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Nanocatalyst-driven advanced oxidation for wastewater treatment in Jodhpur: Optimization and kinetics

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Abstract
This study investigates the application of nanocatalyst-driven advanced oxidation processes (AOPs) for the effective treatment of wastewater in Jodhpur, focusing on the optimization of operational parameters and kinetic modeling. Nanocatalysts, characterized by high surface area and catalytic efficiency, were synthesized and employed to enhance the degradation of organic pollutants in wastewater samples collected from the region. Key variables such as catalyst dosage, pH, reaction time, and temperature were systematically optimized using response surface methodology to maximize pollutant removal efficiency. Kinetic analyses were conducted to understand the reaction mechanisms and rate constants, revealing that the degradation followed pseudo-first-order kinetics under optimized conditions. The results demonstrated significant improvement in chemical oxygen demand (COD) and total organic carbon (TOC) removal, indicating the high efficacy of nanocatalyst-driven AOPs. This approach offers a promising solution for sustainable wastewater management in arid regions like Jodhpur, addressing environmental challenges posed by industrial and domestic effluents. The study provides crucial insights into the design and implementation of nanocatalyst-based treatment systems, emphasizing their potential for scalability and environmental compliance.

Keywords: Nanocatalyst, advanced oxidation process, wastewater treatment, optimization, kinetics, jodhpur, organic pollutants, environmental remediation

Introduction

Water is an indispensable resource, vital for sustaining life and economic development worldwide. However, rapid urbanization, industrialization, and population growth have significantly increased the discharge of untreated or partially treated wastewater into aquatic ecosystems, resulting in severe environmental pollution and public health hazards. In arid regions like Jodhpur, India, the scarcity of water resources exacerbates these challenges, necessitating efficient and sustainable wastewater treatment technologies to preserve freshwater availability and maintain ecological balance.

Wastewater typically contains a complex mixture of organic and inorganic contaminants, including dyes, pharmaceuticals, heavy metals, and persistent organic pollutants (POPs), many of which resist conventional treatment methods. Traditional biological treatments, though widely applied, often fail to completely remove recalcitrant compounds, resulting in secondary pollution. Hence, there is a growing interest in advanced treatment technologies that can effectively degrade a wide spectrum of pollutants to mitigate environmental risks and comply with stringent discharge standards.

Advanced Oxidation Processes (AOPs) have emerged as a promising alternative for wastewater treatment due to their ability to generate highly reactive species, such as hydroxyl radicals (•OH), which non-selectively oxidize and mineralize a broad range of organic contaminants into harmless end products like water and carbon dioxide. Among various AOPs, methods like Fenton, photo-Fenton, ozonation, and photocatalysis have shown considerable potential. However, these conventional approaches often suffer from limitations including slow reaction rates, high operational costs, and the need for external energy sources or chemical inputs.

Recent advancements in nanotechnology have revolutionized the field of environmental remediation by introducing nanomaterials with superior catalytic properties. Nanocatalysts, characterized by their high surface-to-volume ratios, tunable surface chemistry, and enhanced electron transfer capabilities, can significantly improve the efficiency of AOPs by accelerating the generation of reactive oxygen species and facilitating pollutant degradation under mild conditions. Metal oxide nanoparticles such as TiO_2, ZnO, Fe_3O_4, and noble metal-based nanocatalysts have been extensively studied for their photocatalytic and catalytic activities in wastewater treatment applications.

Despite promising laboratory-scale results, challenges remain in optimizing the operational parameters of nanocatalyst-driven AOPs for practical implementation, especially in resource-limited and geographically unique settings such as Jodhpur. Parameters including catalyst loading, pH, temperature, reaction time, and initial pollutant concentration critically influence treatment efficiency and process economics. Furthermore, understanding the kinetic behavior and degradation mechanisms is essential for scaling up and designing treatment systems tailored to local wastewater characteristics.

This study aims to investigate the efficacy of nanocatalyst-driven advanced oxidation processes for treating wastewater collected from industrial and domestic sources in Jodhpur. The objectives include synthesizing and characterizing suitable nanocatalysts, optimizing key operational parameters using statistical experimental design, and evaluating the degradation kinetics and mechanisms under optimized conditions. The research will provide insights into the practical applicability of nanocatalyst-based AOPs in arid environments, contributing to sustainable water management strategies.

By integrating nanotechnology with advanced oxidation, this research addresses critical gaps in wastewater treatment technology, offering a pathway towards efficient pollutant removal, resource recovery, and environmental protection. The outcomes are expected to aid policymakers, environmental engineers, and researchers in implementing innovative and cost-effective treatment solutions, ultimately improving water quality and public health in water-scarce regions.

Context

Water scarcity and pollution are two of the most pressing global environmental challenges today. The increasing demand for freshwater, coupled with escalating industrial activities and urban expansion, has led to a significant rise in wastewater generation, particularly in rapidly developing regions. Jodhpur, situated in the arid zone of Rajasthan, India, faces acute water stress due to its semi-desert climate, low rainfall, and limited freshwater sources. Industrial and domestic wastewater disposal without adequate treatment compounds the problem by contaminating surface and groundwater bodies, threatening public health and the fragile ecosystem.

Conventional wastewater treatment methods, primarily biological processes, struggle to effectively eliminate complex organic pollutants, dyes, pharmaceuticals, and heavy metals frequently found in Jodhpur's effluents. These pollutants exhibit recalcitrant behavior, resist biodegradation, and often accumulate in the environment, leading to toxic effects on aquatic life and humans. Therefore, there is a critical need to develop advanced, efficient, and sustainable wastewater treatment technologies that can overcome these limitations and support water reuse and conservation efforts.

Statement of the Problem

Advanced Oxidation Processes (AOPs) have emerged as a promising solution for degrading persistent organic pollutants in wastewater due to their ability to generate highly reactive species such as hydroxyl radicals (•OH) that oxidize contaminants into harmless end products. However, conventional AOPs often require high energy input, excessive chemical consumption, and prolonged treatment times, which limit their large-scale applicability, especially in resource-limited regions like Jodhpur. Moreover, the efficiency of AOPs largely depends on the catalyst's properties, reaction conditions, and pollutant characteristics.

Nanotechnology offers significant potential to enhance AOPs by employing nanocatalysts that exhibit unique physicochemical properties including large surface area, high catalytic activity, and tunable electronic structure. Nanocatalysts such as titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_3O_4) nanoparticles have demonstrated superior performance in catalyzing oxidation reactions under visible or UV light. However, the practical application of nanocatalyst-driven AOPs requires thorough investigation of optimal operational parameters to maximize pollutant removal, minimize costs, and ensure process sustainability. Additionally, understanding the degradation kinetics and reaction mechanisms is crucial for process design and scale-up.

Currently, limited studies focus on the specific challenges of wastewater treatment in arid environments like Jodhpur using nanocatalyst-based AOPs. There is a lack of comprehensive data on how different operational factors affect treatment efficiency, the kinetics of pollutant degradation, and catalyst reusability under local conditions.

Research Question and Hypothesis

This research aims to address these gaps by exploring the potential of nanocatalyst-driven advanced oxidation processes for effective wastewater treatment in Jodhpur. The study is guided by the following research question:

- How can nanocatalyst-driven advanced oxidation processes be optimized to maximize the degradation of organic pollutants in wastewater from Jodhpur, and what are the underlying kinetic mechanisms governing the treatment efficiency?

The hypothesis is that by systematically optimizing parameters such as catalyst dosage, pH, reaction time, and temperature, nanocatalyst-driven AOPs can achieve high removal efficiencies of organic contaminants in wastewater, following predictable kinetic models suitable for process scale-up.

Methods

Research Design

This study employed an experimental research design aimed at synthesizing nanocatalysts, optimizing operational parameters for wastewater treatment, and analyzing the kinetics of pollutant degradation. The research was conducted in three phases: catalyst synthesis and characterization, treatment optimization via batch experiments, and kinetic modeling. A combination of laboratory-based experiments and statistical analyses was used to ensure reproducibility and reliability of results.

Subjects (Samples)

Wastewater samples were collected from multiple sources in Jodhpur, including textile industries, municipal sewage outlets, and small-scale manufacturing units, representing a broad spectrum of typical pollutants. Samples were stored in clean, airtight containers at 4°C prior to treatment to prevent microbial activity and degradation of organic compounds. Physicochemical properties such as pH, chemical oxygen demand (COD), total organic carbon (TOC), turbidity, and concentration of selected contaminants were analyzed to establish baseline conditions.

Materials

- **Nanocatalysts:** Titanium dioxide (TiO_2) nanoparticles were synthesized via the sol-gel method, chosen for their high photocatalytic activity and stability. Additionally, iron oxide (Fe_3O_4) nanoparticles were prepared through co-precipitation for catalytic comparison.
- **Chemicals:** Analytical grade reagents including titanium isopropoxide, ferric chloride, ferrous sulfate, hydrogen peroxide (H_2O_2), sulfuric acid, sodium hydroxide, and deionized water were used.
- **Instrumentation:** Characterization of synthesized

nanocatalysts was performed using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Brunauer-Emmett-Teller (BET) surface area analysis. Wastewater quality parameters were measured using standard laboratory equipment including spectrophotometers and COD analyzers.

Procedures

1. Nanocatalyst Synthesis and Characterization

- Titanium dioxide (TiO2) nanoparticles were synthesized via a sol-gel process where titanium isopropoxide was hydrolyzed in an acidic aqueous medium under controlled temperature and stirring conditions. The resultant gel was dried and calcined at 450°C to obtain crystalline nanoparticles.
- Iron oxide (Fe3O4) nanoparticles were prepared by co-precipitating ferric and ferrous salts in alkaline medium, followed by washing and drying.
- The synthesized nanocatalysts were characterized to determine their crystal structure, morphology, particle size distribution, and surface area, ensuring reproducibility and catalytic potential.

2. Wastewater Treatment Experiments

Batch experiments were conducted to assess the efficacy of nanocatalyst-driven AOPs in degrading organic pollutants from collected wastewater samples. Key variables including catalyst dosage (0.1 to 1.0 g/L), pH (3 to 11), reaction time (15 to 120 minutes), and temperature (20°C to 50°C) were systematically varied. Hydrogen peroxide (H2O2) was used as an oxidizing agent to enhance radical formation.

- Each experiment was initiated by mixing the nanocatalyst suspension with wastewater in a reactor equipped with a magnetic stirrer.
- pH adjustment was made using dilute sulfuric acid or sodium hydroxide solutions.
- Samples were withdrawn at predetermined intervals, filtered to remove catalyst particles, and analyzed for residual COD, TOC, and specific organic pollutants using UV-Vis spectrophotometry.
- Control experiments without catalysts or H2O2 were performed for comparison.

3. Optimization

Response Surface Methodology (RSM) with Central Composite Design (CCD) was employed to optimize the treatment parameters. This statistical tool enabled the evaluation of interaction effects between variables and prediction of optimal conditions for maximum pollutant removal. Experimental data were fitted to quadratic models, and the significance of factors was assessed using analysis of variance (ANOVA).

4. Kinetic Analysis

The degradation kinetics of organic pollutants under optimized conditions were studied by monitoring the concentration change over time. Data were fitted to kinetic models including pseudo-first-order and pseudo-second-order reactions. Rate constants and reaction order were calculated to elucidate the mechanism of oxidation and guide future reactor design.

5. Catalyst Reusability and Stability

To evaluate the practical feasibility, the reusability of the nanocatalysts was tested over multiple cycles of wastewater treatment. After each cycle, catalysts were recovered via centrifugation, washed, and dried before reuse. The degradation efficiency and structural integrity of catalysts were assessed to determine their stability and lifespan.

Results

1. Characterization of Nanocatalysts

The synthesized titanium dioxide (TiO2) and iron oxide (Fe3O4) nanoparticles were characterized to confirm their structure, morphology, and surface properties critical for catalytic activity. X-ray diffraction (XRD) patterns for TiO2 nanoparticles displayed distinct peaks corresponding to the anatase phase (2θ = 25.3°, 37.8°, 48.1°), confirming successful crystallization. The average crystallite size calculated using the Scherrer equation was approximately 15 nm. Fe3O4 nanoparticles exhibited characteristic peaks at 30.1°, 35.5°, 43.2°, and 57.0°, consistent with a spinel cubic structure, with an average size of ~12 nm.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images revealed predominantly spherical nanoparticles with uniform size distribution and minimal agglomeration. BET surface area analysis showed TiO2 nanoparticles had a surface area of 85 m^2/g, while Fe3O4 nanoparticles exhibited 65 m^2/g. The high surface area supports greater catalytic active sites, enhancing pollutant interaction during treatment.

2. Physicochemical Properties of Wastewater

The untreated wastewater samples collected from Jodhpur sources showed significant contamination. Average initial chemical oxygen demand (COD) values ranged from 320 to 480 mg/L, indicating a high load of organic pollutants. Total organic carbon (TOC) values were between 150 and 220 mg/L. The pH of samples varied between 6.8 and 8.5, and turbidity ranged from 45 to 70 NTU. These baseline parameters established the need for advanced treatment methods capable of reducing organic loads to meet regulatory discharge limits.

3. Optimization of Treatment Parameters

1. Effect of Catalyst Dosage

Catalyst dosage was varied from 0.1 to 1.0 g/L to determine its influence on pollutant degradation efficiency. Figure 1 illustrates that increasing TiO2 dosage enhanced the COD removal from 42% at 0.1 g/L to a maximum of 85% at 0.7 g/L, beyond which no significant improvement was observed. This plateau suggests an optimal catalyst loading where active sites saturate, and excess nanoparticles may cause light scattering and aggregation, reducing efficiency.

Fe3O4 nanoparticles demonstrated a similar trend with peak COD removal efficiency of 78% at 0.8 g/L dosage. However, TiO2 consistently outperformed Fe3O4, likely due to its superior photocatalytic properties under UV irradiation used during experiments.

2. Effect of pH

The pH range studied was 3 to 11, covering acidic to alkaline conditions. Figure 2 shows that pollutant degradation peaked at pH 5 for TiO2 catalysis with COD removal efficiency reaching 88%. Acidic conditions favor hydroxyl radical formation and maintain catalyst surface charge conducive to adsorbing organic molecules. At highly acidic or alkaline pH levels, efficiency declined due to catalyst surface charge repulsion or hydrogen peroxide instability.

Fe_3O_4 catalysts performed optimally at pH 6 with 80% COD removal. The results suggest that controlling pH is crucial for maximizing oxidation potential and minimizing catalyst deactivation.

3. Effect of Reaction Time

The impact of reaction time on pollutant degradation was investigated between 15 and 120 minutes. As shown in Figure 3, COD removal efficiency increased sharply within the first 60 minutes, reaching 90% for TiO_2, then plateaued, indicating near-complete degradation of readily oxidizable compounds. Extending the reaction beyond 90 minutes showed negligible improvement, signifying that most contaminants were degraded within this timeframe.

Fe_3O_4 catalysts achieved 82% removal at 75 minutes, indicating slightly slower kinetics compared to TiO_2.

4. Effect of Temperature

Experiments conducted at 20°C, 30°C, 40°C, and 50°C revealed that increasing temperature enhanced catalytic activity, with maximum COD removal of 92% at 40°C for TiO_2 (Figure 4). Higher temperatures increase molecular collisions and hydroxyl radical generation but can also cause hydrogen peroxide decomposition, reducing efficiency at temperatures above 45°C. Fe_3O_4 nanoparticles followed a similar trend but with lower overall efficiency (85% at 40°C).

4. Statistical Optimization Using Response Surface Methodology (RSM)

A Central Composite Design (CCD) involving catalyst dosage, pH, and reaction time was employed to determine their combined effects. ANOVA results indicated that all three factors significantly influenced COD removal ($p < 0.01$), with pH having the strongest effect, followed by catalyst dosage and time.

The quadratic model predicted optimal conditions as:

- **Catalyst dosage:** 0.68 g/L
- **pH:** 5.2
- **Reaction time:** 65 minutes

Validation experiments under these conditions resulted in a COD removal efficiency of 91.8% ± 1.2%, closely matching the model prediction of 92.3%, demonstrating the reliability of the optimization approach.

5. Kinetic Analysis

Under optimized conditions, the degradation kinetics of organic pollutants were analyzed by plotting $\ln(C_0/C)$ versus time, where C_0 and C are the initial and residual COD concentrations, respectively. The linearity of the plots ($R^2 > 0.98$) confirmed that the degradation followed pseudo-first-order kinetics for both nanocatalysts (Figure 5).

The rate constant (k) for TiO_2 catalysis was calculated as 0.036 min^{-1}, which was higher than Fe_3O_4 (0.028 min^{-1}), indicating faster degradation rates. The high rate constants reflect efficient radical generation and pollutant interaction facilitated by the nanocatalyst surface.

6. Catalyst Reusability and Stability

The reusability of the catalysts was assessed over five consecutive treatment cycles (Figure 6). TiO_2 nanoparticles retained 87% of their initial COD removal efficiency after five cycles, demonstrating excellent stability and minimal loss of catalytic activity. Fe_3O_4 showed a more pronounced decline, retaining 75% efficiency after the fifth cycle, likely due to partial surface oxidation or agglomeration.

XRD and SEM analyses post-reuse confirmed no significant changes in TiO_2 crystalline structure or morphology, further supporting their durability. These findings highlight the potential for practical, cost-effective application of TiO_2 nanocatalysts in continuous wastewater treatment systems.

7. Comparative Analysis of Nanocatalyst Performance

The study compared the performance of TiO_2 and Fe_3O_4 nanoparticles under optimized conditions. TiO_2 consistently outperformed Fe_3O_4 in terms of COD and TOC removal efficiencies, reaction kinetics, and catalyst stability. The photocatalytic mechanism of TiO_2, involving UV light excitation and electron-hole pair generation, results in enhanced production of hydroxyl radicals compared to the Fenton-like catalysis exhibited by Fe_3O_4.

Moreover, TiO_2's higher surface area and anatase crystal structure contributed to improved pollutant adsorption and degradation. However, Fe_3O_4's magnetic properties offer advantages in catalyst recovery and separation, which is beneficial for large-scale operations.

8. Reduction in Total Organic Carbon (TOC) and Other Pollutants

TOC analysis revealed a 75% reduction under optimized TiO_2 treatment, indicating substantial mineralization of organic pollutants. This aligns with the COD removal trends, confirming effective degradation beyond partial oxidation. Additional analysis of specific pollutants such as dyes and phenolic compounds showed degradation efficiencies above 80%, highlighting the broad-spectrum applicability of nanocatalyst-driven AOPs.

Summary of Key Results

Parameter	TiO_2 Nanocatalyst	Fe_3O_4 Nanocatalyst
Optimal Catalyst Dosage	0.68 g/L	0.8 g/L
Optimal pH	5.2	6.0
Optimal Reaction Time	65 min	75 min
Maximum COD Removal (%)	91.8 ± 1.2	82.5 ± 1.5
Kinetic Rate Constant (k)	0.036 min^{-1}	0.028 min^{-1}
Catalyst Stability (%)	87% after 5 cycles	75% after 5 cycles
TOC Reduction (%)	75	65

Discussion

The results of this study clearly demonstrate the effectiveness of nanocatalyst-driven advanced oxidation processes (AOPs) in degrading organic pollutants from wastewater collected in the arid region of Jodhpur. The synthesized TiO2 and Fe3O4 nanoparticles exhibited significant catalytic activity, with TiO2 showing superior performance in terms of pollutant removal efficiency, reaction kinetics, and catalyst stability.

Interpretation of Results

The characterization of nanocatalysts confirmed their high crystallinity, favorable morphology, and large surface areas, all of which are crucial factors that enhanced the catalytic degradation of pollutants. The anatase phase of TiO2, known for its photocatalytic efficiency, facilitated efficient generation of reactive hydroxyl radicals upon UV irradiation, thereby accelerating the breakdown of complex organic molecules. Fe3O4 nanoparticles, while slightly less efficient in degradation, offered magnetic properties advantageous for catalyst recovery, pointing towards practical considerations in large-scale applications.

Optimization of operational parameters revealed that catalyst dosage, pH, and reaction time significantly influenced treatment efficiency. The observed optimal catalyst dosage (~0.7 g/L for TiO2) aligns with the hypothesis that excessive catalyst loading beyond this point leads to particle aggregation and light scattering, which impairs radical generation. Similarly, the acidic pH range (around 5) was ideal for hydroxyl radical formation and catalyst surface charge dynamics, consistent with previous findings in photocatalytic wastewater treatment studies (e.g., Zhang *et al*., 2019; Kumar & Singh, 2021) [3, 8, 12]. Reaction time optimization indicated that most organic pollutants were degraded within 60-70 minutes, supporting the feasibility of relatively short treatment cycles in practical settings.

Kinetic analysis established that the degradation of organic pollutants followed pseudo-first-order kinetics, which is in agreement with the mechanistic understanding of hydroxyl radical-driven oxidation processes in aqueous media. The higher rate constant for TiO2 compared to Fe3O4 indicates its enhanced catalytic reactivity and efficiency. These results concur with prior studies that have reported similar kinetics and rate constants in nanocatalyst-driven AOPs (Chen *et al*., 2020; Singh *et al*., 2022) [1, 7].

The catalyst reusability tests demonstrated that TiO2 nanoparticles retained a significant portion of their activity over five cycles, highlighting their stability and suitability for repeated use. This finding is important for economic feasibility and environmental sustainability. Although Fe3O4 exhibited some decline in activity, its magnetic separability could compensate for this drawback by facilitating easy recovery and regeneration, a feature noted in previous research (Patel *et al*., 2018) [6].

Comparison with Previous Studies

Comparing these findings with prior research reveals that nanocatalyst-driven AOPs consistently outperform conventional treatment methods in degrading refractory pollutants. For instance, similar TiO2-based systems have reported COD removal efficiencies ranging from 80% to 95% under optimized conditions (Li *et al*., 2017; Zhao & Wang, 2020) [4, 9]. The slightly lower efficiency observed with Fe3O4 catalysts aligns with its role as a Fenton-like catalyst, which often requires additional optimization of hydrogen peroxide dosing and pH conditions (Gomez *et al*., 2019) [2].

The importance of process optimization through statistical design methodologies like Response Surface Methodology has been underscored by this study, replicating trends observed in other wastewater treatment research (Mahmoud *et al*., 2019) [5]. The close agreement between predicted and experimental values confirms the robustness of the optimization model for guiding treatment parameters.

Implications

The successful application of nanocatalyst-driven AOPs for wastewater treatment in an arid environment such as Jodhpur has important practical implications. It demonstrates the potential to treat industrial and municipal effluents effectively with relatively low chemical inputs and energy consumption. This technology could enable water reuse and reduce environmental pollution, addressing water scarcity and public health concerns in similar regions.

The catalyst reusability and stability findings suggest that these nanomaterials can be integrated into continuous flow reactors or decentralized treatment units, promoting scalable and cost-effective solutions. Moreover, the dual benefits of enhanced degradation and ease of catalyst recovery (especially for Fe3O4) present opportunities for sustainable operational strategies.

Limitations

Despite promising results, some limitations must be acknowledged. The study was conducted under controlled laboratory conditions with synthetic wastewater or representative samples, which may not fully capture the complexity of real industrial effluents containing mixed contaminants and fluctuating compositions. Long-term operational stability, potential catalyst fouling, and effects of competing ions or solids were not extensively evaluated.

Additionally, TiO2's photocatalytic activity relies on UV light, which may limit efficiency under natural sunlight or in turbid water conditions without supplemental light sources. The scalability of the process and economic analysis including catalyst synthesis costs, energy consumption, and maintenance require further investigation.

Future research should focus on pilot-scale studies, exploring hybrid systems combining nanocatalyst-driven AOPs with biological or membrane treatments to enhance overall efficiency. Studies on the environmental impact and toxicity of nanomaterials post-treatment are also essential to ensure safe implementation.

Conclusion

This study successfully demonstrated the potential of nanocatalyst-driven advanced oxidation processes for efficient treatment of wastewater in the water-scarce and pollution-prone region of Jodhpur. Synthesized TiO2 and Fe3O4 nanoparticles exhibited high catalytic activity, with TiO2 achieving up to 92% chemical oxygen demand removal and following pseudo-first-order kinetics under optimized conditions of catalyst dosage, pH, and reaction time.

The use of Response Surface Methodology enabled precise optimization of operational parameters, resulting in a robust, predictive model that matched experimental outcomes.

Catalyst reusability tests confirmed the stability and durability of TiO2 nanoparticles, emphasizing their suitability for repeated application, while Fe3O4's magnetic properties offer advantages for recovery and recycling.

The findings underscore the promise of integrating nanotechnology with advanced oxidation to overcome limitations of conventional wastewater treatment methods, particularly in challenging environments like Jodhpur. This approach not only enhances pollutant degradation but also supports sustainable water management by enabling reuse and reducing environmental risks.

However, translating these laboratory-scale results to real-world applications requires further pilot studies to address challenges related to catalyst fouling, variable wastewater composition, and economic viability. Comprehensive assessments of environmental safety and lifecycle impacts of nanocatalysts are also vital for responsible deployment.

Overall, nanocatalyst-driven AOPs represent a significant advancement toward sustainable wastewater treatment technologies capable of addressing the dual challenges of water pollution and scarcity in arid regions. The insights from this research provide a foundation for future innovation, policy development, and practical implementation of effective wastewater treatment solutions.

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