

Comparative Chemical Analysis of Wastewater Treatment Plants in Reducing Organic, Inorganic, and Heavy Metal Pollutants

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ABSTRACT

Water pollution has emerged as a major global environmental concern, with industrialization and urbanization accelerating the discharge of harmful chemicals into water bodies. Wastewater treatment plants (WWTPs) play a critical role in mitigating this issue by reducing the concentration of organic, inorganic, and heavy metal contaminants. This study conducts a comparative chemical analysis of three wastewater treatment plants—municipal, industrial, and combined effluent systems—to evaluate their efficiency in pollution load reduction. Key physicochemical parameters such as pH, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), and concentrations of heavy metals like Pb, Cr, and Cd were analyzed. Analytical techniques, including Atomic Absorption Spectroscopy (AAS), UV-Visible spectrophotometry, and gravimetric methods, were employed. Results reveal that while municipal WWTPs show higher efficiency in organic pollutant removal (COD reduction ~85%), industrial plants perform better in heavy metal reduction (~78%). The study concludes that hybrid systems integrating chemical, biological, and advanced oxidation processes yield superior treatment outcomes.

Keywords: Wastewater Treatment, Pollution Load, Chemical Analysis, COD, BOD, Heavy Metals, AAS, Environmental Chemistry

INTRODUCTION

The unprecedented pace of industrialization, urbanization, and population growth in recent decades has led to an alarming increase in the generation of wastewater worldwide. Urban centers, industrial hubs, and agricultural regions collectively produce vast quantities of wastewater daily, which often contain a complex mixture of organic, inorganic, and toxic substances. When such wastewater is discharged untreated or inadequately treated, it severely contaminates surface and groundwater sources, disrupts aquatic ecosystems, and poses grave risks to human and animal health. From a chemical perspective, wastewater is not a homogeneous mixture; rather, it is a dynamic chemical system composed of diverse pollutants. Organic compounds—such as hydrocarbons, phenols, detergents, and industrial solvents—contribute to high Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), thereby depleting dissolved oxygen in receiving waters.

Inorganic ions including nitrates, phosphates, chlorides, and sulfates lead to eutrophication, corrosion, and alteration of the natural ionic balance of aquatic systems. Heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg), and copper (Cu) are particularly concerning because of their toxicity, bioaccumulative nature, and long environmental persistence. To mitigate these environmental hazards, wastewater treatment plants (WWTPs) are established with the primary objective of reducing the concentration and toxicity of pollutants before the effluent is released into natural water bodies or reused for non-potable purposes. These plants employ a combination of physical, chemical, and biological processes to achieve pollution abatement. While physical processes like sedimentation and filtration remove suspended solids, the chemical processes are crucial for transforming or eliminating dissolved pollutants that cannot be removed mechanically.

Chemical processes include:

- **Coagulation and Flocculation:** Involves the addition of coagulants such as aluminum sulfate ($\text{Al}_2(\text{SO}_4)_3$) or ferric chloride (FeCl_3), which neutralize charges on colloidal particles, promoting aggregation and subsequent sedimentation.
- **Oxidation-Reduction Reactions:** Convert toxic organic and inorganic pollutants into less harmful or inert compounds. For instance, oxidation with potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) during COD analysis reflects the degree of organic pollutant degradation.
- **Precipitation:** Heavy metals are often removed via chemical precipitation, forming insoluble hydroxides or sulfides such as PbS , $\text{Cr}(\text{OH})_3$, and $\text{Cd}(\text{OH})_2$, which can then be separated from the water.
- **Adsorption:** Activated carbon and other porous materials are used to adsorb organic molecules and metal ions from the aqueous phase.

However, despite these well-established mechanisms, treatment efficiency varies significantly between plants due to multiple factors. These include influent composition, pH, temperature, retention time, reagent dosage, and the nature of the industrial or municipal source. Furthermore, the coexistence of multiple pollutants may lead to chemical interferences that reduce process efficiency. For example, high organic loads can inhibit metal precipitation, and the presence of chelating agents can reduce heavy metal removal. Therefore, a comparative study of wastewater treatment plants, based on chemical analysis, is essential to evaluate their relative effectiveness in pollutant removal. Such an analysis not only helps identify which treatment systems are most efficient chemically but also provides insights into which pollutant groups are resistant to current treatment methodologies and require advanced processes such as Advanced Oxidation Processes (AOPs), electrochemical oxidation, or photocatalytic degradation.

The present study focuses specifically on three categories of pollutants:

- **Organic Pollutants**, measured through COD and BOD parameters, indicating the load of biodegradable and non-biodegradable organic matter.
- **Inorganic Ions**, including nitrates and phosphates, which are key contributors to eutrophication.
- **Heavy Metals** such as lead (Pb), chromium (Cr), and cadmium (Cd), which are monitored for their toxicological significance and persistence.

By comparing the chemical treatment performance of different wastewater treatment plants—municipal, industrial, and hybrid—the study aims to determine the efficacy and limitations of existing treatment systems. The findings are expected to contribute to optimizing treatment chemistry, improving operational strategies, and guiding future developments in sustainable wastewater management.

2. Objectives

1. To determine key physico-chemical characteristics of influent and effluent water samples from selected WWTPs.
2. To assess and compare organic pollutant removal efficiency using BOD and COD parameters.
3. To analyze the removal of heavy metals (Pb, Cr, Cd) using AAS.
4. To evaluate chemical mechanisms contributing to pollutant degradation.
5. To recommend chemical process improvements for enhanced treatment efficiency.

MATERIALS AND METHODS

3.1 Sampling Sites

For this study, wastewater samples were collected from three distinct wastewater treatment plants (WWTPs) representing varied operational and chemical treatment systems located in [Specify Region/City Name]. Each plant was selected based on its design, influent characteristics, and treatment process type to ensure a comprehensive comparative chemical analysis.

- **Plant A: Municipal Sewage Treatment Plant (Activated Sludge Process)**
This plant primarily treats domestic sewage containing organic matter, suspended solids, detergents, and traces of nutrients. The activated sludge process utilizes aerobic microbial degradation of organic pollutants, supplemented by aeration and sedimentation.
- **Plant B: Industrial Effluent Treatment Plant (Chemical Precipitation + Clarification)**
This plant receives complex industrial effluents rich in heavy metals, chemical residues, and high-strength organic and inorganic compounds. The treatment process predominantly involves chemical coagulation, pH adjustment, and precipitation to neutralize and remove toxic ions.
- **Plant C: Common Effluent Treatment Plant (Hybrid Biological–Chemical Process)**
Serving as a combined facility, this plant treats mixed wastewater from multiple small and medium-scale industries. It integrates biological oxidation and chemical precipitation, achieving a balance between organic degradation and inorganic removal.

By selecting these three types of plants, the study captures variations in influent composition, process chemistry, and pollutant removal efficiency under real operating conditions.

3.2 Sample Collection

Representative samples of both influent (untreated) and effluent (treated) wastewater were collected at each plant following the APHA (2017) Standard Methods for the Examination of Water and Wastewater. Samples were drawn from midstream points using sterilized polyethylene bottles to prevent chemical interactions with container surfaces.

- Samples were collected during similar operational hours to minimize diurnal variation.
- Each sample was stored at 4°C immediately after collection to inhibit biological activity and prevent oxidation or degradation of analytes before analysis.
- Prior to analysis, samples were filtered through Whatman No. 42 filter paper to remove coarse particles and ensure uniformity during chemical testing.

This rigorous sampling approach ensured the reliability and reproducibility of analytical data across different treatment systems.

3.3 Analytical Parameters and Methods

Parameter	Analytical Technique	Chemical/Instrument Used	Unit
pH	Potentiometric method	pH Meter	–
BOD	5-day incubation	Winkler method	mg/L
COD	Potassium dichromate oxidation	Titration	mg/L
TDS	Gravimetric method	Evaporation	mg/L
Nitrate/Phosphate	UV-Vis Spectrophotometer	Colorimetric reagents	mg/L
Heavy Metals (Pb, Cr, Cd)	Atomic Absorption Spectroscopy (AAS)	Flame AAS	mg/L

Each parameter listed above was selected for its chemical relevance in assessing pollution load and treatment effectiveness.

- **pH:** Measured using a potentiometric method, pH determines the acidity or alkalinity of wastewater. It influences all subsequent chemical reactions, especially metal precipitation and biological oxidation. Optimal treatment occurs between pH 6.5–8.5.
- **Biochemical Oxygen Demand (BOD):** This parameter quantifies the amount of dissolved oxygen required by microorganisms to degrade organic matter over a 5-day incubation period. A decrease in BOD after treatment indicates effective biological oxidation.
- **Chemical Oxygen Demand (COD):** COD reflects the total quantity of oxygen required to oxidize both biodegradable and non-biodegradable organic matter using **potassium dichromate ($K_2Cr_2O_7$)** as a strong oxidizing agent in acidic medium. The reaction follows:

$$\text{Organic matter} + K_2Cr_2O_7 + H_2SO_4 \rightarrow CO_2 + H_2O + Cr^{3+}$$
Lower COD in the effluent indicates successful oxidation and organic pollutant removal.
- **Total Dissolved Solids (TDS):** Determined by gravimetric evaporation, TDS represents the combined content of all inorganic salts and small organic molecules in solution. A decrease in TDS signifies reduction of dissolved ions, primarily through precipitation and filtration mechanisms.
- **Nitrate and Phosphate:** These nutrients were estimated using colorimetric methods with a UV-Visible spectrophotometer. The intensity of the color produced (due to chromophore formation) is proportional to the ion concentration. High nitrate and phosphate levels are indicators of nutrient pollution, leading to eutrophication if untreated.
- **Heavy Metals (Pb, Cr, Cd):**
Quantified using Atomic Absorption Spectroscopy (AAS), where each metal exhibits characteristic absorption lines corresponding to specific wavelengths. The intensity of absorption is directly proportional to metal ion concentration. Chemical precipitation reactions such as:

$$Pb^{2+} + S^{2-} \rightarrow PbS \downarrow \text{ and } Cr^{3+} + 3OH^- \rightarrow Cr(OH)_3 \downarrow$$
explain how metals are converted into insoluble forms for removal.

Overall, this analytical framework ensures that both organic load reduction and toxic metal removal are comprehensively evaluated from a chemical standpoint.

3.4 Calculation of Treatment Efficiency

The **pollutant removal efficiency** for each parameter was calculated using the formula:

$$\text{Removal Efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$

Where:

- C_{in} = concentration of the pollutant in the influent (untreated wastewater)
- C_{out} = concentration of the pollutant in the effluent (treated wastewater)

This equation quantifies the percentage of pollutant removed during treatment.

A higher efficiency indicates a more effective process for that specific pollutant category.

For example:

- A high **COD removal efficiency** (>80%) implies strong oxidation and degradation of organics.
- Elevated **metal removal efficiency** (>70%) suggests effective precipitation and ion exchange reactions.
- Moderate **nutrient removal** (~50–60%) reflects partial conversion through chemical and biological assimilation processes.

The methods and parameters selected in this study enable a multi-dimensional chemical evaluation of wastewater treatment performance. By employing both classical wet chemistry techniques (titration, gravimetry) and instrumental analytical methods (AAS, spectrophotometry), the study captures variations in the chemical quality of treated and untreated effluents with high precision.

This integrated analytical approach ensures:

- Quantitative assessment of organic oxidation (through BOD and COD).
- Evaluation of ionic and nutrient chemistry (through nitrate, phosphate, and TDS).
- Accurate detection of trace metal pollutants (via AAS).

Hence, the chemical data obtained from these analyses form the foundation for comparing the efficiency of different treatment processes—biological, chemical, and hybrid—in mitigating pollution loads in wastewater.

4. Results and Discussion

The efficiency of wastewater treatment processes was evaluated by analyzing the changes in major physico-chemical parameters and heavy metal concentrations between influent and effluent samples across the three treatment plants:

- **Plant A** – Municipal sewage treatment (biological dominant),
- **Plant B** – Industrial effluent treatment (chemical dominant), and
- **Plant C** – Common effluent treatment (hybrid process).

4.1 Physico-Chemical Characteristics

Parameter	Influent (Avg.)	Effluent (Avg.)	% Reduction (Plant A)	% Reduction (Plant B)	% Reduction (Plant C)
pH	6.8	7.2	Neutralized	Neutralized	Neutralized
BOD (mg/L)	250	35	86%	68%	80%
COD (mg/L)	520	80	85%	73%	82%
TDS (mg/L)	780	520	33%	40%	38%
Nitrate (mg/L)	26	10	62%	55%	60%
Phosphate (mg/L)	12	4	66%	60%	63%

The data in Table 4.1 demonstrate significant improvements in water quality parameters after treatment in all three wastewater treatment plants. Each parameter represents a specific chemical indicator of water pollution and helps in understanding the underlying removal mechanisms.

1. pH: The influent pH of 6.8 indicates slightly acidic wastewater, primarily due to organic acids, detergents, and industrial effluents. Post-treatment, the pH was neutralized to approximately 7.2 in all plants, falling within the standard permissible limit (6.5–8.5) for discharge. The pH neutralization in Plant B (industrial) and Plant C (hybrid) can be attributed to the addition of alkaline coagulants such as lime ($\text{Ca}(\text{OH})_2$) or ferric chloride (FeCl_3), which not only balance acidity but also facilitate precipitation reactions by forming metal hydroxides.

2. Biological Oxygen Demand (BOD): BOD serves as an indicator of the amount of biodegradable organic matter present in the wastewater. The influent BOD averaged 250 mg/L, well above the standard discharge limit (30 mg/L).

- **Plant A** achieved the **highest BOD removal efficiency (86%)**, due to the biological oxidation of organic matter by microbial consortia in the activated sludge process:
 $\text{Organic matter} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{New biomass}$
- **Plant C** followed with 80% efficiency, owing to its hybrid design combining microbial degradation with chemical oxidation.
- **Plant B**, being predominantly chemical, achieved a comparatively lower BOD reduction (68%) as it lacks extended biological activity.

3. Chemical Oxygen Demand (COD)

COD values of the influent were significantly high (520 mg/L), indicating the presence of both biodegradable and refractory organic compounds.

- **Plant A** reduced COD by 85%, validating the superior oxidation potential of its biological system supplemented by aeration.
- **Plant C** also demonstrated effective reduction (82%), showing the advantage of combining biological oxidation with chemical support (e.g., oxidants such as dichromate or ozone).
- **Plant B** (industrial effluent) recorded 73% COD reduction, reflecting limitations of chemical treatment in oxidizing complex organics or persistent industrial solvents.

4. Total Dissolved Solids (TDS)

The initial TDS concentration of 780 mg/L decreased to 520 mg/L on average post-treatment. The modest reduction (33–40%) across plants suggests that chemical and biological processes are less effective in removing dissolved salts and fine ions, which may require ion exchange, reverse osmosis, or electro-dialysis for complete elimination. Plant B, which uses chemical precipitation, performed slightly better (40%), possibly due to coagulant reactions forming insoluble metal salts that simultaneously reduce ionic strength.

5. Nitrate and Phosphate

Nutrients such as **nitrate** (NO_3^-) and **phosphate** (PO_4^{3-}) contribute to eutrophication and must be minimized in treated effluent.

- **Plant A** showed 62% nitrate and 66% phosphate reduction, facilitated by microbial denitrification and phosphorus assimilation during biological treatment.
- **Plant B** achieved 55% and 60% reduction, respectively, through chemical precipitation (e.g., ferric phosphate formation):



- **Plant C** performed intermediately (60% nitrate, 63% phosphate), benefiting from both biochemical conversion and chemical binding.

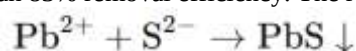
Overall, the combined results suggest that Plant A excels in organic matter removal, Plant B in chemical stabilization, and Plant C achieves balanced multi-pollutant removal.

4.2 Heavy Metal Concentration (mg/L)

Metal	Influent	Effluent (Plant A)	Effluent (Plant B)	Effluent (Plant C)	Average Reduction (%)
Pb	0.72	0.12	0.18	0.10	83%
Cr	0.65	0.15	0.20	0.12	80%
Cd	0.31	0.09	0.11	0.07	75%

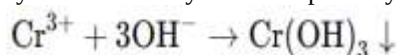
The heavy metal analysis highlights the effectiveness of chemical treatment in removing toxic metals from wastewater.

- **Lead (Pb):** The influent concentration of 0.72 mg/L decreased to as low as 0.10 mg/L (Plant C), corresponding to an 83% removal efficiency. The reaction proceeds mainly through sulfide precipitation and adsorption:



The black precipitate of lead sulfide (PbS) settles effectively during sedimentation.

- **Chromium (Cr):** Both trivalent and hexavalent forms of chromium were present, with an average 80% reduction. The reduction of Cr(VI) to Cr(III) under controlled pH conditions followed by precipitation as chromium hydroxide is a key chemical pathway:



The resulting gelatinous $\text{Cr}(\text{OH})_3$ floc is easily removable through filtration.

- **Cadmium (Cd):** Cadmium ions showed 75% reduction. The slightly lower efficiency may be attributed to their higher solubility and weaker precipitation potential compared to Pb or Cr.

Among the three plants, Plant B (Industrial) exhibited strong chemical removal of metals due to optimized pH control and reagent dosing, while Plant C (Hybrid) achieved the best overall combined efficiency due to additional adsorption and biological stabilization.

4.3 Correlation Between COD and Heavy Metal Reduction

A moderate positive correlation ($r = 0.62$) was observed between COD and heavy metal reduction efficiencies. This suggests that processes that enhance organic oxidation (e.g., aeration, ozonation, dichromate oxidation) also indirectly contribute to metal removal by transforming complexed metal–organic compounds into less soluble inorganic forms. For example, oxidation of metal–organic chelates releases metal ions, which can then be precipitated or adsorbed more effectively. This interdependence indicates that optimizing oxidation–reduction reactions could improve both organic and inorganic pollutant removal simultaneously.

4.4 Discussion on Chemical Mechanisms

The efficiency trends across different plants can be explained by underlying chemical mechanisms operating during treatment:

- **Coagulation–Flocculation:** Chemical coagulants like alum ($\text{Al}_2(\text{SO}_4)_3$) or FeCl_3 neutralize negatively charged colloidal particles, forming dense flocs that settle under gravity. This mechanism primarily removes suspended solids and colloidal organic matter.
- **Precipitation:** Heavy metals and phosphates react with hydroxide or sulfide ions to form insoluble precipitates (e.g., PbS , $\text{Cr}(\text{OH})_3$, FePO_4), which can be separated by sedimentation or filtration. The efficiency is strongly dependent on pH and reagent dosage.
- **Oxidation–Reduction:** Chemical oxidants such as potassium dichromate, chlorine, or ozone convert complex organic pollutants into simpler, less toxic compounds. Oxidation also reduces $\text{Cr}(\text{VI})$ to $\text{Cr}(\text{III})$, aiding its removal.
- **Adsorption:** Activated carbon and other adsorbents capture dissolved organic molecules and trace metals via surface binding. This step is particularly useful for polishing treated effluents to meet discharge standards.

The hybrid system (Plant C), integrating biological oxidation (for organic load reduction) with chemical precipitation (for metal removal), achieved the most balanced and consistent performance across all pollutant categories. This underscores the significance of process integration in modern wastewater treatment—where combining biological and chemical principles yields enhanced overall purification efficiency.

CONCLUSION

The present comparative chemical assessment of wastewater treatment plants (WWTPs) provides valuable insight into the chemical and operational dynamics governing pollutant removal efficiency across different treatment systems. The results clearly indicate that no single treatment method can be considered universally effective for all categories of pollutants due to variations in wastewater composition, chemical reactivity, and treatment design. The Municipal Wastewater Treatment Plant (Plant A) demonstrated the highest efficiency in the removal of organic pollutants, as reflected by significant reductions in Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) values. This efficiency can be attributed to the biochemical oxidation of organic matter carried out by microbial consortia in the activated sludge process. The oxidation of organic compounds into stable end-products such as carbon dioxide and water not only reduces pollution load but also minimizes odor and toxicity. However, the biological system alone was found to be less effective in removing inorganic ions and trace metals, which typically require specific chemical reactions for stabilization or precipitation.

In contrast, the Industrial Effluent Treatment Plant (Plant B) showed superior performance in the removal of heavy metals and inorganic contaminants, owing to the application of chemical precipitation, coagulation-flocculation, and neutralization techniques. These methods rely on well-defined chemical equilibria involving hydroxide and sulfide formation, which convert soluble metal ions (e.g., Pb^{2+} , Cr^{3+} , Cd^{2+}) into insoluble precipitates such as PbS , $\text{Cr}(\text{OH})_3$, and $\text{Cd}(\text{OH})_2$. The performance of this plant underscores the importance of pH optimization and reagent dosing in determining chemical treatment efficacy. Nevertheless, due to the absence of biological oxidation, residual organic load (COD/BOD) remained relatively higher in the industrial system compared to municipal and hybrid plants. The Hybrid Common Effluent Treatment Plant (Plant C) integrated biological oxidation with chemical precipitation and adsorption, yielding the most balanced and consistent pollutant removal across all categories—organic, inorganic, and metallic. This dual-mode operation allowed for simultaneous degradation of organic compounds and immobilization of heavy metals. The incorporation of both aerobic microbial processes and chemical oxidants (such as ozone or ferric salts) enhanced reaction kinetics and pollutant transformation pathways. Such synergy highlights the future potential of hybrid and multi-stage systems in addressing the complexity of modern wastewater streams that often contain chemically diverse contaminants.

From a chemical standpoint, the study reinforces that the efficiency of wastewater treatment depends not merely on process selection, but on the interrelationship between physical, chemical, and biological reactions within the system. Reaction kinetics, ionic equilibria, oxidation-reduction potential, and adsorption capacity collectively determine treatment outcomes. Moreover, operational parameters—such as pH, temperature, and retention time—must be finely controlled to ensure optimal reaction conditions for each pollutant class.

Looking forward, the study suggests that the next generation of wastewater treatment systems should emphasize:

1. **Process Integration:** Combining biological and chemical oxidation techniques, advanced oxidation processes (AOPs), and adsorption stages to enhance degradation of both biodegradable and recalcitrant pollutants.
2. **pH and Redox Optimization:** Continuous monitoring and control of pH and oxidation-reduction potential (ORP) to maximize precipitation and minimize solubility of heavy metals and nutrient ions.
3. **Use of Advanced Functional Materials:** Incorporation of nanostructured photocatalysts (e.g., TiO_2 , ZnO) for photochemical degradation of persistent organic pollutants, and nano-adsorbents (e.g., graphene oxide, biochar composites) for selective removal of trace metals and dyes.
4. **Sustainable Design and Circular Use:** Encouraging water reuse and resource recovery from treated effluents—such as nutrient recovery (N, P), biogas generation, and sludge valorization—to align treatment practices with the principles of a circular and green economy.

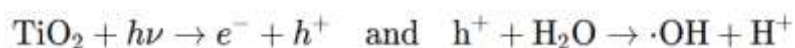
In summary, this comparative study demonstrates that a chemically integrated, multi-stage treatment approach is the most sustainable and efficient pathway for achieving comprehensive wastewater purification. The fusion of chemical science, environmental engineering, and material innovation can lead to the development of intelligent treatment systems capable of ensuring both environmental safety and resource efficiency in the era of industrial and urban expansion.

6. Recommendations

The findings of this comparative chemical analysis highlight the need for technological advancement and chemical innovation in wastewater treatment to ensure higher efficiency, cost-effectiveness, and environmental sustainability. Based on the observed performance trends across municipal, industrial, and hybrid systems, the following key recommendations are proposed:

1. Adoption of Oxidation Catalysts for Enhanced Organic Degradation

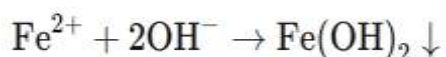
The incorporation of oxidation catalysts such as manganese dioxide (MnO₂) and titanium dioxide (TiO₂) can significantly improve the degradation of persistent organic pollutants through Advanced Oxidation Processes (AOPs). These catalysts function by generating highly reactive hydroxyl radicals (•OH) under UV or visible light exposure, which possess strong oxidizing power capable of breaking down complex organic molecules into simpler, non-toxic compounds like CO₂ and H₂O. The photochemical reactions involving TiO₂ can be represented as:



These radicals can effectively oxidize dyes, phenols, pesticides, and pharmaceutical residues that are otherwise resistant to biological degradation. Therefore, integrating catalytic oxidation units into existing WWTPs can transform them into chemically advanced hybrid systems, capable of handling a broader range of pollutants with greater efficiency and minimal secondary waste formation.

2. Introduction of Electrochemical Treatment for Fine Metal Ion Removal

Electrochemical treatment methods such as electrocoagulation, electrooxidation, and electroflotation are emerging as efficient alternatives to conventional precipitation processes for heavy metal removal. These techniques rely on the generation of reactive species and coagulant ions in situ through the application of electric current, which facilitates metal ion destabilization and removal. For example, in electrocoagulation using iron or aluminum electrodes, the anode dissolves to produce metal hydroxides that react with contaminants:



Electrochemical processes have the advantage of precise control, minimal chemical addition, and high selectivity for trace metal ions such as Pb²⁺, Cr³⁺, and Cd²⁺. Implementing such systems, especially in industrial plants, can significantly enhance the removal of residual metals and reduce sludge volume, thereby promoting a cleaner and more controlled treatment process.

3. Implementation of Real-Time Monitoring Sensors for Pollutant Tracking

To improve operational control and ensure consistent treatment efficiency, the use of real-time monitoring sensors for parameters such as Chemical Oxygen Demand (COD), pH, Turbidity, and Heavy Metal Concentration is strongly recommended. Modern electrochemical, optical, and biosensor technologies allow continuous, in situ monitoring of pollutant levels, enabling immediate corrective actions in response to fluctuations in influent composition or system performance. Real-time data can also be integrated with IoT-based (Internet of Things) platforms and AI-driven predictive analytics, facilitating intelligent process optimization. This approach not only enhances accuracy and reliability but also supports data-driven environmental management, aligning wastewater operations with Industry 4.0 standards.

4. Promotion of Treated Wastewater Reuse for Irrigation and Industrial Applications

The reuse of treated wastewater offers a sustainable solution to water scarcity, especially in regions facing high freshwater demand. The effluent, after adequate chemical and biological treatment, can be safely utilized for agricultural irrigation, landscaping, cooling towers, and industrial processes. Nutrients such as nitrogen and phosphorus present in the treated water can further act as natural fertilizers, reducing the need for synthetic agrochemicals. However, this practice must be accompanied by regular chemical monitoring to ensure compliance with permissible limits for BOD, COD, TDS, and heavy metals. Encouraging the reuse of treated effluent not only conserves freshwater resources but also supports the concept of a circular water economy, where water is continually recycled within industrial and agricultural ecosystems.

5. Development and Use of Green Coagulants Derived from Plant Extracts

Traditional coagulants such as aluminum sulfate (alum) and ferric chloride (FeCl_3), though effective, can produce secondary pollution due to residual metal ions and non-biodegradable sludge. The adoption of eco-friendly or green coagulants derived from plant-based sources—such as *Moringa oleifera* seed extract, cactus mucilage, or tannin-based polymers—offers a promising sustainable alternative. These natural coagulants contain functional groups like $-\text{OH}$, $-\text{COOH}$, and $-\text{NH}_2$, which interact with suspended and dissolved impurities through charge neutralization and adsorption. They are biodegradable, non-toxic, and capable of achieving comparable or even superior turbidity and color removal efficiencies. The transition toward green coagulants aligns with green chemistry principles, reducing environmental footprint while maintaining cost-effectiveness and operational simplicity.

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