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MAIN LIMITATIONS OF THE APPLICATION OF ADVANCED OXIDATION PROCESSES IN THE TREATMENT OF WASTEWATER FROM THE PETROLEUM REFINING INDUSTRY

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Advanced oxidation processes (AOPs) have attracted considerable attention in recent years for the treatment of petroleum refinery wastewater, mainly because of their ability to degrade persistent organic pollutants. Despite this, their practical application at an industrial scale remains limited. This review discusses the main factors that restrict the performance of AOPs in real wastewater systems. Particular emphasis is placed on the effects of wastewater composition, including radical scavenging, variability of the matrix, and the presence of complex organic and inorganic constituents. In addition, issues such as incomplete mineralization and the formation of potentially toxic by-products are highlighted. Operational challenges, including high energy and chemical consumption, pH sensitivity, and catalyst-related limitations, are also addressed. While combining AOPs with other treatment methods can improve overall efficiency, such approaches often increase process complexity and cost. Overall, further research is needed to better understand process behaviour under real conditions and to support the development of more practical and scalable treatment strategies.

Keywords: petroleum wastewater, advanced oxidation processes, catalytic oxidation, hydroxyl radical

INTRODUCTION

Petroleum production and refining processes result in the generation of large volumes of wastewater. These wastewater effluents contain free and emulsified oil, various petroleum hydrocarbons, phenols, benzene, toluene, ethylbenzene, xylene, ammonia, sulfides, and heavy metals, as well as various dissolved organic and inorganic substances [1-2]. The composition of such waters is highly complex and variable. If not treated properly, these effluents can exhibit high toxicity, low biodegradability, and cause serious environmental problems. Conventional physicochemical and biological treatment methods, such as oil–water separation, coagulation–flocculation, and activated sludge systems, often show limited efficiency in the removal of persistent organic pollutants. Furthermore, these technologies may require high capital and operating costs [3-4].

In recent years, interest in advanced oxidation processes (AOPs) such as Fenton and photo-Fenton, electro-Fenton, H_2O_2/UV systems, ozonation, heterogeneous photocatalysis, and persulfate-based AOPs has increased significantly. These processes generate reactive

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oxygen species, including hydroxyl radicals, sulfate radicals, and superoxide radicals, in the reaction medium. Due to their high oxidation potential, these radicals enable the rapid degradation of various organic pollutants [5-6]. Numerous studies on petroleum wastewater have demonstrated that, under optimized conditions, Fenton-based processes, electrochemical oxidation, photocatalysis, ozone-based AOPs, and persulfate-based AOPs can reduce chemical oxygen demand (COD) and phenolic compounds by more than 90%. Therefore, these systems are considered promising methods for the treatment of petroleum wastewater [7], [8].

They are particularly effective in degrading the persistent organic fraction that is difficult to remove by conventional methods [9-10]. Nonetheless, despite numerous laboratory studies conducted over the past decades, only a limited number of AOPs have reached the pilot- or industrial-scale application stage [11-12].

In the petroleum sector, the application of these techno logies remains limited. Previous studies demonstrate that many AOPs are associated with high energy consumption and chemical usage, strict pH requirements, and catalyst-related challenges. At the same time, the lack of standardized experimental conditions makes it difficult to compare results across studies and to apply them at an industrial scale [13].

Furthermore, high salinity, suspended solids, surfactants, and complex organic compounds commonly present in petroleum wastewater further affect process performance. These components promote radical scavenging by influencing radical formation and reaction mechanisms, thereby reducing overall process efficiency. This review analyses the main limitations and challenges associated with the application of AOPs for the treatment of petroleum wastewater. Based on the existing literature [14-15], the discussion focuses on limitations related to wastewater composition and reaction mechanisms, as well as technical challenges at the process and reactor levels.

EXPERIMENTAL

This review was prepared by evaluating published studies examining the application of AOPs in the treatment of petroleum refinery wastewater. Relevant publications were identified from the Scopus, Web of Science and Google Scholar databases. The literature review primarily covered studies published between 2020 and 2025. However, earlier publications that provided fundamental information on the field were also included. The literature review used the following search terms: 'petroleum refinery wastewater', 'advanced oxidation processes', 'Fenton', 'photo-Fenton', 'electro-Fenton', 'ozonation', "photocatalysis", 'persulfate oxidation', 'industrial wastewater', 'process limitations' and 'scale-up'. The studies identified through the review were selected for detailed evaluation based on their focus on the treatment of petroleum refinery wastewater. The information obtained was analysed taking into account the main factors limiting the performance of advanced oxidation processes, such as the effects of the wastewater matrix, incomplete mineralisation, process-specific limitations, economic consideration and challenges related to large-scale applications. The key findings from the studies reviewed are summarised in Table 1, which outlines the main limitations regarding the application of advanced oxidation processes in the treatment of petroleum refinery wastewater.

RESULTS AND DISCUSSION

Influence of complex wastewater matrices

AOPs can be applied in the treatment of wastewater for various purposes. In some cases, these treatment techniques are used as an additional treatment step to remove recalcitrant organic matter remaining after primary or secondary treatment. In other cases, their purpose is to increase the biodegradability of the wastewater and enhance the effectiveness of subsequent biological treatment or membrane filtration processes.

Furthermore, AOPs can also be integrated into hybrid systems combined with adsorption, membrane technologies, or biological processes [16]. When applied to real petroleum wastewater, the efficiency of these oxidation processes often differs from the results obtained under laboratory conditions. This discrepancy is primarily attributed to the complex and variable composition of wastewater, as well as fluctuations in operational conditions.

Radical scavenging and competitive reactions

In petroleum wastewater, various components such as bicarbonate, carbonate, chloride, bromide ions, natural organic matter, and surfactants can be present at high concentrations [2, 6]. These substances can react with hydroxyl and sulfate radicals, reducing the number of radicals available for the oxidation of target pollutants. Studies on industrial and petroleum refining wastewater indicate that the effectiveness of the treatment process is dependent on the water matrix. High salinity, dissolved anionsand various organic substances can weaken radical-based oxidation processes and alter the reaction mechanism [7,9]. For example, chloride and bromide ions can react with hydroxyl radicals, leading to the formation of less reactive halogen radicals [8].

Furthermore, high concentrations of organic carbon can also react with radicals, competing with target contaminants and reducing the effectiveness of the process. Elevated ionic strength and multivalent cations can significantly influence treatment performance. These factors affect ozone solubility, catalyst surface charge, and particle aggregation, as a result, higher oxidant doses and longer reaction times are required.

Variability and heterogeneity of petroleum wastewater

Refinery and produced water do not have a uniform and constant composition. The composition of these waters can vary depending on the type of crude oil, the refining processes applied, and the chemicals used, such as corrosion inhibitors and demulsifiers, as well as the process conditions. Studies have shown that the effectiveness of AOPs is significantly dependent not only on the characteristics of the target pollutants but also on the overall chemical composition of the wastewater matrix. As a result, it is not always possible to apply process parameters optimised for one petroleum refinery in the same way at other plants.

Process control systems must be able to adapt to changes in wastewater composition and pollutant load. Furthermore, when designing pilot- and industrial-scale systems, certain safety margins are often incorporated to ensure stable and effective process performance. This can lead to increased chemical consumption and energy consumption. The highly variable composition of the wastewater makes reactor design and real-time process control more complex. At the same time, this factor also gives rise to concerns about the long-term reliability of AOPs for large-scale treatment of petroleum wastewater.

Incomplete mineralization and by-product formation

AOPs can demonstrate high efficiency in reducing COD and removing specific pollutants. Nevertheless, AOP-based systems do not always result in the complete mineralization of organic matter to CO_2 and H_2O. In many cases, various intermediate oxidation products are formed during treatment. Studies on industrial effluents and petroleum wastewater, particularly produced water, show that AOPs can degrade dissolved hydrocarbons and phenolic compounds.

However, depending on process conditions, the formation of more polar and sometimes more toxic by-products is also possible. Studies indicate that two main problems are of particular concern when applying AOPs.

Firstly, transformation products, especially in complex petroleum wastewater, are often not fully characterised or accurately quantified.

Secondly, the toxicity and biodegradability of the treated effluent and intermediate products remain insufficiently assessed. The presence of aromatic hydrocarbons, heterocyclic compounds, and surfactants in petroleum wastewater can lead to the formation of aldehydes, organic acids, and other oxidation products during partial oxidation. If no further treatment is applied after this stage, these intermediate products may remain in the treated wastewater.

Consequently, even if COD or colour reduction appears satisfactory, residual toxicity may persist, creating challenges in meeting regulatory requirements. Therefore, recent studies recommend routine toxicity testing and the analysis of by-products when applying AOPs.

Challenges in the application of AOPs

Fenton and Photo-Fenton Processes

Advanced Fenton-based oxidation processes are considered one of the most extensively researched methods for the treatment of petroleum refining and industrial wastewater. Under optimal conditions, these methods can achieve a high degree of COD and phenol removal. Nevertheless, the practical application of Fenton processes is accompanied by a number of limitations. One of the most significant of these limitations is the very narrow optimal pH range required for the process [8].

The conventional Fenton reaction is typically most effective in the pH 2–4 range. However, petroleum wastewaters are often neutral or mildly alkaline, while the pH of production waters is in most cases close to 8 [13]. Consequently, when applying the Fenton process, the pH of the wastewater must first be lowered by adding acid, and after the process is complete, it must be neutralised again.

These stages not only increase chemical consumption but also raise corrosion risks and lead to the formation of additional sludge. The generation of sludge is considered one of the main problems of Fenton processes. Homogeneous Fenton systems generate iron-containing sludge, which requires subsequent dewatering and disposal. In particular, the volume of sludge generated during the treatment of petroleum refining wastewater can be substantial, creating an additional solid waste problem.

The correct maintenance of the Fe^{2+} and H_2O_2 balance is also of great importance for the process's effectiveness. An excess of iron ions increases the amount of sludge; conversely, a deficiency of iron weakens the generation of radicals and reduces the treatment efficiency. The recovery and reuse of iron in complex petroleum wastewater systems is considered technically challenging.

The use of hydrogen peroxide can also create additional difficulties. In many cases, high doses are required, but H_2O_2can decompose in the presence of metals and other components, reducing the process's effectiveness. Furthermore, the large-scale storage and transport of high-concentration hydrogen peroxide pose certain safety risks. In certain cases, the Photo-Fenton process can allow for an expansion of the pH range and a further enhancement of radical generation.

This process also has a number of limitations. Photo-Fenton systems typically require a higher iron dosages, and the application of reactors with sufficient UV or solar radiation is necessary for the process to operate effectively. Nevertheless, the high turbidity, colour, and suspended solids often present in petroleum wastewater limit light penetration into the water and can consequently reduce the overall effectiveness of the Photo-Fenton process.

Ozonation and Ozone-Based AOPs

Ozone and its various combinations, such as O_3/H_2O_2, O_3/UV, and catalytic ozonation systems, are widely used for the oxidation of dissolved organic pollutants, including polycyclic aromatic hydrocarbons and phenols, in petroleum wastewater, particularly in produced water. Although AOP-based systems have demonstrated high efficiency in many cases, there are certain limitations in their practical application. These problems are mainly related to the technical characteristics of the process and the complex composition of the wastewater [17-18].

One of the main problems is the low solubility of ozone and the limited transfer from the gas phase to the liquid phase. This is particularly evident in saline and high-viscosity wastewater. Under such conditions, ozone dissolution and its effective transfer into the reaction medium are slow.

Consequently, higher energy consumption is required to ensure process efficiency, and the use of reactors designed to improve gas–liquid mass transfer becomes necessary. Furthermore, ozone can undergo self-decomposition under certain conditions or react with matrix components such as bicarbonate, bromide ions, and surfactants. These interactions reduce the amount of ozone available for effective oxidation.

At the same time, high bromide concentrations in produced water increase the risk of the formation of bromate and other regulated by-products. To overcome these limitations and enhance radical generation, combined ozonation processes, such as O_3/H_2O_2 and catalytic ozonation systems, have been proposed. However, such approaches increase process complexity. The effective operation of these systems requires precise optimisation of process parameters and continuous monitoring.

Heterogeneous Photocatalysis and Uv-Based AOPs

Heterogeneous photocatalysis such as TiO_2, ZnO and UV/H_2O_2 systems are considered promising AOPs as they do not require the use of additional metal reagents and do not produce sludge. Nevertheless, a number of limitations arise during the practical application of these treatment strategies. One of the main problems is related to light penetration. Petroleum wastewater is often characterised by high turbidity, colour, and the presence of suspended solids.

These factors significantly attenuate the penetration of UV and visible light into the aqueous medium, thereby limiting not only photon availability but also the depth of light penetration within the reactor. Another significant challenge is associated with the separation and recovery of the catalyst. For photocatalysts used in suspension, such as TiO_2, it is necessary to separate fine catalyst particles from the wastewater after the process is complete. This necessitates the application of additional stages such as filtration or sedimentation, thereby increasing the overall complexity of the process.

Although immobilised catalysts can partially address this problem, such systems may lead to issues such as mass transfer limitations and a reduction in active surface area. Fouling and catalyst deactivation are also significant problems in the application of photocatalytic processes. Oil residues, surfactants, scaling, and metal precipitates, which are common in petroleum wastewater, can block active sites and lead to a decrease in catalytic activity over time.

This results in reduced process performance and increased maintenance requirements. Energy consumption is another significant factor that limits the application of these technologies. UV systems based on mercury lamps, in addition to high energy consumption, require regular replacement.

Although UV-LED and vacuum UV technologies offer improved efficiency, their application in petroleum wastewater, which has high light absorption, is still at an early stage of development. For example, a recent study on the treatment of petroleum wastewater using a $TiO_2/UV/H_2O_2$ system showed that under optimised laboratory conditions, approximately 98–99% pollutant removal was achieved within 40 minutes [7]. It should be noted that the wastewater was pre-emulsified and tested under controlled laboratory conditions. The industrial-scale application of such results to real, variable-composition petroleum wastewater remains uncertain.

Advanced Electrochemical Oxidation Processes and Electro-Fenton

In electrochemical oxidation and electro-Fenton processes, reactive radicals are generated as a result of reactions occurring at the electrode surface or through the decomposition of reagents. Laboratory studies have shown that these methods can provide high removal efficiency with relatively low energy consumption in terms of reducing COD in petroleum wastewater. However, the practical application of these technologies is accompanied by a number of limitations.

One of these limitations relates to the cost and durability of the electrode materials used. Although materials such as boron-doped diamond electrodes and dimensionally stable anodes possess high oxidant potential, they can face durability issues under conditions such as high salinity, scaling, and electrode surface fouling. Furthermore, the use of such materials can require high capital expenditure.

Another significant challenge is the risk of the formation of intermediate oxidation products. In chloride-rich produced water, electrochemical oxidation can lead to the formation of chlorate, perchlorate, and other oxidative by-products. Another significant challenge encountered during the implementation of the process is the precise control of the electric current and the provision of a stable power supply.

These factors directly affect electrical energy efficiency (EE/O) and overall process performance. At the same time, the suspended solids and oil droplets present in the wastewater can cause the electrode surface to passivate, which can restrict mass transfer processes. The electro-Fenton process also encounters problems inherent to the classic Fenton process to a certain extent. These include factors such as pH control, iron dosing, and sludge formation. In this process, iron can be added as a reagent or generated in situ within the system as a result of electrochemical reactions.

Advanced Persulfate-Based Oxidation Processes

The activation of persulfate and peroxymonosulfate results in the formation of sulfate radicals and other reactive species. The selectivity and sensitivity of these radicals to the chemical composition of wastewater differ from those of hydroxyl radicals. It is precisely these properties that make persulfate-based systems promising technologies for the treatment of complex industrial wastewater [19]. Comparative studies in recent years have shown that persulfate-based radical systems can ensure the effective degradation of pollutants within a short contact time. Nevertheless, these systems are sensitive to radical scavengers present in the wastewater and often require high oxidant dosages to maintain process effectiveness. Non-radical mechanisms, such as the generation of singlet oxygen or reactions involving surface-activated persulfate, are considered to be less sensitive to the influence of water constituents.

However, these processes are typically characterised by a lower reaction rate and may require higher energy consumption per unit of pollutant removal. The presence of high salinity and complex organic matter in petroleum wastewater, particularly in produced water, can further complicate the activation mechanism of persulfate. Furthermore, in some cases, issues such as catalyst leaching, selective reactivity toward certain functional groups, and the formation of sulfonated intermediate products may arise. The relatively high cost of persulfate reagents and the logistical challenges associated with their use in wastewater treatment are also among the factors that can limit the practical application of this technology [17].

Economic and environmental challenges

High Energy and Chemical Consumption

One of the main factors limiting the widespread industrial application of AOPs is the high consumption of energy and chemicals. This consumption is particularly associated with the energy requirements of UV irradiation, ozonation, and electrochemical systems, as well as the use of oxidising agents, pH-regulating reagents, and various catalysts [8, 15]. Review studies indicate that in many laboratory-scale investigations, good purification results are achieved by applying high oxidant dosages, intensive irradiation, or long reaction times [8], [11-12].

However, in these studies, energy consumption and reagent use are often not sufficiently evaluated and a comparative analysis with other treatment methods is not conducted. In the treatment of petroleum wastewater, particularly in produced water streams, the large flow volumes and the continuous presence of pollutants can lead to an increase in overall process costs. Indicators such as EE/O and specific oxidant usage show that additional optimisationmeasures are required for the economically efficient industrial application of many AOPs [12, 17].

Furthermore, the application of pre-treatment and post-treatment stages, such as filtration, adsorption, or biological polishing, leads to a more complex overall treatment system, thereby increasing the overall operating costs [9-10].

Secondary pollution: sludge, catalysts and by-products

As previously discussed, homogeneous Fenton and similar processes are associated with the generation of large amounts of sludge, which requires further handling and disposal. In heterogeneous systems, catalysts such as metal oxides or supported nanoparticles may lead to the leaching of metals into the treated water or may require periodic replacement or regeneration. Review studies also indicate that some newly developed catalysts for AOPs may pose additional risks in terms of toxicity or resource sustainability. In many cases, their long-term stability and behavior under real wastewater conditions have not yet been sufficiently investigated [11, 15].

Furthermore, the formation of various transformation products and halogenated by-products may occur during the oxidation process. These may include compounds such as bromate and chlorate, as well as potentially nitrosated compounds in nitrogen-containing waters. Such risks are particularly relevant in waters rich in chloride and bromide ions. The presence of these secondary pollutants can create environmental and regulatory challenges that cannot be ignored [20].

Addressing these risks requires comprehensive risk assessment and careful monitoring. In many cases, the implementation of additional treatment stages, such as filtration, adsorption, or biological polishing, is necessary to ensure process safety. However, these additional stages not only increase the complexity of the overall treatment system but also lead to higher operational costs.

Scale-up, reactor design, and process control

A major issue discussed in AOP research is the gap between laboratory studies and real pilot- or full-scale applications. Many review papers point out recurring limitations in current experimental approaches. Most laboratory studies are carried out in ideal batch reactors using synthetic wastewater. This does not fully reflect real industrial conditions or the actual composition of wastewater. Furthermore, crucial information such as oxidant dosages, energy consumption, and water quality parameters is often not presented in a complete and systematic manner. Consequently, it becomes difficult to compare the results of different studies and to assess the feasibility of applying these treatment strategies on an industrial scale. In addition, the selected pollutants and process performance metrics used in some studies may not fully represent real wastewater mixtures, particularly the complex composition of petroleum wastewater [21].

At the reactor level, a number of additional challenges arise during the treatment of oil wastewater. For example, the presence of oil droplets and emulsions in ozone- and UV-based reactors can lead to problems such as fouling and surface coating. Furthermore, in turbid and coloured wastewaters, it is difficult to ensure an even distribution of light within the reactor for the effective operation of UV and photocatalytic processes.

The large flow volumes in production effluents can also make it difficult to ensure sufficient contact time and effective mixing [22]. In addition, the operational management of modern oxidation processes in oil refineries is considered complex.

This is primarily associated with frequent variations in the composition and flow rate of the wastewater. Such variable conditions require the implementation of advanced monitoring and automation systems to ensure stable and effective process operation. Nevertheless, such systems are not yet widely implemented in the industry [1].

Integration with other processes and benefits

Hybrid and combined treatment systems are often proposed to overcome the existing limitations of AOPs. These approaches include combining AOPs with biological treatment, membrane technologies, and adsorption processes, as well as the combined application of electro-oxidation and photocatalysis [23]. The application of such integrated systems during the treatment of petroleum wastewater, particularly produced water, can offer a number of advantages.

For example, when AOPs are used as a pretreatment step, they increase the biodegradability of the wastewater, reduce toxicity, and can consequently enhance the efficiency of subsequent biological treatment processes. Furthermore, AOPs can also be applied as a further treatment stage to remove residual organic matter after biological treatment and to meet the discharge or reuse requirements of the wastewater. Combining AOPs with adsorption may help to increase the removal rate of pollutants and reduce the amount of oxidant dosagesused.

The combined application of electro-oxidation and photocatalysis in laboratory studies has led to a higher COD removal and relatively low energy consumption than when each process is used alone. Nevertheless, the application of integrated systems also presents new challenges. Such approaches increase the complexity of the overall process and require advanced control strategies due to the presence of multiple treatment stages. There are some process risks associated with AOPs, mainly due tocross-interference between different treatment steps.

For example, intermediates formed during AOP-based treatment can inhibit subsequent biological activity, and residual catalysts or degradation by-products may lead to membrane fouling [25]. Another issue is the lack of pilot-scale studies that provide long-term performance data and cost–benefit analyses for petroleum wastewater treatment. In addition, there are still limited design tools and decision-making approaches available in the literature for selecting and optimizing hybrid systems for specific conditions. Although integrated systems are considered promising, techno-economic and environmental evaluations under real refinery conditions are still quite limited [25].

As summarised in Table 1, the limitations of AOPs in petroleum wastewater treatment include matrix effects, process-specific constraints, economic challenges, and integration-related issues.

Table 1. Key categories of limitations of AOPs in petroleum wastewater treatment

Limitation category	Specific issues in petroleum wastewater	References
Matrix effects	Radical scavenging by salts/TOC, high salinity, variability, emulsions	[1],[2],[3]
Incomplete mineralization	Formation of unknown/toxic intermediates, limited toxicity data	[5],[6]
Fenton-type constraints	Narrow pH, sludge, iron handling, H_2O_2 safety	[4],[10],[15]
Ozone systems	Mass-transfer limits, scavenging, bromate, off-gas handling	[8],[12]
Photocatalysis/UV	Light attenuation, catalyst separation/fouling, energy demand	[7],[14]
Electrochemical/PS	Electrode cost/durability, halogenate by-products, energy, PS cost	[19]
Economics & scale-up	High EE/O, oxidant use, limited pilot data	[11],[13]
Integration challenges	Process complexity, cross-interference, limited long-term data	[12], [18]

The studies reviewed demonstrate that AOPs are highly effective in removing recalcitrant organic pollutants found in oil refinery effluents. High removal efficiencies for COD, phenolic compounds and petroleum hydrocarbons have been reported under laboratory conditions. However, the same performance is not always achieved in the treatment of real petroleum refinery wastewater.

One of the main reasons for this is the complex composition of petroleum refinery wastewater. Dissolved organic matter, inorganic ions, suspended solids, surfactants and emulsified oils compete with the target pollutants for reactive radicals. As a result, the amount of radicals available for oxidation decreases and the treatment efficiency reduces.

Another significant limitation is the lack of complete mineralisation. Whilst many AOPs are effective at breaking down parent pollutants, it is not always possible to convert them entirely into carbon dioxide and water. Consequently, intermediate oxidation products may remain in the treated effluent, and the potential toxicity of these products must be assessed alongside pollutant removal.

Each AOP also has its own specific operational limitations. Fenton oxidation requires acidic conditions and produces iron-containing sludge. Ozonation is limited by mass transfer of ozone and can lead to the formation of bromate in waters containingbromide. Photocatalytic systems are affected by insufficient light penetration and catalyst fouling, whilst electrochemical oxidation may be limited by the degradation of electrodes over time and high operating costs. Persulphate-based systems, whilst possessing significant potential, have performance that is largely dependent on the composition of the wastewater and the activation conditions.

Economic feasibility is also highlighted in the literature as a challenge. Whilst many laboratory-scale studies report high treatment efficiencies, information regarding energy consumption and operating costs is often limited. These factors become even more important when assessing the industrial-scale applicability of these processes.

To overcome these limitations, many studies have proposed the use of AOPs in combination with biological treatment, adsorption or membrane filtration. Such hybrid systems can enhance overall treatment performance whilst reducing oxidant consumption. However, they also increase process complexity and require further evaluation under real operating conditions.

Future directions

Recent studies focusing on petroleum wastewater and AOPs highlight several important research priorities for future development. First and foremost, the application of standardised experimental methods is considered crucial to facilitate the comparison of results from different studies and to more accurately assess the suitability of data obtained under laboratory conditions for industrial application. Furthermore, conducting more pilot-scale studies using real petroleum wastewater could help to determine the effectiveness of laboratory results under practical conditions. At the same time, a more detailed investigation of the by-products generated during the process and their toxicity is of critical importance. Research in this area could also play an important role in assessing the environmental safety of AOPs. Another important direction is the development of catalyst and electrode materials that are resistant to fouling and high salinity.

CONCLUSION

AOPs are considered one of the most effective methods for the degradation of persistent organic pollutants in petroleum wastewater and have demonstrated high removal efficiency under laboratory conditions. The large-scale application of these technologies in the petroleum industry is accompanied by a number of limitations. These limitations include the influence of wastewater composition, the formation of intermediate and by-products, high energy and chemical consumption, the risk of secondary pollution, and technical challenges associated with industrial application. The high salinity, complex organic compounds, and emulsified oil of petroleum wastewater further complicate the application of such methods. Combining AOPs with biological treatment, membrane filtration, or adsorption methods can mitigate some of these problems. Nevertheless, the industrial-scale application of such systems has not yet been fully investigated. The future development of AOPs largely depends on conducting experimental research under conditions that closely resemble real-world scenarios. Furthermore, the in-depth study of reaction mechanisms and the toxicity of transformation products, as well as the development of selective catalysts and reactor designs for oily and highly saline waters, is of particular importance. Overcoming these limitations could enable the future application of AOPs as a more reliable and economically viable technology for the treatment of petroleum wastewater.

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