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Advanced Catalytic Oxidative Processes and Multivariate Physicochemical Analysis integrated with Machine Learning and IoT for Wastewater Treatment

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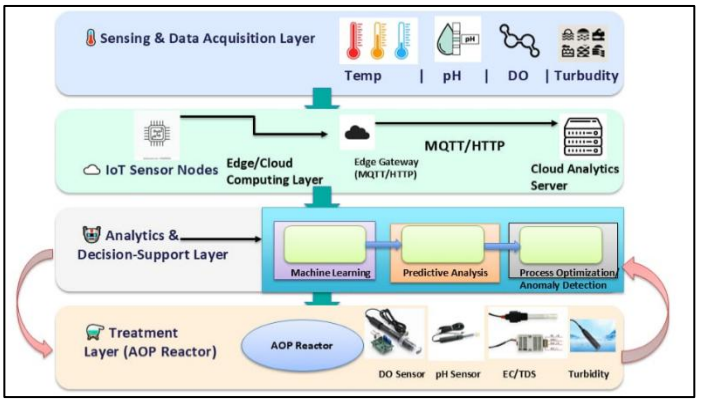
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Abstract

High level of anthropogenic pollution in the groundwater can negatively impact both aquatic organisms and human health. Worldwide population relies on groundwater and poor waste disposal practices and industrial effluents worsen this vulnerability. This article will focus on the assessment of advanced catalytic oxidative processes (AOPs) and multivariate (MV) physicochemical analysis for wastewater management. The combination of multivariate analysis tools and ACOPs like ozonation, UV oxidation, and catalytic oxidation offers a comprehensive strategy to address water quality issues. Among the key areas that require further research to enhance the impact and effectiveness of treatment, the critical aspects that stand out are catalyst preparation and optimization techniques. However, several technical and financial issues require more policy intervention and effective management. The potential areas that can open the way for the enhancement of the processes and the achievement of the sustainable management of wastewater include machine learning, IoT and other modern technologies. The integration of machine learning (ML), Internet of Things (IoT), multivariate (MV) physicochemical analysis, and advanced catalytic oxidative processes (ACOPs) enables continuous monitoring of wastewater quality predictive identification of pollutant behaviour, intelligent optimization of treatment conditions, and efficient degradation of emerging contaminants.



Collectively, these technologies improve treatment efficiency, reduce energy and chemical consumption, minimize anthropogenic pollution, and support sustainable environmental and public health protection. Hence there is a need for a comprehensive, evidence-based strategy to address the growing and concerning issue of groundwater pollution along with the formulation of well-structured strategies for sustainable management of the resource.

Keywords: Waste water remediation; Multivariate analysis; Advanced oxidation; Catalytic processes; Machine Learning; IoT and Sustainability

1.Introduction

Rapid industrialization, urbanization, population growth and intensive agricultural practices have significantly increased the discharge of complex and persistent pollutants into aquatic systems. wastewater containing pharmaceuticals, dyes, pesticides, personal care products, endocrine-disrupting compounds, per- and polyfluoroalkyl substances (PFAS), microplastics, and toxic heavy metals. . Their persistence in aquatic environments poses serious risks to ecosystems, biodiversity, and public health, thereby necessitating the development of more efficient, sustainable, and intelligent wastewater treatment technologies.

Conventional wastewater treatment technologies including coagulation-flocculation, sedimentation, activated sludge, membrane filtration, adsorption, and biological oxidation, have demonstrated satisfactory performance for the removal of suspended solids and biodegradable organic matter. These methods are often insufficient for the complete removal of emerging contaminants because of incomplete mineralization, membrane fouling, excessive sludge production, high operational costs, and poor adaptability to rapidly changing wastewater compositions.

Among the available advanced technologies, **Advanced Catalytic Oxidative Processes (ACOPs)** have emerged as one of the most promising approaches for wastewater remediation.. (Ania et al., 2020). The inclusion of integrated multivariate physicochemical analysis in ACOPs will provide information necessary for the identification of the contaminant type and the ACOP's specified requirements for treatment measures (Solomon et al., 2020). ACOPs can also offer the most beneficial and economical treatment results, using less energy than the traditional techniques and norms which will help in overcoming the new problems arising in the effluent management (Park et al., 2017). Moreover, applying other analytical tools enables monitoring of the treatment processes as well as the utilization of water resources in the most optimal manner, the ideas concerning the issue of rational use of water (Holkar et al., 2016).

In this context, advanced catalytic oxidative processes (ACOPs) have emerged as highly effective and versatile techniques capable of generating reactive oxygen species for the mineralization of refractory organic pollutants. These processes, including photocatalysis, Fenton and photo-Fenton reactions, ozonation, and electrochemical oxidation, provide a promising route toward sustainable and efficient water purification.

However, the performance of ACOPs strongly depends on a wide range of physicochemical parameters such as pH, temperature, catalyst dosage, oxidant concentration, and pollutant composition. The complexity and interdependence of these variables necessitate the use of multivariate physicochemical analysis for accurate interpretation, optimization, and prediction of treatment efficiency. Statistical and chemo metric tools such as principal component analysis (PCA), cluster analysis (CA), and response surface methodology (RSM) enable comprehensive evaluation of water quality data, identification of key controlling factors, and intelligent process optimization.

The integration of Internet of Things (IoT) technologies into wastewater treatment systems offers an additional transformative advantage. IoT-based sensors and real-time monitoring platforms enable continuous acquisition of water quality parameters, remote process control, and data-driven decision making.

When combined with multivariate analysis and catalytic oxidation processes, IoT frameworks can significantly enhance operational efficiency, reduce energy consumption, and ensure consistent treatment performance under dynamic environmental conditions.

This review focuses on the synergistic integration of advanced catalytic oxidative processes with multivariate physicochemical analysis and IoT-enabled monitoring systems for next-generation wastewater treatment. It highlights recent developments, key mechanisms, analytical methodologies, and technological advancements, while also discussing current challenges and future research directions toward achieving smart, efficient, and sustainable water purification systems (Sharma et al 2023). The principal objective of this review is to propose an integrated framework that supports the development of next-generation smart, sustainable and data-driven waste water treatment systems

2. Methods for wastewater treatment

2.1 Traditional methods

Conventional treatment processes are used to address wastewater quality issues. These methods involve critical physicochemical parameter evaluations for determining the extent of groundwater pollution resulting from human activities (Garrido-Cardenas et al., 2019). Emerging wastewater treatment (WWT) technologies, such as advanced oxidation processes, membrane filtration techniques, microbial electrolysis cell technologies, which are currently in the development and deployment stages, have also been discussed (Sangamnere et.al.2023). Notably, the parameters including dissolved oxygen, total dissolved solids, and pH are still being used in present-day water quality testing, which confirms the importance of conventional methods in the assessment of water contamination and prevention (Drioli et al.,2011). Furthermore, the use of interdisciplinary approaches corresponds with the universal nature of previous methods, stressing the need to include various analytical and ecotoxicological points of view in evaluating the effectiveness of the treatment (Kleiber & Nychka, 2012). AOPs are promising technologies for partial or complete mineralization of contaminants of emerging concern by highly reactive hydroxyl, hydroperoxyl, superoxide, and sulphate radicals(**Priyadarshin et.al.2022).**

2.2 Limitations of conventional treatment processes

Advancements in the understanding of extensively used wastewater treatment processes have highlighted the limitations of traditional techniques, leading to the search for more effective alternatives. Although various chemical and physical treatment methods yield considerable results, they are ineffective for the removal of CECs and POPs from contaminated water (Mantzavinos et al., 2009). Traditional treatment methods are energy-intensive and usually generate large volumes of sludge, which requires further treatment. In addition, they are inefficient against antibiotic-resistant bacteria, heavy metals, and endocrine-disrupting compounds, which raises concerns about secondary pollution. The constant increase in pollutants resulting from human activity and industrial emissions also presents a significant challengefor sewage treatment technologies to overcome (Henry et al.,2019). For instance, the need to increase the efficiency and coverage of removal of these long-standing and numerous pollutants indicates the need for ACOPs that can address and remove an expanded range of contaminants found in wastewater (Cassano et al., 2001). Thus, the combination of physicochemical analysis along with ACOPs can be viewed as the most efficient method to develop future innovative technologies for the treatment of wastewater and generate successful outcomes in their treatment (Rueda-Márquez et al., 2015). Conventional wastewater treatment plants struggle to eliminate contaminants of emerging concern (CECs), heavy metals (HMs), and Escherichia coli (*E. coli*) owing to their small size, persistence, and complex nature(Matesun et.al 2024). Newer methods, such as advanced oxidation, ultraviolet disinfection, membrane bioreactors, reverse osmosis, artificial intelligence optimization, and nanofiltration, which enhance contaminant removal but may incur high costs and energy demands(Shamshad et.al.2024).

Nanofiltration considered as the boon for treating the wastewater with a dye removal efficiency achieved to be 98%. The removal efficiencies by exploring AOPs vary 45–100% for specific contaminants but, increase the energy consumption cost by 60–150% (Shah et. al. 2020)

2.3 Need for advanced oxidative processes

Advanced oxidation processes(AOP) have been extensively incorporated into conventional wastewater treatment technologies due to their prowess in the degradation of nondegradable pollutants (Tickner et al.,2020).Conceptual framework is proposed to illustrate integration points between AI techniques and AOP mechanisms, including kinetic moeling, multi-objective optimization, pollutant-specific degradation, and real-time system control(Reyhan Ata 2025) .AOPs, such as Titanium dioxide/UV light and Fenton's reagent, are utilized due to their capability to generate highly reactive free radicals, such as hydroxyl radicals (•OH), which proficiently degrade pollutants via oxidative degradation within a short reaction time.The presence of AOPs in combination with traditional treatment processes enhances the ability to deal with challenges concerning contaminants in wastewater (Athanasopoulos & Athanasopoulos, 1998). This paper seeks to establish a systematic account of how AOPs act as catalysts and show oxidative properties in order to address the challenges posed by discharged effluents into the environment. AOPs depict current innovations in the waste management industry that need to be expanded through further research and adaptation to innovative technologies in approaches (Trache et al., 2020).). AOP technologies, including Fenton processes, ozone-based AOPs, persulfate-based AOPs, photocatalytic AOPs, electrochemical AOPs, and sonochemical AOPs, by optimizing AOP technologies, the deep mineralization of harmful substances in wastewater can be achieved, reducing the potential pollution risks to groundwater and soil.(**Zheng et.al.2025**) Catalysts play a pivotal role in improving the efficiency and selectivity of AOPs; however, challenges such as poor stability, secondary pollution, and limited large-scale applicability remain major concerns(Zhu et.al.2026).

2.4.Multi variate physicochemical analysis

In the context of wastewater treatment, the key focus is made on the multifaceted area of physicochemical analysis as well as the application of advanced catalytic oxidation processes (Shao et al., 2022). These analytical techniques and treatment strategies play a crucial role in monitoring and managing the composition and pollution levels of the water resources of the area, ensuring better water quality.(Raafat & Sahl, 2009). Multivariate physicochemical analysisenables the comprehensive scrutinization of different factors that influence water quality; meanwhile, the ACOPs offer innovative solutions for the degradation and removal of pollutants (**Figure 1**).

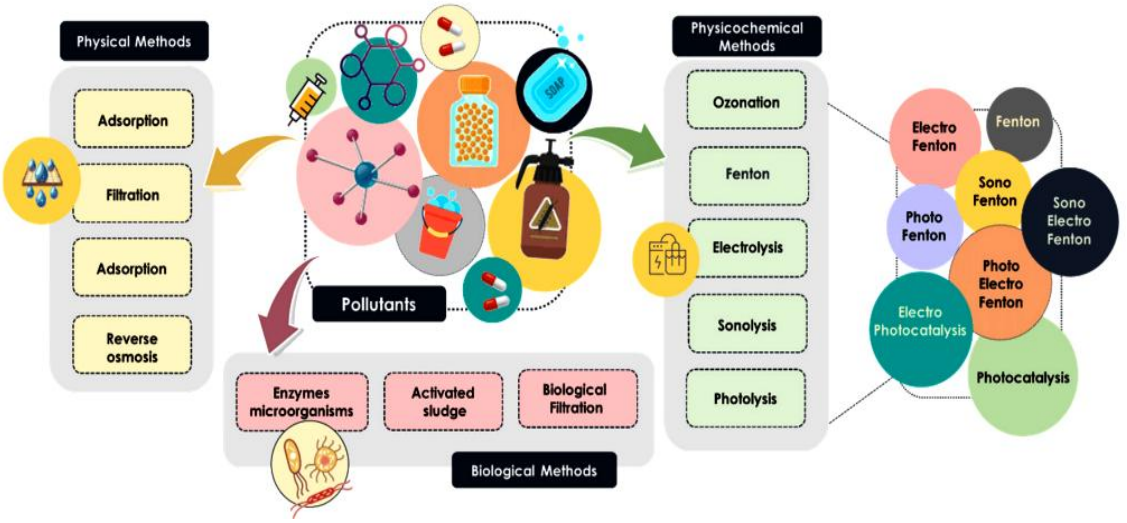


Figure 1. Multivariate Analysis (MV) of Wastewater by Different Methods.

In this approach, the scientific components are combined in a systematic manner considering all the stages of the wastewater treatment process (Hu et al., 2014). Therefore, the application of the new approaches to treatment along with the analytical accuracy of the model makes this one more efficient for the enhancement of the environment and health status of the population. The information discussed in the cited literature, together with the emphasis on the systematic approach to the physical and chemical diagnosis and development of new strategies, is in line with the objectives of this highly systematic academic study (Dasgupta et al., 2015).

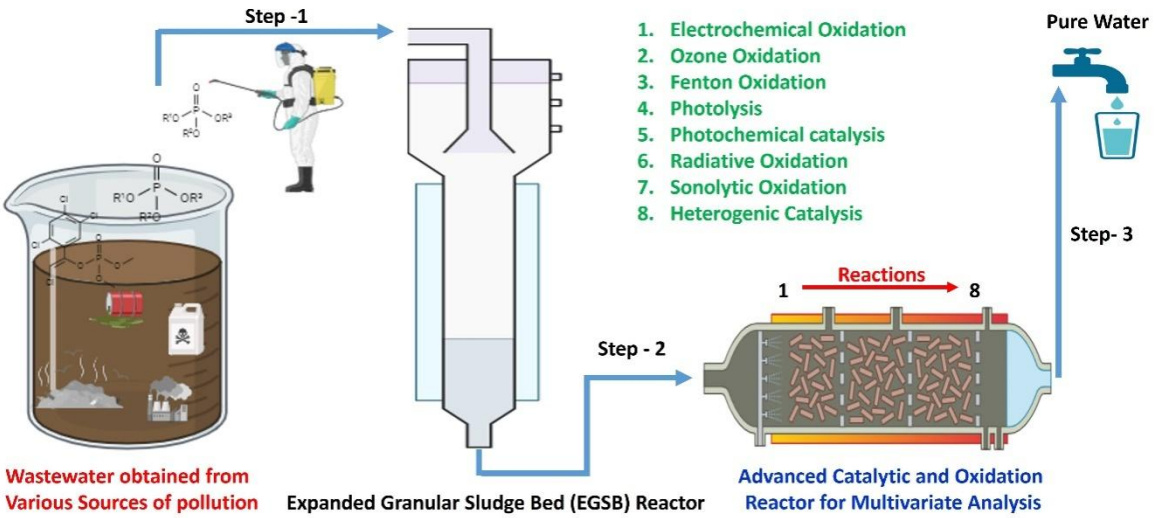


Figure 2: Three Step treatment for Wastewater by ACOP & MV Process

Various existing wastewater treatment technologiesrequire improvement in terms of efficiency and ecologicalsustainability. Chemical water index (CWI), as a quantitative metric provides a broad picture of

water quality based on certain parameters including Ph, COD, BOD, etc. but does not give information about the specific treatment needed for remediation of the contaminated water. Multivariate analysis of water quality parameters reveals the relationship between the parameters and helps in the determination of the specific treatment required for improving water quality (Genovese et al., 2017). The integration of ACOPs and MV process into the treatment system enhances the efficiency of pollutant removal and is more suitable for the removal of relatively modern pollutants (**Figure 2**).

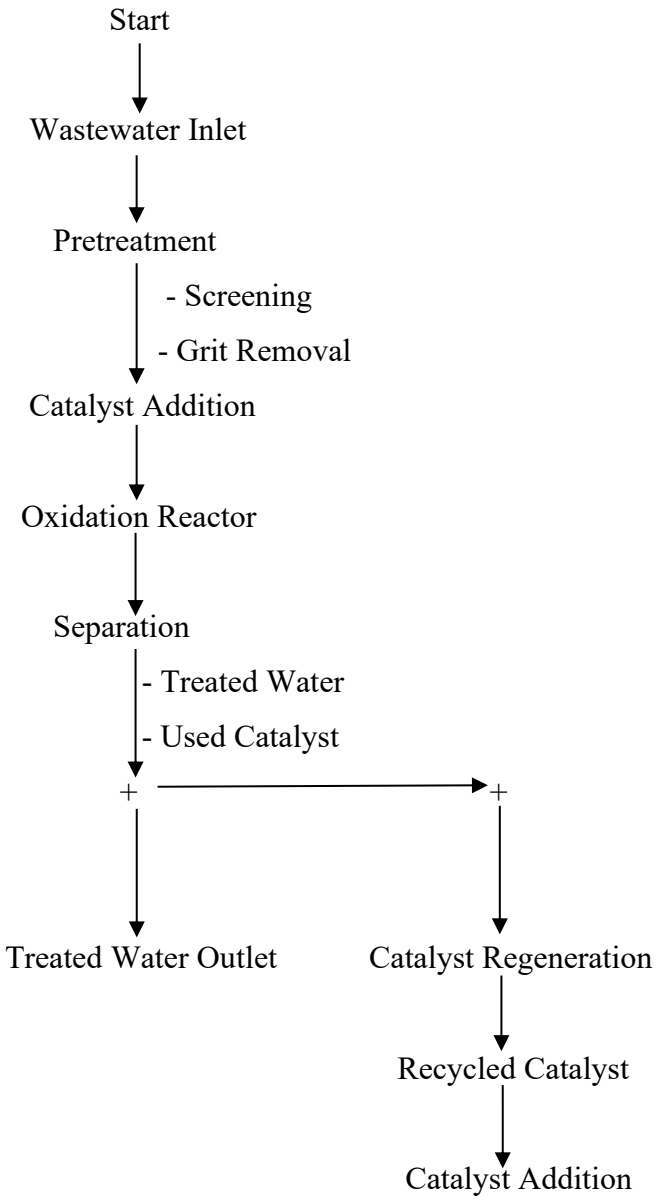


Figure 3.**Flow Chart of Wastewater Treatment using ACOPs Technique**

The oxidizing character of these reactions makes the treatment method more selective and efficient (Li, 2010). Apart from contributing to the enhanced degradation of pollutants, the intensive physicochemical analysis in

conjunction with the advanced catalyticoxidation methods will also be of great importance in formulating efficient and holistic strategies towards wastewater treatment in the region, thereby improving the health of the aquatic environment (Serfling, 2002). Flow chart showing the process of waste water treatment using ACOPs technique is mentioned in **figure 3.**

3. Advanced catalytic oxidative processes and Analytical methods

AOPs and Multivariate Physio-chemical analysis are significant components of methods used in wastewater treatment to solve water quality problems. The availability of new tools and a deeper understanding of wastewater processes also mean that the efficiency of water quality measurements and hence, the decisions made in wastewater management, are improved (Chen et al., 2016). These methods work hand in hand to solve various factors that affect the content of wastewater and the levels of pollutants (Rojas-Cervantes & Castillejos, 2019). Such tools are however important in the sense that they help in gaining additional information on the sources of pollutants, their relationships as well as the effectiveness of the remediation technologies that would enable adequate and effective restoration (Comninellis et al., 2008). The principles and the performance objectives presented in these methods indicate the need for further research to improve the efficiency of the wastewater treatment systems in order to minimize the chances of polluting the environment and posing health risks to people Boucher & Friot (2017).

3.1. Advanced catalytic oxidation process in degradation of organic pollutants

Advanced catalytic oxidation processes (ACOPs) have emerged as highly efficient and environmentally sustainable techniques for the removal of persistent organic and inorganic pollutants from water and wastewater systems. These processes are primarily based on the in-situ generation of highly reactive species, such as hydroxyl radicals (•OH), sulfate radicals ($SO_4•^-$), and superoxide radicals ($O_2•^-$), which possess strong oxidation potentials and are capable of non-selectively degrading a wide range of contaminants into harmless end products such as CO_2, H_2O, and inorganic ions.The fundamental principle of ACOPs involves the activation of oxidants such as hydrogen peroxide (H_2O_2), persulfate ($S_2O_8^{2-}$), or peroxymonosulfate (PMS) using suitable catalysts, including metal oxides, transition metals, and nanostructured materials. Among these, heterogeneous catalysts have gained significant attention due to their high surface area, stability, and reusability (Sharma et al 2023).

Catalytic activation leads to the formation of reactive oxygen species (ROS), which initiate a series of oxidation reactions, ultimately resulting in the mineralization of complex pollutants.For organic pollutants such as dyes, pharmaceuticals, pesticides, and endocrine-disrupting compounds, ACOPs effectively break down complex molecular structures through radical-driven pathways. The degradation typically proceeds via hydroxylation, dealkylation, ring-opening reactions, and eventual mineralization. In contrast, inorganic pollutants such as heavy metals are not degraded but are transformed into less toxic or more easily removable forms through redox reactions. For example, toxic Cr(VI) can be reduced to the less harmful Cr(III), facilitating its precipitation and removal.Recent advancements in nanotechnology have significantly enhanced the efficiency of ACOPs.

Nanostructured catalysts, including metal oxides (e.g., TiO_2, ZnO, Fe_3O_4), carbon-based materials, and hybrid composites, provide improved catalytic activity due to their high surface-to-volume ratio, enhanced active sites, and superior electron transfer capabilities. Additionally, doping and heterojunction formation have been widely employed to improve charge separation efficiency and extend light absorption in photocatalytic systems.Among various ACOPs, photocatalysis, Fenton and photo-Fenton processes, and sulphate radical-based oxidation have been extensively studied.

Photocatalytic systems utilize light energy to excite electrons, generating electron–hole pairs that participate in redox reactions. Fenton-based processes rely on Fe^{2+}-mediated decomposition of H_2O_2 to generate hydroxyl radicals, while sulphate radical-based systems offer higher selectivity and stability over a broader pH range.Despite their advantages, ACOPs face certain challenges, including catalyst deactivation, limited efficiency under real wastewater conditions, and the potential formation of intermediate by-products. Therefore, ongoing research is focused on developing robust, low-cost, and highly efficient catalytic systems with improved stability and recyclability.

3.2 Types of catalytic oxidative processes

There are diverse categories of catalytic oxidative processes that are crucial in the advancement of wastewater treatment strategies, especially on issues that pertain to complicated pollutants. Catalytic oxidation comprises a number of processes in which heterogeneous catalysts facilitate the breakdown of pollutants by oxidation (**Figure 4**) (Ambec& Lanoie2008).

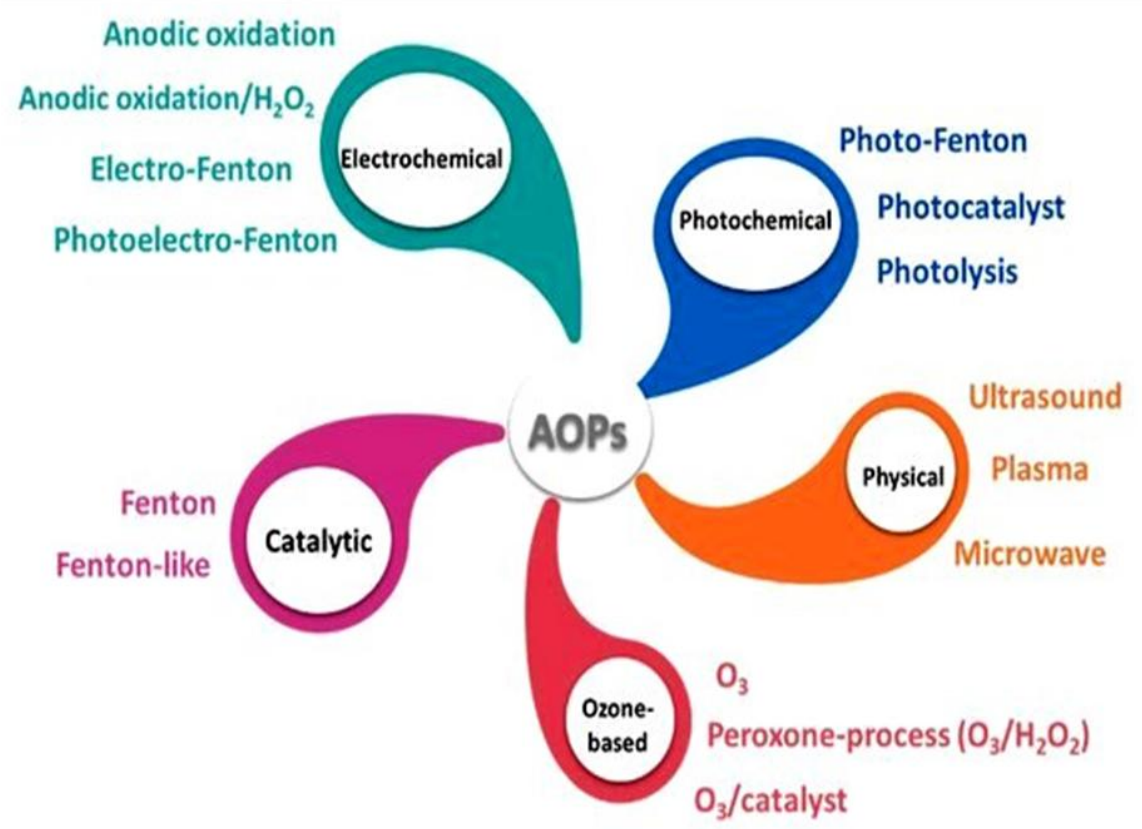


Figure 4: Different types of advanced catalytic oxidation processes (ACOPs).

These processes hold vast possibilities for improving the performance of treatments through the removal of recalcitrant pollutants and the minimization of the environmental issues related to them. Thus, ACOPs are considered to be more selective towards the degradation of certain pollutants and Fenton and photo-Fenton processes use hydroxyl radicals to degrade pollutants (Ahmad et al., 2015). The comparison of the catalytic oxidation and the oxidative cycles in these processes reveals that these processes are quite sustainable and can be applied in different manners for the treatment of water, meaning that more work must be done to decipher these catalytic pathways (Borralho et al., 2023).

Catalytic oxidative processes play a crucial role in the efficient degradation of organic and inorganic pollutants in wastewater treatment. These processes are broadly classified based on the type of oxidant used, activation mechanism, and energy source involved. The primary objective of these processes is the generation of highly reactive species, such as hydroxyl radicals (•OH) and sulphate radicals ($SO_4•^-$), which can effectively mineralize complex contaminants into harmless products(.Poyatos et.al.,2010)

One of the most widely studied catalytic oxidative processes is photocatalysis, which involves the activation of semiconductor catalysts (e.g., TiO_2, ZnO, g-C_3N_4) under ultraviolet or visible light irradiation. Upon light excitation, electron–hole pairs are generated, which participate in redox reactions to produce reactive oxygen species. These radicals attack and degrade pollutants through oxidation pathways, making photocatalysis highly effective for treating dyes, pharmaceuticals, and other persistent organic compounds.(Mishra & Sundaram 2024)

Another important category is the Fenton and photo-Fenton processes, which are based on the catalytic decomposition of hydrogen peroxide (H_2O_2) in the presence of iron ions (Fe^{2+}/Fe^{3+}). This reaction generates hydroxyl radicals with strong oxidation potential. The photo-Fenton process further enhances efficiency by using light irradiation to regenerate Fe^{2+} ions, thereby sustaining the reaction cycle. These processes are particularly effective for the degradation of refractory organic pollutants.(Klaudia Całus-Makowska et.al.2025)

Electrochemical oxidation is another promising approach, where electric current is used to generate oxidizing species either directly on the electrode surface or indirectly through electrolytes. Advanced electrode materials, such as boron-doped diamond (BDD) and metal oxide electrodes, facilitate the production of hydroxyl radicals, enabling efficient degradation of a wide range of contaminants. This method offers precise control over reaction conditions and is suitable for continuous treatment systems.(Ganiyu et.al.2021)

Ozonation and catalytic ozonation involve the use of ozone (O_3) as a powerful oxidant. In catalytic ozonation, catalysts are employed to enhance ozone decomposition, leading to the formation of additional hydroxyl radicals. This process is highly effective for the removal of colour, odour, and toxic organic compounds. The combination of ozone with catalysts improves oxidation efficiency and reduces ozone consumption.(Das et.al.2024)

Another emerging category is sulphate radical-based oxidation processes, which utilize oxidants such as persulphate ($S_2O_8^{2-}$) and peroxymonosulphate (PMS). These oxidants are activated using heat, light, or catalysts to generate sulphate radicals, which exhibit high oxidation potential and greater stability over a wide pH range compared to hydroxyl radicals. This makes them particularly suitable for treating complex wastewater matrices.(Domingues et.al.2022)

In addition to these individual processes, hybrid catalytic systems have gained significant attention in recent years. These systems combine two or more oxidation techniques, such as photocatalysis coupled with Fenton reactions or electrochemical oxidation integrated with ozonation, to achieve synergistic effects (Sharma et al 2020). Hybrid systems enhance pollutant degradation efficiency, reduce treatment time, and improve overall process performance.

In conclusion, various types of catalytic oxidative processes offer distinct advantages and are suitable for different wastewater treatment applications. The selection of an appropriate process depends on factors such as pollutant type, operating conditions, and economic feasibility. Continued advancements in catalyst design and process integration are expected to further enhance the efficiency and applicability of these technologies.

3.3. Chromatography method

Chromatography is applied for the assessment of the efficiency of wastewater treatment and to compare the heterogeneous catalytic oxidative reactions. Common techniques used in the separation of complex mixtures are gas chromatography,liquid chromatography, and high-performance liquid chromatography because they are very particular and very effective in their separation (Oke et al., 2017). This level of accuracy is particularly crucial in the identification of CECs and the evaluation of the treatment systems' removal capabilities. Chromatographic methods help in the detection of all types of pollutants, whether organic or inorganic, in the wastewater and hence the best treatment method to apply (Rasheed et al., 2019). Chromatography will also enhance the reliability and selectivity of the water quality parameters which are essential in the multivariate physicochemical analysis model of wastewater (Vakros, 2023).

3.4. Optical Spectroscopy Method

Optical spectroscopy is another beneficial technique for assessing the effectiveness of wastewater treatment processes by identifying the molecular composition and transformations of pollutants (Hakeem et al.,2022). UV-visible spectroscopy and fluorescence spectroscopy are the most widely used optical spectrometric techniques that allow researchers to investigate the interactions between pharmaceuticals, industrial chemicals, and organic pollutants in a matrix of wastewater. These methods assist in determining specific spectral signatures of the target analyses, measuring and tracking their concentration over time, and contributing to the assessment of treatment effectiveness and contaminant removal efficiency (Rajapaksha et al., 2016).The combination of multivariate analysis with spectral data increases the possibilities of interpreting multivariate data, identification of pollutants, and applying treatment methods according to spectral features (Jin et al., 2012). The coupling of spectrometry with other methodologies underlines its role in the advancement of methods for wastewater treatment, proving its efficacy in environmental treatment processes and the establishment of effective approaches to water management (Chu et al., 2022).

3.5 Mass spectrometry Method

Mass spectrometry assists in the analysis of the composition of the pollutants in the wastewater as an analytical method that helps to break down large molecular formations (Mohan et al., 2014). It is a method that can be employed for the detection of contaminants in wastewater samples because of its high sensitivity and capability to sort ions based on the m/z ratios (Monteagudo et al., 2012). Owing to the advanced methods like mass spectrometry (MS), GC-MS (Gas Chromatography-Mass Spectrometry), and HRMS (High-Resolution Mass Spectrometry)it is possible to identify all known pollutants and detect other compounds present in sewage."(Liu, et al., 2013). This analytical approach is pertinent with the fact that to understanding the chemical array in the wastewater and to define the degree of efficiency in the catalytic oxidizing treatment, more research work has to be conducted (Ambaye et al., 2020). Multivariate physicochemical analysis along with mass spectroscopy might be used as a proficient technique to demonstrate the efficiency of the treatment, degradation of pollutants and possible treatment solutions for wastewater-related problems.

4. Machine learning for waste water data analysis

Machine learning plays an important role in optimizing wastewater treatment processes and increasing pollutant removal efficiency (Stevenson, C. M. 1968). Optimization of the treatment parameters, system

performance, and diagnostics of the specific areas of the body that require attention are some of the areas that are facilitated through the use of advanced algorithms and data analytical tools in machine learning (Dewil et al., 2017). This technology enables constant monitoring of the changes in the water quality parameters and also enables the control measures to be adjusted following the changes in the water quality (Deheuvels et al., 1983).

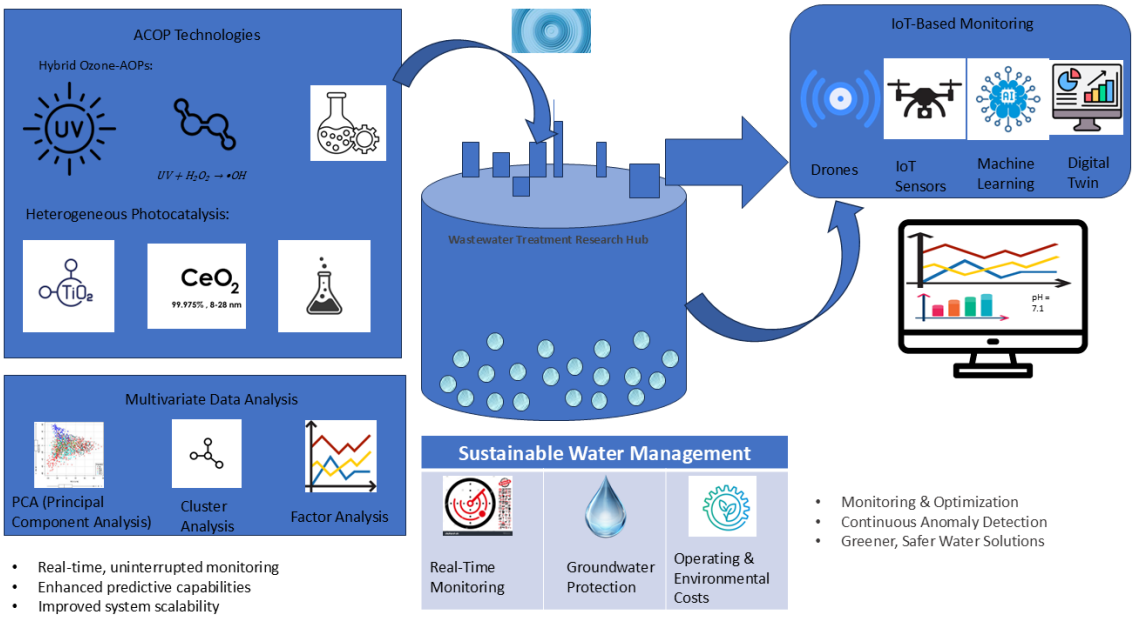


Figure 5: Integration of multivariate analysis, ACOP, and Machine learning for sustainable wastewater management.

Machine learning models are used in wastewater treatment systems and assist the operators in optimizing the systems, using less energy, and producing quality results. It also helps in figuring out trends in the huge dataset and associating this with the quality of water or utilization of water or making decisions and improving the process as well (Albaigés, 2017). This paper adds to the current literature on sustainable and proactive data-driven environmental management in the context of wastewater treatment through the application of machine learning techniques (Laurita et al., 2015).**Figure 5** shows integration of multivariate analysis, ACOP, and Machine learning for sustainable wastewater management. ML enables high-throughput catalyst fabrication and targeted oxidation pathway modulation through predictions of active sites and reactive species, while consolidating data-driven optimization strategies for AOPs(Ning et.al 2026). ML-assisted catalyst design, illustrating how data-driven strategies transcend simple kinetic predictions to enable the precise engineering of active sites and reaction microenvironments (**Anqi et.al 2026**).

Table 1. Comparison of Machine Learning Algorithms for Wastewater Treatment

Algorithm	Typical Input Variables	Primary Application	Major Advantages	Main Limitations
ANN	pH, COD, BOD, TOC, turbidity	Effluent quality prediction	Excellent nonlinear modelling	Requires large datasets
Random Forest	Multi-sensor data	Water quality classification	Robust, interpretable, resistant to overfitting	Higher computational cost
SVM	Physicochemical variables	Contaminant prediction	High accuracy with limited datasets	Kernel selection required
XGBoost	Sensor networks	Process optimization	Excellent predictive performance	Parameter tuning needed
LSTM	Time-series IoT data	Dynamic forecasting	Captures temporal relationships	High training complexity

4.1. Data visualization tools

Data visualization tools are very useful in wastewater treatment since they assist in analyzing various parameters derived from the multivariate physicochemical analysis and ACOPs. These tools are mostly applied in data mining and analysis to determine the correlation between several variables and treatment outcomes from big data (Khan & Ali, 2018). The help of modern tools enables the researchers to present the results in a more comprehensible manner, identify the outliners, and make the right decision depending on the representation of the data (Araújo et al., 2008). Also, data visualization tools assist in the research and development of efficient and sustainable wastewater treatment technologies (Marcinowski et al., 2020). This assertion is supported by other research that has also established that these tools are important in presenting the results of the analysis in a form that can be easily understood and also provides a systematic manner of presenting the analysis for dissemination among the researchers (Taniguchi et al., 2019).

4.2. Multivariate statistical methods

Several commonly used multivariate statistical techniques are applied in the analysis of multivariate data in wastewater treatment studies. By employing tests like the principal component analysis or factor analysis, for instance, among other modern statistical tests, one can easily identify the key factors of the quality of water (Boczkaj& Fernandes, 2017). These methods show how different variables are linked to one another and the overall quality of the wastewater as well as the functioning of ACOPs (Abdo, 2023). The application of multivariate statistical analysis aids in comparing the performance of the treatment technology, identifying the most essential factors influencing the optimality, as well as determining a suitable solution for water resources' optimal usage. Moreover, such techniques encourage the use of data to make decisions on methods to adopt in the management of wastewater treatment systems, making the systems more efficient and sustainable (Handbook of Environmental Analysis: Chemical Pollutants in Air, Water, Soil, and Solid Wastes., 1997).

4.3. Variables affecting efficiency

The efficiency and effectiveness of wastewater treatment are influenced by several key factors, among the AOPs, photocatalysis with titanium dioxide and UV light as well as Fenton's reagent may be classified as suitable technologies for the removal of ROCs in the context of sustainable water treatment technologies (Lama et al., 2022). The quality of the input parameters used for the analysis of Physico-chemical characteristics of groundwater samples from the region is questionable and therefore requires proper attention to be paid for better and accurate predictions and suitable treatment measures (Diallo et al., 2013). It is therefore essential to understand the relationship between the BOD, COD, DO, and pH to improve the treatments (Rizzo et al., 2019). An in-depth Multidisciplinary and Advanced catalytic oxidative processes research focuses on determining the factors that influence efficiency in wastewater treatment and, therefore, enhances the sustainable water management practices in the region (Malik et al., 2023).

4.4. Optimization techniques

This paper identifies that optimization techniques used in wastewater treatment technology are effective tools for enhancing the efficiency of treatment processes and rational use of resources. This is because maintaining the physicochemical conditions is challenging, and wastewater contains a diverse range of contaminants Several contributors have explained optimization methods that can be of significant help when it comes to enhancing the outcome of treatments and reducing the usage of resources (Deheuvels, 1983). These strategies include the operational variables, reactor configuration, and catalyst activity in attaining enhanced treatment efficiency. Studies in this area use multivariate physicochemical analysis and ACOPs, to find lasting solutions to the wastewater treatment problem in the area and contribute to global challenges on water scarcity (Verma et al., 2024).

5. Catalytic oxidative processes (COPs) for Wastewater treatment

COPs are among the most effective technologies for wastewater management, as they facilitate the attainment of higher pollutant concentrations.Such reactions are catalyzed by various catalysts, which influence the transformation pathways and fate of the pollutants in the wastewater (Tripathi & Sharma, 2022). These processes involve the use of different catalysts which are quite influential in the determination of the time that is taken in the degradation of the pollutants in the wastewater (Gopalakrishnan et al., 2023). From the improvement that has been made in the recent past, the photocatalytic activity of titanium dioxide as a catalyst has given a fairly good account of itself in the elimination of organic contaminants (Huang et al., 2013). Similarly, the usage of Fenton reactions together with iron as a catalyst has provided promising results concerning the removal of organic materials in the process of treating water (Sharma & Bhattacharya, 2017). The selection and development of catalysts are important as far as the effectiveness of the COPs in the treatment of wastewater. The properties of different catalysts as well as their conditions of use are important in achieving the desired efficiency of pollutants' breakdown while ensuring appropriate wastewater management at the same time(Gnedin, 1993). It is important to have adequate information on the various types of catalysts that may be used in the treatment of wastewater using ACOPs. Each catalyst has its specific properties and level of effectiveness, which are crucial for achieving maximum contaminant removal and ensuring appropriate water usage(Kamali et al., 2019).

5.1. Catalyst regeneration and reuse

Catalyst regeneration is a crucial aspect of ACOPs. Regenerability is a major area of concern when it comes to the ability to further improve upon the sustainability and cost-effectiveness of the WWT processes. Taking from the analysis of literature sources provided by Deng & Zhao (2015), the disposal of catalyst remnants receives significant attention due to its potential to compromise the subsequent catalytic

effectiveness and durability of ACOP materials(Brillas & Martínez-Huitle 2015). The regeneration process poses a challenge as it involves optimizing operational parameters, improving regeneration efficiency, and ensuring cost-effectiveness, all of which are crucial for the successful implementation of these innovative treatment processes. (Gnedin, 1993). Additionally, other studies present the emergence of various strategies for the regeneration of catalysts, which requires the creation of systems that promote the concept of circular economy in wastewater treatment processes. This is in line with the overall notion of sustainable water management by enhancing ACOPs as remediation tools in sustainable development (Zhang, 2002)

5.2. Mechanisms of COPs

Identifying the chemical reactions that take place in wastewater treatment systems is crucial, as it relies on understanding the relationships between pollutants and the applied treatment methods (Aguado et al., 2008). Some of the benefits of multivariate physicochemical analyses include an understanding of the interrelationships between factors like oxygen, pH, BOD, and TDS. This systematic approach also allows for gathering a comprehensive view of the dynamic changes that take place during ACOPs (Sahu & Chaudhari, 2014). By extending the focus on the chemical changes that are triggered by the treatments, a better understanding of the various pathways through which pollutants can be removed can be gained, which partially sheds light on the effectiveness and feasibility of pollution treatment strategies (Jozala et al., 2016).

5.3. Role of catalysts in reaction mechanisms

Catalytic activities involved in wastewater treatment are highly complex, particularly in the context of AOPs, and play a crucial role in pollutant degradation. In reaction mechanisms, catalysts are involved directly in the process of changing contaminants into less hazardous byproducts through oxidation (Karadzic, 2021). In the catalytic field, nanomaterials, and nanotechnology offer better opportunities for further advancements in sustainable wastewater treatment practices and environmental conservation."(Kourmentza et al., 2017). This is in line with the goals and objectives of ACOPs that FARA and other Asian agricultural development studies have postulated, that there is a need to promote and implement efficient and sustainable wastewater treatment programs with nanomaterials catalysts. A new generation of catalytic systems enhances the efficiency of wastewater removal systems, thus addressing the general problem of pollutant control (Ledakowicz et al., 2001).Thus, utilizing catalytic properties to increase pollutant removal and water treatment efficacy can strengthen the interaction between catalytic mechanisms and oxidative processes(Marugán et al., 2006). Advancement of machine learning (ML) and its algorithmic classification has significantly propelled the progress in ML-assisted catalyst screening, active site prediction, the discovery of acceleration mechanisms, and catalyst structural research(Yuan et. Al. 2025).

5.4. Influence of wastewater composition

In the context of exploring or considering high-tech catalytic oxidative processes for wastewater treatment, it is imperative to understand the role of wastewater matrix in the determination of the effectiveness of the above-stated processes (Chen et al., 2003). Wastewater is comprised of several pollutants and chemicals and therefore, there is no procedure to fully remove wastes and purify the water (Ghernaout, 2020). The complexity of the biological and chemical load of waste, as well as the presence of heavy metals, pathogens, and new-generationpollutants, require individual approaches to the management of specific contaminants (Shankar et al., 2018).Varying the composition and variation of the flow of wastewater and the differences between them, it is necessary to develop generic and comprehensive methods for evaluating certain characteristics of each type of wastewater(Subhan et al., 2021).The combination of multivariate physicochemical analysis with ACOPs provides extensive information about WWTPs and allows the creation

of the proper treatment procedure that will be effective for the removal of the pollutants and friendly to the environment (Muñoz et al., 2008).

6. Evaluation of wastewater treatment efficiency

6.1. Removal of organic pollutants

The principal objective of treating wastewater is the elimination of all organic pollutants in the water. Oil remediation can be performed comprehensively with the help of multivariate physicochemical analysis and ACOPs to offset the maximum level of pollutants in water bodies (Chen et al., 2022). ACOPs effectively degrade very large and complex organic molecules that are resistant to other reactions by forming highly oxidizing hydroxyl radicals, which thereby offer a good solution to the 'vicious cycle' of the organic pollutants in wastewater (Serfling, 2002). Comparing the strategies, implementing these changes systematically and conducting the physicochemical analysis, the efficiency of the organic pollutants' removal is optimized and the general success of the wastewater treatment strategies for the region is enhanced (Daneshvar et al., 2019).

6.2. Reduction of toxic metals

The following are some of the ways through which the metal removal efficacy of the remediation processes of wastewater management is affected: The efficiency of the remediation processes in the management of wastewater not only depends on the concentration of metals in the water but also the toxicity of the metals as well (Simeonidis et al.,2016).Industrial wastewater is a mixture of contaminants that primarily includes organic compounds, inorganic substances, and heavy metals. Heavy metals are extremely hazardous due to their toxic properties, posing serious risks to both human health and the environment.Since the oxidation reactions are enhanced by ACOPs, they offer a promising solution to the problem by facilitating the breakdown of contaminants such as toxic metals(Gagol, et al., 2018). Seemingly, the several characteristics analyzed using various physicochemical parameters mean are used to establish the correlation between the rates of metal uptake and elimination (Hun-Kyun Bae, 2018). However, it should be noted that this integrated strategy fully complies with the objectives stipulated concept for the research area which is devoted to wastewater treatment efficiency improvement as well as the need for targeted measures aimed at decreasing the adverse effects of toxic metals on water ecosystem and its inhabitants (Tijing et al., 2020).

6.3. Impact on biological demand

The biological factors to be taken into consideration while determining demand assessment of wastewater treatment are the factors' interdependency and the biological factors related to these factors. BOD is the most significant factor here because it quantifies the pollution load in water bodies by indicating the existence of biodegradable substances that deplete the oxygen essential for sustaining aquatic life(Zhang et al., 2012). Concerning this, advanced oxidative processes are significant as they are capable of triggering ambient pollution removal and system efficiency enhancement. The sampling methods that are used include the determination of certain crucial parameters like BOD, COD, and TDS to present a comprehensive picture of the biological impact on the quality of water (Maksoud et al., 2020). One way of reducing the biological demand and preserving water sources for future environmental sustainability might be to combine ACOPs and other, more complex analytical techniques (Lucas et al., 2021).

7. Environmental impact assessment

7.1. Short-term impacts

It is high time that the short-term impact of the multivariate physicochemical analysis and ACOPs used for wastewater treatment should be given due consideration to assess their effects on water and health. ACOPs-based methods are the most promising methods for the elimination of contaminants and, at the same

time, the chief concern is the possibility of the formation of by-products and residual chemicals during the treatment, which may exert negative effects on ecosystems and human health (Behme, 2012). Furthermore, multivariate physicochemical analysis will reveal alteration in the basic characteristics including dissolved oxygen, biochemical oxygen demand, total dissolved solids,and other characteristics with time after treatment (Mishra, 2023).Knowledge of the link between the utilized treatment process and short-term outcomes is vital in determining the efficiency and sustainability of wastewater treatment measures to ensure suitable decision-making for promoting environmental protection. (Singh et al., 2020).

7.2. Long-term sustainability

A long-term sustainable strategy for the treatment of wastewater involves the integration of the latest technology in the field, and the least negative effects on the environment with the most effective use of resources (Ullah et al., 2022). Major factors include the innovation of treatment approaches to deal with emerging contaminants efficiently in terms of energy and cost. Adopting a holistic evaluation framework that integrates physicochemical analysis with cutting-edge catalytic oxidation technology is critical for the long-term success of water quality management, which faces rising contamination challenges (Lin & Ho, 2022). To make wastewater treatment sustainable, it is recommended that society and the government sustain the practices and continue researching the availability of resources for future generations as well as protecting the environment (Lacombe et al., 2019). Wastewater treatment plants (WWTPs) are among an important source of global greenhouse gas emissions. The use of artificial intelligence (AI) offers a promising route to make WWTPs low-carbon and smart. AI can balance effluent quality, energy use, and carbon emissions, and model-based and reinforcement learning control can further unlock energy saving and emission reduction potential. (Yiting et.al.2026).

7.3. Regulatory compliance

Regulation in wastewater treatment can be defined as the process of adhering to certain policies that have been laid down to avoid causing harm to the surrounding environment and people (Verplanck et al., 2014). It makes sure that the effluent that is released into the water bodies does not pollute them and does not have detrimental effects on the health of the people. The following measures must be implemented to ensure that the effluent's quality, particularly its BOD, COD, and TDS levels, complies with regulatory standards (Zeghioud et al., 2022). It is for this reason that regulatory frameworks are important in defining limits for contaminants and guiding treatment strategies as well as promoting efficient disposal of wastewater (Ioannou et al., 2015). Moreover, the importance of pH measurements is stressed to achieve accurate predictions in water quality standards control; all of this underlines the mutual dependence between compliances, analytical evaluations, and proficient treatments in the sphere of environmental protection and resource management (Lama et al., 2022).

8. IoT-Enabled Monitoring and Multivariate Analysis Framework

The issue of urbanization, industrialization and appearance of new pollutants that complicate the composition of wastewater is why it requires systems of treatment that not only provide effective removal of pollutants but also ability to control the adaptive processes. Most of the traditional wastewater treatment plants are based on online laboratory tests, and infrequent sample-based testing, which limits the dynamism of operational optimization and the ability to capture dynamic changes in water quality. Digital monitoring technologies have seen popularity in advanced treatment research. Internet of Things (IoT) can provide a scheme of continuous physicochemical measurements and systematic treatment performance analysis in the scientific work on the Advanced Catalytic Oxidative Processes (ACOPs). Since a higher frequency sensor data

is needed to analyse the process dynamics at more detail, and the oxidation efficiency is to be quantified. When IoT-monitored data are combined with multivariate physicochemical analysis, the searching of the relationships and interdependencies in the operating conditions and water quality indicators with classical and discrete samples-based techniques will become trivial. Three key layers of the proposed research structure are combined together:

(i) the matter layer of treatment,

(ii) the sensing and data collection layer, and

(iii) the third layer is the decision-support and analytics layer.

Physical removal of the wastewater is done by advanced catalytic oxidative techniques such as ozonation, UV-assisted oxidation and heterogeneous catalytic oxidation. The processes break down reluctant organic contaminants creating exceptionally reactive oxidative species. The sensing layer is made up of IoT-enabled sensors located in the direct position of the reactor or treatment tank in the wastewater (**Figure 6**). These sensors have critical physicochemical parameters such as pH, temperature, dissolved oxygen, (DO), turbidity, electrical conductivity (EC), total dissolved solids (TDS) and, where applicable, ammonia or chemical oxygen demand (COD). In order to understand the high-dimensional data generated by the IoT sensors, the analytics layer is using machine learning and multivariate statistical analysis. This tier consists of trend analysis, optimisation of processes, the identification of anomalies and predictive performance analysis.

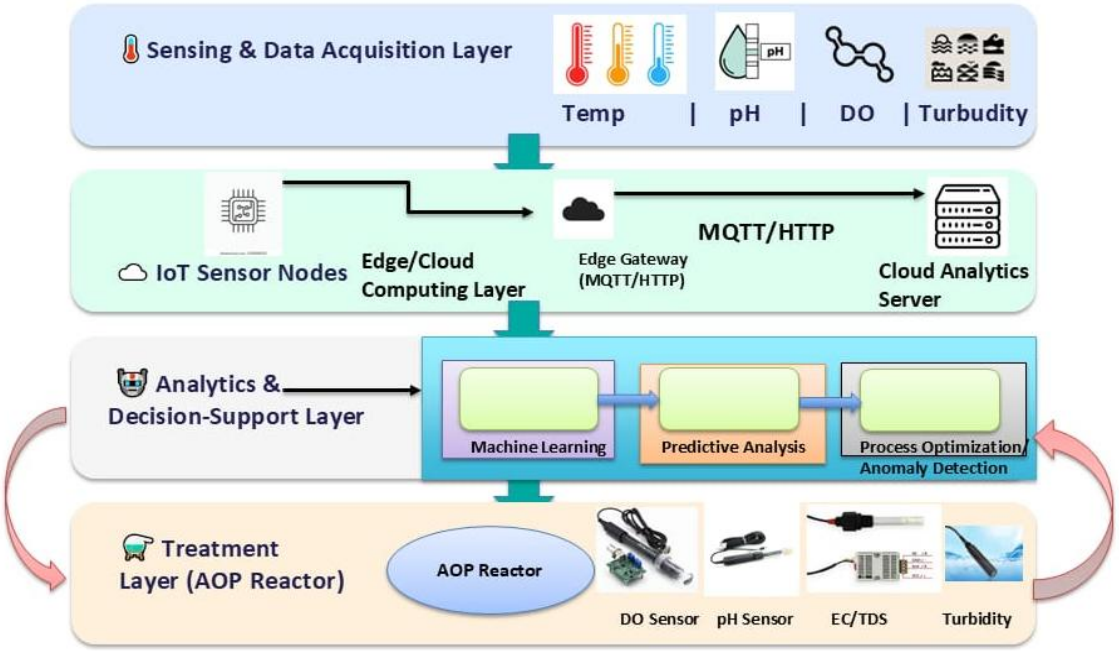


Figure6. IoT-enabled advanced catalytic oxidative process for wastewater treatment

In laboratory-scale and pilot-scale investigations, the source of wastewater is typically a controlled tank or reactor, which contains real or synthetic wastewater. The utilization of this reactor is on the basis of an experimental platform concerning the evaluation of the ACOP efficiency under diverse operating conditions. Reactor comprises of sampling, catalyst implantation, oxidant dosing and sensor ports. The integration of IoT

ensures that irregularities are not recorded but any major physicochemical changes that occur during the oxidation reactions are continually recorded. The selection of the appropriate sensors is of great importance to the success of the research that is based on the IoT. Such common sensors in an ACOP research are:

Table 2. IoT Sensors Commonly Used in ACOP-Based Wastewater Treatment

Sensor	Parameter Measured	Typical Function	Importance in ACOP
pH sensor	Acidity/alkalinity	Reaction control	Determines radical generation efficiency
DO sensor	Dissolved oxygen	Aeration monitoring	Indicates oxidation conditions
ORP sensor	Oxidation-reduction potential	Oxidation efficiency	Monitors catalyst activity
EC sensor	Electrical conductivity	Ionic strength	Tracks mineralization trends
Turbidity sensor	Suspended solids	Clarification efficiency	Indicates particulate removal
Temperature sensor	Reaction temperature	Kinetic control	Influences oxidation rate
Online COD analyzer	Chemical oxygen demand	Organic pollution	Measures treatment performance
Ammonia/Nitrate sensor	Nutrient concentration	Nutrient removal	Evaluates nitrogen transformation

(i) pH sensors to measure the variations in acid base during oxidation processes.
(ii) Temperature sensors in order to measure the influence of temperature on the kinetics of reactions.
(iii) Dissolved oxygen sensors to monitor the oxidative conditions and the oxygen availability.
(iv) Turbidity detectors to check the elimination of particle and colloidal substance.
(v) EC/TDS sensors to determine the trends of mineralization and ionic strength.
(vi) Optional are ammonia, nitrate or oxidation-reduction potential (ORP) sensors.

These real-time sensors are connected with microcontrollers or single-board computers that gather data. An IoT edge gateway, such as a Raspberry Pi or other similar embedded system, is the data collection and pre processing unit. The gateway collects the raw sensor data, filters and authenticates this data and prepares the data to be further processed. Edge computing reduces the loss of data, minimizes latency, and performs primary analytics on the data source (**Figure 7**). This is highly essential in ACOP experiments where rapid turnovers in physicochemical may occur.

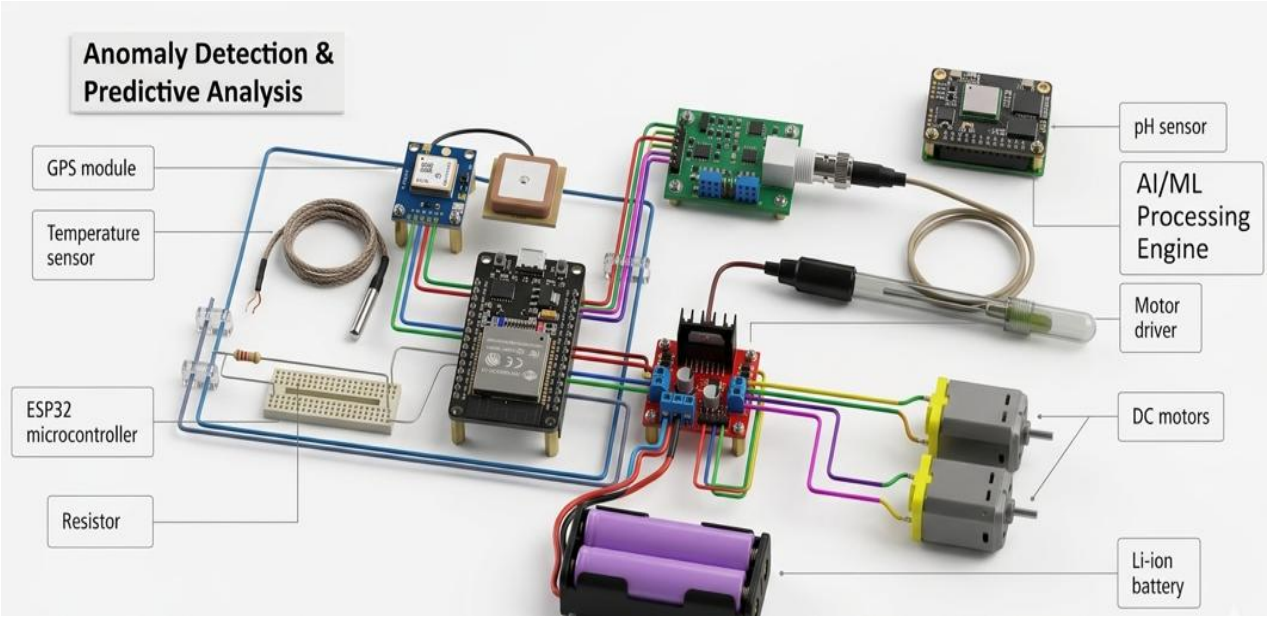


Figure. 7 Circuit Diagram of IoT enabled, AI/ML assisted wastewater monitoring and treatment framework

The edge gateway transmits data to local servers or cloud platform(s) via customary IoT communication protocols such as MQTT or HTTP. The protocols used in the system are suitable to long-term investigations, and real-time studies, as these protocols ensure reliability, low-power, and scalable data transport. Depending on the requirements of the experiment and the capabilities of the sensor, the transmission of data can occur on a continuous basis or at a fixed rate. The broad expanse of interacting physicochemical variables is present in the process of wastewater treatment. The conductivity, turbidity, temperature, and pH, which are not quite often independent, determine oxidation efficiency (Yadav et al. 2025). Univariate analysis cannot give full credit to these complex associations. The datasets obtained through the IoT are ideal in complex statistical and chemometric approaches since they are multivariate and high-frequency in their nature. One uses multivariate tools such as the one shown below to analyze sensor data being continuously gathered:

(i) PCA to identify the most influential variables on the efficiency of treatment.

(ii) Clustering to provide similar water quality patterns or states of operation.

(iii) Correlation and regression in order to scan the relationships between the elimination of pollutants and physicochemical parameters.

(iv) Improving the behavior of dynamic systems when oxidizing by time-series analysis. The techniques provide a better insight into efficiency of the processes, their stability and optimization paths.

IoT data can be used to use machine learning and artificial intelligence models outside the environment of multivariate analysis. Such models will be trained to detect anomalies, predict the outcomes of treatment, and recommend the optimal conditions of work. By way of example, by predicting the reduction of COD or turbidity (before it happens) with machine learning algorithms, using real-time sensor data, the oxidant dose or catalyst loading can then be adjusted proactively. Such prediction capabilities significantly enhance the strength and stability of the ACOP-based treatment systems. User interfaces and dashboards are very crucial in IoT-enabled

research (**Figure 8**). Visualization technologies can help researchers to comprehend complicated datasets with ease since they present actual-time tendencies, many-variable graphs, and warning signals. Through the presentation of raw sensor data and processed analysis data, dashboards facilitate sound decision making and allow rapid system performance analysis. Incorporation of IoT in ACOP research has a number of advantages:

(i) Up-to-date, continuous monitoring of treatment processes.

(ii) Better insights into the physicochemical interactions with the help of multivariate analysis.

(iii) Reduced reliance on the time-intensive sample and lab analysis.

(iv) More data richness and reliability.

(v) Scalability of systems between laboratory, pilot and full-scale.

Research-wise, the IoT-based systems make it easier to optimize evidence-based, as well as accelerate the employment of modern oxidation among real-world environments.

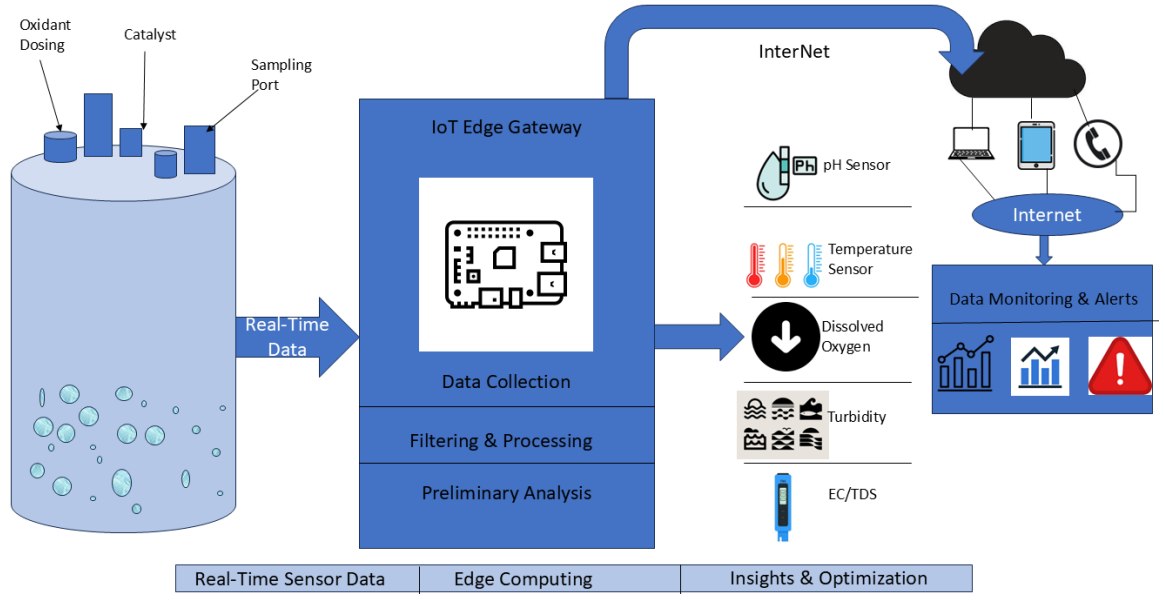


Figure 8. Schematic representation of IoT-assisted ACOP reactor setup

Increasing the integration of IoT through digital twins, more sensors, and adaptive control methods, are some of the ways that future studies can implement them. The existing possibilities of machine learning, multivariate analytics, and Internet of Things may yield enormous prospects of creating intelligent, self-optimizing wastewater treatment systems that can be used to foster the goals of sustainability and intelligent water management. Recent literature greatly helps in integrating advanced oxidation technologies with data-driven and multivariate techniques of analyzing and efficient wastewater treatment. Ozone-based AOPs have been demonstrated to be effective at disrupting recalcitrant organic contaminants, particularly with the addition of UV light, hydrogen peroxide or heterogeneous catalysts to enhance the generation of hydroxyl radicals. Regarding efficiency of mineralization and having potential detoxification property, these hybrid systems show considerably higher effectiveness than pure ozonation.

The combination of multivariate analysis, ACOPs and IoT has great implications to sustainable water management. The threat of groundwater pollution is also reduced through continuous monitoring that will detect the inefficiency of treatment and the breakthrough of the pollutants. According to data-driven optimization, power and chemical consumption is minimized, and thus, operating costs and environmental impact are minimized. Open data visualization and analytics may also be used to aid in policy development, community engagement, and compliance, raising the popularity of innovative treatment technology among society.

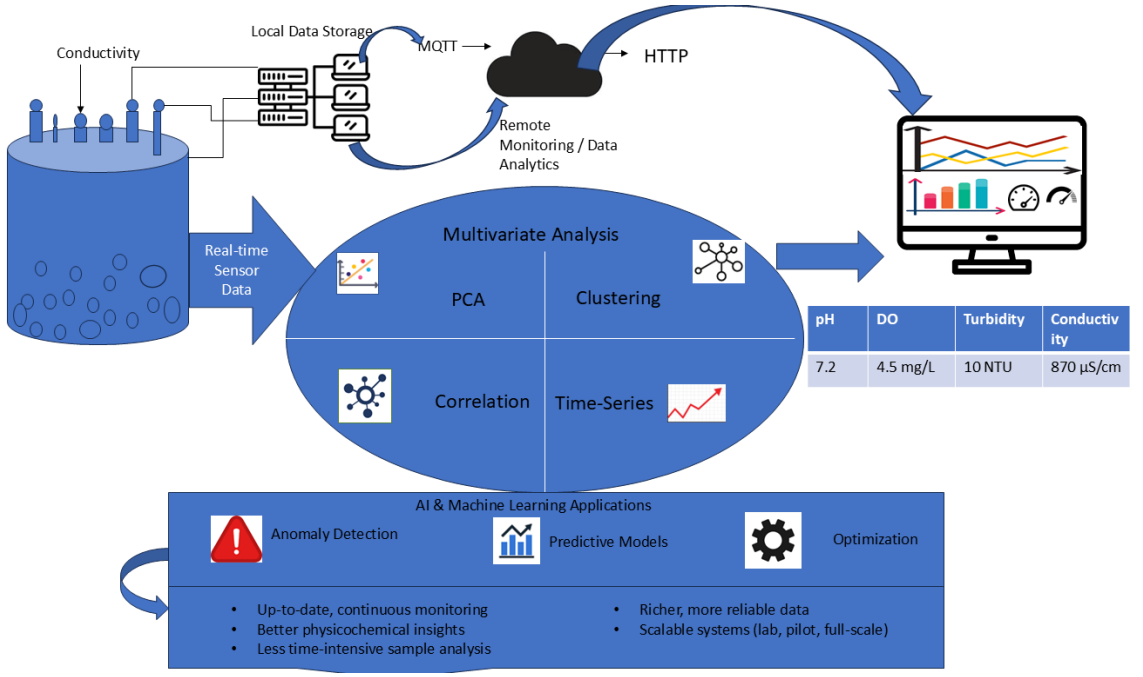


Figure9. Schematic representation of IoT-enabled ACOP and multivariate data analytics in wastewater treatment systems.

Fenton and photo-Fenton processes remain some of the best studied homogenous AOPs, specifically in the splitting of aromatic and nitro-organic compounds. It has been demonstrated that photo-assisted Fenton systems can be effectively higher in terms regarding the mineralization efficiencies compared to the conventional Fenton reactions due to a longer period of radical generation and enhancement of the regeneration of Fe2+. These findings reveal the importance of a very strict control over physicochemical parameters such as pH, oxidant dosage, and irradiation conditions, which are most effective under the conditions of real-time gauging using sensing instruments based on the IoT (**Figure 9**). Heterogeneous photocatalytic ACOPs which are based on TiO_2 and CeO_2 have been of interest because of their stability, reusability and their applicability to continuous-flow reactors. The concepts of the metal doping, hybrid composite design and catalyst immobilization have been used recently to resolve critical problems of secondary pollution and the recovery of catalysts. Such developments follow the contemporary paradigm of research, involving the application of multivariate analysis and constantly measured sensor data to dynamically estimate the performance of catalysts.

The main approaches to multivariate statistics that could be commonly applied to comprehend the highly complex water quality data and detect the primary contamination sources and controlling factors are principal component analysis, cluster analysis, and factor analysis. Case studies of rivers, lakes and reclaimed water systems and groundwater indicate that multivariate approaches provide a more comprehensive picture of spatiotemporal variation and interactions between pollutants in comparison to the use of univariate techniques. The IoT-based data collection can address a vital gap since most of the existing studies are based on intermittent efforts to sample instead of constant monitoring. However, more recently, machine learning-based watershed monitoring systems are effective additions to traditional chemometric techniques. These technologies can store large and high-dimensional datasets and can also identify non-linear relationships between the variables of water quality.

Connecting machine learning models to an IoT platform ensures better decision support to an advanced treatment system, allowing real-time characterization, anomaly detection, and predictive assessment of water quality. The proposed integrated approach that includes advanced catalytic oxidative reactions, multivariate physicochemical informatics, and IoT-based monitoring denotes the integration of three previously unrelated study domains. This built-in platform simplifies scalability, reproducibility and practical application and enhances process understanding and optimization at the process scale.

9. Conclusions

Due to the multilinear physicochemical parameters and ACOPs identified for wastewater treatment, the following key findings have emerged as influential. It has also disclosed the relationships between different physicochemical parameters in groundwater, revealing that many levels of contamination exceeded permissible limits, which calls for immediate attention. The widespread contamination reinforces the fact that strong water quality interventions are critical; failure to do so would escalate the groundwater crisis, leaving residents of the region helpless and subjected to unhealthy water. In addition, the possibility of using new AOPs was estimated to be very good for eliminating emerging pollutants, which also proves the need for the application of the technologies in the comprehensive treatment of wastewater. Therefore, there is a need to adopt an interdisciplinary solution with innovative technological intervention to have sustainable water management to protect the environment and health of the people.

The technological application of advanced control options of processes and multivariate physicochemical analysis has shifted the paradigm in the treatment of wastewater using ACOPs. These advanced technologies improve the effectiveness and accuracy in the removal of impurities and also aid in proper water usage. ACOP integration can be seen as epitomizing the rise of technologies, but it also points to the continued need for new-stage water treatment to address new forms of pollution. This has made it possible to improve the treatment processes for the provision of the best solution to the problem through the integration of analytical methodologies and catalytic oxidation processes leading to improved overall water quality outcomes and going a notch higher towards sustainable and effective treatment of wastewater. The strategy of wastewater management also speaks about inter professional cooperation and the application of technologies as ways to protect the environment and the population's health.

One of the critical issues that must be considered in planning future research and practice around ACOPs for wastewater treatment is addressing the identified research gaps in the current literature(Table 3). The innovation of multivariate physicochemical analysis methods is a prospective direction for improving wastewater treatment systems, efficiency, and effectiveness. The integration of these modern analytical methods with cutting-edge ACOPs, such as ozone-driven processes and photo catalytic oxidation, may lead to improved total elimination of CECs. Secondly, the practice of thinking in terms of a 'global' approach regarding the elaboration of sustainable and energy-efficient treatment Matos Filho methods becomes important, as it

emphasizes the importance of interdisciplinary relations and the practical application of research results to ensure environmental and public health gains. Concerning wastewater treatment, multivariate physicochemical analysis combined with catalytic oxidative processes is an integrated new approach for ensuring the effective removal of contaminants. The study aims to evaluate the types and impacts of methods associated with advanced treatment technologies to understand the intricate facets and benefits of using combinations of these processes in environmental remediation programs, referring to a multiple approach through a critical assessment of methodologies and impacts related to these advanced treatment technologies. This structured analytical framework reviews the current evaluation of these methods and identifies key research areas that need additional investigation to increase the efficiency of wastewater treatment.

Table-3: Research Gaps and Future Research Priorities

Current Challenge	Research Gap	Proposed Future Direction
Catalyst deactivation	Limited long-term stability	Develop recyclable, earth-abundant catalysts
Real wastewater complexity	Few pilot/full-scale studies	Validate ACOPs under real operating conditions
High energy consumption	Energy-intensive UV/ozone processes	Solar-driven and renewable-energy-assisted ACOPs
Fragmented monitoring	Limited real-time data integration	IoT-enabled continuous monitoring
Black-box AI models	Limited interpretability	Explainable AI (XAI) and hybrid physics-informed models
Lack of standardization	Difficult comparison between studies	Harmonized testing and reporting protocols
Process optimization	Mostly offline optimization	Digital twins and autonomous process control

The integration of Artificial Intelligence into industrial wastewater treatment represents a paradigm shift, demonstrating exceptional potential for enhancing operational efficiency, reducing energy consumption, and improving effluent quality through predictive models with remarkable accuracy.(Matos Filho et.al.2026).

10.Future Perspectives

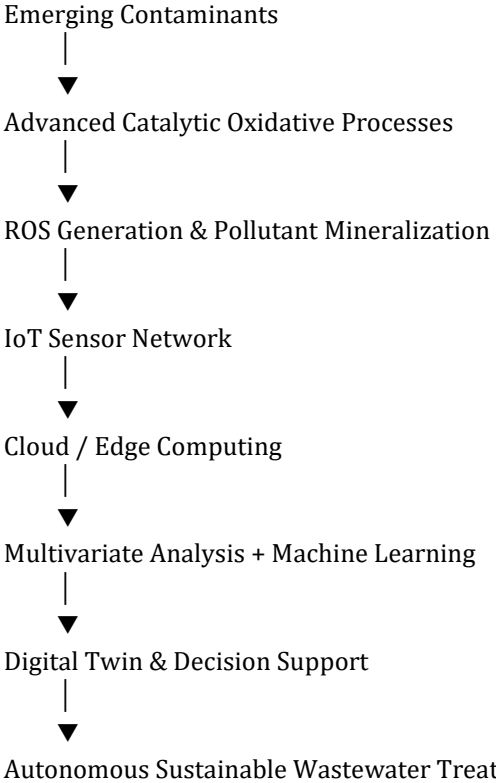
The integration of artificial intelligence (AI) and machine learning (ML) with advanced catalytic oxidative processes (ACOPs) and multivariate physicochemical analysis is expected to transform wastewater treatment into a data-driven and predictive system. By processing large datasets obtained from IoT-enabled sensors (pH, COD, BOD, TOC, turbidity, and metal ions), ML algorithms can identify hidden correlations and optimize operational parameters in real time. Predictive models can forecast pollutant load variations, catalyst performance, and system efficiency, enabling proactive adjustments in oxidant dosage, reaction time, and catalyst loading. Furthermore, AI-driven digital twins of treatment plants can simulate process behaviour, minimize energy consumption, and enhance overall reliability, leading to intelligent and autonomous wastewater treatment systems.

Sustainability will be a key driver in future wastewater treatment strategies. Green synthesis approaches using plant extracts, agricultural waste, and environmentally benign solvents will reduce the ecological footprint of catalyst production. The integration of renewable energy sources, particularly solar-driven photocatalysis, will significantly lower energy requirements. Moreover, the use of low-cost, earth-

abundant materials will enhance economic feasibility. Coupling ACOPs with resource recovery strategies such as reclaiming clean water, nutrients, and valuable metals will support the transition toward a circular economy. These developments will ensure that wastewater treatment processes are not only effective but also environmentally and economically sustainable.

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Roadmap for Next-Generation Intelligent Wastewater Treatment



Machine Learning (ML), Deep Learning(DL) and Internet of Things(IoT) technologies can extensively be used in supporting sustainable water resource management by enabling accurate real time Water Quality Prediction(WQP) and contributing to global sustainability goals including SDG 6 Clean Water and Sanitation. Future research should focus on Edge AI, Federated Learning and explainable AI, models to improve secure, reliable, adaptive, and scalable WQP systems.(Pandey et.al.2026).

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