastewater

As technology continues to evolve, particularly in fields such as catalyst development and energy efficiency, coupled with the integration of Artificial Intelligence (AI) into treatment systems and supportive policies promoting sustainable practices, AOPs in wastewater treatment offer a promising outlook. These advancements seek to improve the sustainability, cost-effectiveness, and widespread utilization of AOPs, especially in industries like rubber processing that encounter complex wastewater treatment issues.

Advanced Oxidation Processes (AOPs) are a potential solution for treating industrial wastewater such as those produced in rubber processing, benefiting both the environment and the economy. Yet, these mechanisms need to be pursued in the right balance of ecological benefits, economic viability and public policy subsidies. AOP-treated effluents have various environmental advantages. They enable the elimination of Persistent Organic Pollutants (POPs), such as toxic phenols, heavy metals, and compounds from rubber processing, complying with environmental regulations governing effluent discharge (Miklos et al. 2018b). AOPs additionally enhance the reusability of water, with treated effluents suitable for reuse in industrial processes, decreasing water consumption and preserving freshwater sources

(Garrido-Cardenas et al. 2020). Additionally, AOPs have been demonstrated to minimize greenhouse gas emissions relative to conventional processes, because they prevent methane emissions which can occur with anaerobic biological treatments, and give solar-driven AOP systems as a more sustainable alternative to energy-intensive traditional UV systems (Arzate et al. 2019). The improvement of secondary pollution, i.e., sludge production, is also less in the case of AOP systems, which are cheaper and easier to handle compared to the massive sludge from conventional treatment systems (Arzate et al. 2019).

Depending on the nature and size of the rubber processing facility, the economic feasibility of AOP implementation is influenced by operational characteristics of the rubber processing facility. The capital and operational costs for AOP systems, including UV reactors or ozone generators, prove challenging for small-scale industries. Reagents such as hydrogen peroxide and catalysts are also expensive, leaving other industries with no option amid a shortage of expertise. Small-scale solutions also involve solar-driven or modular AOP systems, which help decrease capital expenses, and a shared treatment facility to save on costs (Ho et al. 2023). On the other hand, the large-scale industries enjoy economies of scale, in which the costs of treatment per unit are minimized due to increased volumes of treatment. AOPs can be combined with other biological or chemical treatments, which can improve efficiency across industries, delivering long-term cost savings and greater return on investment (ROI) due to lower environmental fines, the possibility of water reuse and better regulatory compliance. A large rubber processing plant that implemented a hybrid AOP-biological system observed a cumulative 60% decrease in operating costs (Ho et al. 2023).

For mass-scale implementation of AOPs, favorable policy frameworks are critical, especially for the rubber-processing industries. Governments globally are realizing the significance of AOPs for industrial wastewater treatment and are adopting policies to facilitate their usage. Pollutant discharge standards (COD, BOD, heavy metals), therefore, can motivate industries to employ AOPs in order to comply with them. Another trend is the increasing adoption of zero-liquid discharge (ZLD) policies, which compel industries to treat their wastewater to the extent that no liquid waste is discharged often making advanced oxidation processes (AOPs) an attractive option in industrial wastewater treatment.

The future of AOPs in wastewater treatment is going to be driven by technology evolution in the areas of catalyst development, energy efficiency and AI-based solutions as evident in all industries including rubber processing. In addition, the development of efficient catalysts, low-energy conversion processes such as plasma-assisted and solar-driven AOPs, and the coupling of biological treatments or membranes to AOPs will enhance the sustainability and reduce

the cost of wastewater treatments (Priyadarshini et al. 2022; Qasim et al. 2025). Moreover, through the integration of AI and the application of process modeling, getting real-time steering, predictive maintenance, and dynamic adjustments of new AOPs will turn into an easy, simple, quick reality, effectively dealing with the demand-planner challenges. Encouraging development and adoption of AOPs based on favorable policy frameworks, such as regulatory standards, financial incentives, and industrial certifications will be essential to unlocking AOPs' potential. With increasing investments in these technologies from governments and industries, along with support from R&D, AOPs will play a core role in wastewater treatment strategies across many sectors. With the potential of combining advanced technologies and demonstrating sustainability through a supportive policy framework, AOPs can address the environmental burdens in the industries while ensuring the economic viability of wastewater treatment technologies.

Governments in various countries have long underpinned the adoption of Advanced Oxidation Processes (AOPs) through various incentives, and the USA government may consider enabling similar incentives at Federal level to support the early adoption of proven technologies whilst maintaining flexibility that encourages innovation. These include research and development grants that promote the development of environmentally friendly wastewater technologies and assist industries in moving towards greener practices. Infrastructure grants are also available to assist in constructing treatment plants applying AOPs, alleviating the financial impact of advanced treatment system implementation (Muñoz et al. 2008; Mohajerani et al. 2009). Tax incentives are also at play, in the form of environmental tax credits and carbon credit programs that reward industries for implementing low-emission or sustainable technologies, thereby lessening the financial burden on companies investing in AOPs. Generally speaking, such government incentives not only overcome financial boundaries, but they also promote green practices as well as technological innovation that makes AOPs a more potential and commonly integrated treatment for various industries.

In turn, green financing programs and public-private partnerships (PPPs) offer concessional loans and collaborative funding opportunities for large-scale wastewater treatment projects (Meridian Micro Technology). In another dimension, regulatory support is one of the biggest incentives, as the government provides industries with compliance-based rewards such as certifications or reduced regulatory charges when AOPs are implemented that meet tight environmental criteria. Noteworthy global examples of such support are the European Union's Horizon 2020 program that supports research and innovation projects covering several areas such as wastewater treatment technologies, for instance, AOPs; the Indian Ministry of Environment,

Forest, and Climate Change grants that provide funding for projects that develop zero-liquid-discharge technologies to ensure environmentally sustainable wastewater management; and the U.S. Environmental Protection Agency's (EPA) Clean Water State Revolving Fund (CWSRF), which offers low-cost financing for water quality infrastructure projects, including projects that use advanced treatment technologies (Haugen 2014; Anica 2023).

To improve the sustainability of the natural rubber sector, Global Platform for Sustainable Natural Rubber has developed a policy framework aimed at improving sustainability within the natural rubber sector. This framework promotes sustainable practices, such as the use of more advanced treatment technologies to improve the environmental problems. Eco-certifications (ISO 14001 environmental management standard) can be awarded to companies applying advanced wastewater treatment technologies. Another avenue for incentivizing AOP implementation, particularly within large-scale industrial applications, involves the adaptation of public-private partnerships (PPPs). Partnerships can help share the financial burden and offer technical guidance for the wider implementation of AOP systems. Research and development (R&D) support is also essential for AOP technologies to keep on progressing. Funding from governments and private entities can be used to carry out R&D work to advance economical and energy-efficient AOP systems. International conferences and research forums are examples of knowledge-sharing platforms that support exchanging examples of best practices and technological advances to enhance global adoption.

Conclusion

This study employed the technique (AOPs) for the rubber industry, which contains persistent organic pollutants, heavy metals, and toxic chemicals, which are environmental hazards. Advanced oxidation processes (AOPs) have proved to be a potential solution in this regard due to their ability to mineralize various recalcitrant compounds, decolorize, reduce chemical oxygen demand (COD) and biological oxygen demand (BOD). AOPs offer several advantages over traditional methods including the capability of treating a wide variety of industrial effluents (phenols, sulfides, and aromatic hydrocarbons in rubber processing wastewater), environmental friendliness and low carbon emissions. Fenton and photo-Fenton processes, ozonation, UV/H₂O₂ photolysis, electrochemical AOPs (EAOPs) and hybrid systems, which show potential in rubber industry wastewater treatment, are discussed in detail in this review. Heterogeneous processes like Fenton and photo-Fenton enhance biodegradability of high COD wastewater, ozonation removes color and toxicity, and UV/H₂O₂ targets

phenolics, especially with membrane filtration. Though AOPs are standalone systems, they do not work in isolation and should be paired with biological or physical treatments in hybrid systems for optimal mass transfer, as has also been discussed in detail. Future research should emphasize the engineering of energy-efficient catalysts and renewable AOP systems, and industrial involvement in pilot-size schemes and commercialization of contemporary AOP reactors would be a necessity. AI and machine learning will be used for the optimization of processes and predictive maintenance, which will further increase efficiency. Research, investment and cross-sector collaboration will be essential to ensuring AOPs become a mainstream solution for achieving sustainable and environmentally compliant industrial wastewater management.

Acknowledgements This research was supported by the Ministry of Higher Education Malaysia (Project code: FRGS/1/2024/STG04/UMS/02/3) in collaboration with the Research Management Center of Universiti Malaysia Sabah (Project Code: FRG0641-1/2024) and is gratefully acknowledged. The authors extend their sincere appreciation to Tuaran Crumb Sdn Bhd, Kampung Sungai Damit, Tuaran 89200, Sabah, for their generous facilitation of knowledge exchange and sampling activities.

Author contribution ZU: wrote the manuscript; CGJ: funding acquisition, wrote the manuscript, supervision; ZYT, SHT., JAG., RS: wrote and edited the manuscript, interpretation of data; KA and PS.: data collection, acquisition and interpretation of data, wrote the manuscript; AKA., MNK., and MSI: wrote and edited the manuscript.

Funding This work received funding from project code: FRGS/1/2024/STG04/UMS/02/3.

Data availability Our manuscript has no associated data.

Declarations

Ethical approval This is not applicable.

Consent to participate This is not applicable.

Consent for publication This is not applicable.

Competing interests The authors declare no competing interests.

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