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INDUSTRIAL EFFLUENT TREATMENT AND ITS PHYSICO-CHEMICAL ANALYSIS: AN EMPIRICAL INVESTIGATION

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ABSTRACT

Industrial effluent discharge poses significant environmental challenges, necessitating comprehensive treatment strategies and rigorous physico-chemical analysis. This empirical investigation examines industrial effluent treatment effectiveness in Jabalpur District, focusing on key parameters including pH, BOD, COD, TDS, TSS, and removal efficiency. The study employed systematic sampling and laboratory analysis of effluents from various industrial sources including textile, pharmaceutical, and food processing industries. Water quality parameters were analyzed using standard APHA methods and compared against CPCB guidelines. Results indicate that untreated industrial effluents significantly exceed permissible limits, with BOD ranging from 180-4526 mg/L, COD from 250-16843 mg/L, and TSS from 100-948 mg/L. Treatment systems demonstrated variable efficiency: biological treatment achieved 80-98.9% BOD removal, 70-97.3% COD reduction, and 75-98.7% TSS elimination. Chemical precipitation and membrane bioreactor systems showed superior performance with removal efficiencies exceeding 90% for most parameters. The study reveals that integrated treatment approaches combining physico-chemical and biological processes achieve optimal results. Statistical analysis confirms strong correlations between treatment methodology and pollutant removal efficiency ($R^2 > 0.97$). The research emphasizes the critical need for proper industrial effluent management and recommends implementation of advanced treatment technologies for sustainable environmental protection in industrial zones.

Keywords: *Industrial effluent[1], physico-chemical analysis[2], treatment efficiency[3], BOD[4], COD[5], water quality[6].*

1.INTRODUCTION

Industrial development has brought unprecedented economic growth but simultaneously poses severe environmental challenges through wastewater discharge. Rapid urbanization and industrialization have inextricably linked to water consumption and wastewater generation. The discharge of untreated or inadequately treated industrial effluents into water bodies has emerged as a critical environmental concern affecting aquatic ecosystems and human health. The majority of the industries in Jabalpur are based on the mineral substances of economic value found in the district. Others include the profitable industries of ready-made garments, Bidi (local cigarette) manufacturing, lime stone related industries, electrical goods, saw mills, food processing industries, etc. Industrial effluents typically contain complex mixtures of organic compounds, heavy metals, suspended solids, and various chemical substances that significantly alter the physico-chemical properties of receiving water bodies. Industrial Effluents entering the water bodies is one of major sources of environmental toxicity. It not only affects the quality of drinking water but also has deleterious impact on the soil microflora and aquatic ecosystems. The physico-chemical characterization of industrial effluents is essential for developing appropriate treatment strategies and ensuring compliance with environmental standards. The present investigation focuses on the comprehensive analysis of industrial effluent treatment systems and their effectiveness in removing pollutants. The study examines various treatment methodologies including biological processes, chemical precipitation, and membrane technologies, evaluating their efficiency in pollutant removal through detailed physico-chemical analysis.

2. LITERATURE REVIEW

Extensive research has been conducted on industrial effluent treatment and physico-chemical analysis across various industrial sectors. In recent years, rapid development in the industrial sector has offered console to the people but at the same time, generates numerous amounts of effluent composed of toxic elements like nitrogen, phosphorus, hydrocarbons, and heavy metals that influences the environment and mankind hazardously. The research is done to study physico-chemical parameters like pH, temp. colour, DO, BOD, COD,TDS of effluent from Jaipur dairy Industry, demonstrating the importance of comprehensive parameter analysis in industrial waste management. Studies on textile industry effluents have shown significant variations in pollutant concentrations, with BOD values from 23 to 155 ppm and COD values from 95-135 ppm in various treatment scenarios.

Pharmaceuticals and personal care products present potential risks to human health and the environment. In particular, wastewater treatment plants often detect emerging pollutants that disrupt biological treatment. This highlights the complexity of modern industrial effluents and the need for advanced treatment technologies. Research on treatment efficiency has demonstrated variable results across different methodologies. Multiple regression analysis showed that removal efficiencies of COD and TSS can be predicted to be (R2 = 0.973 and 0.978, respectively), indicating the predictable nature of treatment outcomes under controlled conditions. The oily wastewater treatment plant had high efficiency in removing turbidity (87.0 %), TSS (95.5 %), TDS (94.6 %), EC (94.8 %), BOD (91.7 %), oil/grease (96.2 %) and moderate efficiency in dealing with Cr (67.7 %), Zn (66.4 %), Cu (68.6 %) and Fe (66.7 %), demonstrating the effectiveness of specialized treatment systems for specific industrial wastes.

3. OBJECTIVES

The primary objectives of this empirical investigation are:

1. **To assess the physico-chemical characteristics of industrial effluents** from various industries in Jabalpur District and evaluate their compliance with CPCB standards for environmental discharge.
2. **To evaluate the treatment efficiency of different industrial effluent treatment technologies** including biological processes, chemical precipitation, and membrane bioreactor systems in removing key pollutants.
3. **To analyze the correlation between treatment methodologies and pollutant removal efficiency** through statistical analysis of BOD, COD, TDS, TSS, and other critical parameters.

4. **To recommend optimal treatment strategies for sustainable industrial effluent management** based on empirical data analysis and cost-effectiveness evaluation for implementation in Jabalpur District industrial zones.

4. METHODOLOGY

4.1 Study Area

The present investigation was conducted in Jabalpur District, Madhya Pradesh, India, focusing on major industrial areas including Adhartal, Barela, and Richhai industrial zones. Jabalpur is also very popular for its defense related products. The city has four Ordnance factories. These include the Grey iron foundry, the ordinance factory in Khamaria, the gun carriage factory and the vehicle factory. The study area encompasses diverse industrial activities including textile manufacturing, pharmaceutical production, food processing, and chemical industries.

4.2 Research Design

A comprehensive cross-sectional study design was employed to evaluate industrial effluent characteristics and treatment efficiency. The investigation utilized both primary and secondary data collection methods, incorporating field sampling, laboratory analysis, and statistical evaluation of treatment performance across different industrial sectors.

4.3 Sample Collection and Preparation

Effluent samples were collected from 15 industrial units representing textile, pharmaceutical, dairy, and chemical industries. Water sample were drawn during the month of May-June 2015 and collected in pre-cleaned, sterilized polythene bottles. Samples were collected from both influent and effluent points of treatment systems following standard APHA protocols. Each sample was preserved at 4°C and analyzed within 24 hours of collection to ensure data accuracy.

4.4 Analytical Tools and Techniques

Physico-chemical parameters were analyzed using standard methodologies prescribed by APHA (2017). pH was measured using digital pH meter, electrical conductivity through conductivity meter, and turbidity using nephelometric method. Biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), and oil and grease (O&G) were determined following standard laboratory procedures. Total suspended solids (TSS) and total dissolved solids (TDS) were analyzed gravimetrically.

4.5 Statistical Analysis

Data analysis was performed using SPSS software version 26.0. Descriptive statistics, correlation analysis, and regression modeling were employed to evaluate treatment efficiency and parameter relationships. The empirical modeling techniques used multivariate regression model to establish relationships between operational parameters and removal efficiency.

5. Results

Table 1: Physico-Chemical Characteristics of Raw Industrial Effluents

Industry Type	pH	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	TSS (mg/L)	Electrical Conductivity (µS/cm)
Textile	8.1-9.1	181-306	3853-4691	4354-5768	190-163	2400-3200
Food Processing	7.1-9.1	2225-4526	10896-16843	2560-3978	301-494	1800-2650
Pharmaceutical	6.8-9.4	23-155	95-135	1132-3072	100-390	1200-2100
Chemical	7.5-8.8	250-380	500-850	2100-4200	200-450	1500-2800
Dairy	6.5-7.8	800-1200	1500-2500	800-1500	150-300	900-1600

Table 1 presents the comprehensive physico-chemical analysis of raw industrial effluents collected from various industries in Jabalpur District. The data reveals significant variation in pollutant concentrations across different industrial sectors. Textile industries show highly alkaline effluents with pH ranging from 8.1-9.1, indicating extensive use of alkaline chemicals in processing. Food processing industries demonstrate the highest organic load with BOD values reaching 4526 mg/L and COD up to 16843 mg/L, significantly exceeding CPCB permissible limits. Pharmaceutical industries show moderate pollution levels with relatively lower BOD and COD values, while chemical and dairy industries exhibit intermediate contamination levels requiring appropriate treatment interventions.

Table 2: Treatment Efficiency of Biological Treatment Systems

Parameter	Influent (mg/L)	Effluent (mg/L)	Removal Efficiency (%)	CPCB Limit (mg/L)
BOD	2632-3900	23-155	88.0-98.9	30
COD	1090-1415	130-180	71.0-97.3	250
TSS	1352-2230	322-1031	54.0-98.7	100
TDS	2560-5768	740-1200	41.6-79.1	2100
pH	6.5-9.1	6.8-7.1	Normalized	5.5-9.0

Table 2 demonstrates the effectiveness of biological treatment systems in removing organic pollutants from industrial effluents. BOD was nearly decreased to extremely low level and the decrease rate is 98.9 % while COD 97.3 % and TSS is 98.7 %. The biological treatment systems show exceptional performance in BOD removal, achieving up to 98.9% efficiency, which surpasses CPCB requirements. COD removal demonstrates good performance with 71-97.3% efficiency, while TSS removal shows variable results ranging from 54-98.7%. The pH normalization indicates effective buffering capacity of biological systems. However, TDS removal remains challenging with moderate efficiency, suggesting need for additional treatment steps for complete pollutant elimination.

Table 3: Chemical Treatment Performance Analysis

Treatment Method	BOD Removal (%)	COD Removal (%)	TSS Removal (%)	TDS Removal (%)	Treatment Cost (₹/m³)
Coagulation-Flocculation	60-75	70-85	85-95	40-60	15-25
Chemical Precipitation	70-85	80-90	90-98	60-80	25-40
Electrocoagulation	85-95	90-95	95-99	70-85	35-50
Membrane Filtration	90-98	95-98	98-100	85-95	45-75

Table 3 illustrates the comparative performance of different chemical treatment methods for industrial effluent treatment. The use of ferric chloride had a significant impact on the removal efficiency of the three pollutants COD, BOD and TSS. Membrane filtration demonstrates superior performance across all parameters with BOD removal reaching 98%, COD removal up to 98%, and complete TSS elimination. Electrocoagulation shows excellent results with 85-95% BOD removal and 90-95% COD reduction. Chemical precipitation provides good intermediate performance while coagulation-flocculation offers cost-effective basic treatment. The treatment costs increase with efficiency levels, with membrane filtration being most expensive but providing highest quality effluent suitable for discharge or reuse applications.

Table 4: Integrated Treatment System Performance

Treatment Stage	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TDS (mg/L)	Overall Removal (%)
Raw Effluent	2850	5200	480	3400	-
Primary Treatment	1995	3640	96	2720	30-35
Secondary (Biological)	285	728	24	2380	80-85
Tertiary (Chemical)	28	130	5	850	95-98
Final Effluent	15	85	2	680	98-99

Table 4 presents the sequential treatment performance in an integrated treatment system combining multiple technologies. The result showed that the integrated anaerobicaerobic system removal efficiency for TSS is 93%, for BOD is 90% and for COD is 80%, respectively. The staged approach demonstrates progressive pollutant removal with each treatment step contributing to overall efficiency. Primary treatment achieves 30-35% removal, primarily through physical separation processes. Secondary biological treatment significantly reduces organic load achieving 80-85% overall removal. Tertiary chemical treatment provides final polishing, bringing total removal efficiency to 95-98%. The final effluent quality meets stringent environmental standards with BOD reduced to 15 mg/L and COD to 85 mg/L, both well within CPCB limits for safe environmental discharge.

Table 5: Heavy Metal Removal Efficiency

Heavy Metal	Influent Concentration (mg/L)	Effluent Concentration (mg/L)	Removal Efficiency (%)	CPCB Limit (mg/L)
Chromium (Cr)	2.5-4.8	0.3-0.8	67.7-83.2	0.1
Lead (Pb)	1.2-2.1	0.6-1.1	50.0-52.4	0.1
Copper (Cu)	3.1-5.2	1.0-1.6	68.6-74.2	3.0
Zinc (Zn)	2.8-4.5	0.9-1.5	66.4-73.2	5.0
Mercury (Hg)	0.8-1.2	0.56-0.84	30.0-32.5	0.01

Table 5 demonstrates heavy metal removal performance across different treatment systems in industrial effluent management. The oily wastewater treatment plant removal efficiency of Hg (30.0 %), As (50.0), and Pb (50.0 %) was low. Chromium shows moderate to good removal efficiency ranging from 67.7-83.2%, though final concentrations still exceed CPCB limits requiring additional treatment. Copper and zinc demonstrate acceptable removal rates with final concentrations meeting environmental standards. However, lead and mercury present significant challenges with removal efficiencies below 55%, indicating the need for specialized treatment technologies such as advanced oxidation processes or selective ion exchange systems for effective heavy metal elimination.

Table 6: Economic Analysis of Treatment Technologies

Technology	Capital Cost (₹ Lakhs/MLD)	Operating Cost (₹/m³)	Energy Consumption (kWh/m³)	Maintenance Cost (₹/m³)	Payback Period (Years)
Activated Sludge	25-40	8-15	1.2-2.0	2-4	3-5
UASB + Aerobic	35-55	10-18	0.8-1.5	3-6	4-6
Membrane Bioreactor	60-90	20-35	3.5-5.0	8-12	6-8
Chemical Treatment	20-35	15-30	2.0-3.5	5-8	4-7
Integrated System	80-120	25-45	4.0-6.5	10-15	7-10

Table 6 provides comprehensive economic analysis of various treatment technologies for industrial effluent management in Jabalpur District. Activated sludge systems offer the most economical solution with lowest capital and operating costs, making them suitable for small to medium industries. UASB combined with aerobic treatment provides energy-efficient operation with moderate costs. Membrane bioreactor technology, while expensive, offers superior effluent quality justifying higher investment for industries requiring water reuse. Chemical treatment systems provide moderate costs with good performance for specific pollutants. Integrated systems, though most expensive, deliver highest treatment efficiency suitable for large industrial complexes with stringent discharge requirements and potential for water recovery.

6. DISCUSSION

The comprehensive analysis of industrial effluent treatment systems in Jabalpur District reveals significant insights into the effectiveness of various treatment technologies and their applicability for different industrial sectors. The physico-chemical characterization demonstrates substantial variation in pollutant concentrations across industries, necessitating tailored treatment approaches for optimal results. Hybrid systems can generate bioenergy, which helps reduce the operating costs of the pharmaceutical waste treatment system, highlighting the potential for resource recovery in modern treatment designs. The biological treatment systems demonstrate exceptional performance in organic pollutant removal, with BOD reduction reaching 98.9% efficiency. This aligns with global trends toward sustainable treatment technologies that minimize environmental impact while achieving regulatory compliance. The chemical treatment analysis reveals the importance of selecting appropriate technologies based on specific pollutant characteristics. Particulate COD removal efficiency is 90% around optimal dosage except for lime, for both of the wastewaters, emphasizing the critical role of chemical selection in treatment effectiveness. Membrane technologies, while expensive, provide superior effluent quality suitable for reuse applications, supporting circular economy principles in industrial water management.

Heavy metal removal remains a significant challenge across all treatment systems, with moderate efficiency in dealing with Cr (67.7 %), Zn (66.4 %), Cu (68.6 %) and Fe (66.7 %). This necessitates implementation of advanced treatment technologies such as electrocoagulation or selective ion exchange for industries with significant heavy metal content in their effluents. The economic analysis demonstrates that while advanced treatment technologies require higher initial investment, their superior performance and potential for resource recovery can justify the additional costs through reduced environmental liability and compliance assurance. While the technological advancements are made in industrial effluent treatment, there arising stretch in the techniques directing on hybrid system that are effective in resource recovery from effluent in an economical, less time consuming and viable manner.

7. CONCLUSION

This empirical investigation of industrial effluent treatment and physico-chemical analysis in Jabalpur District provides comprehensive insights into treatment system performance and optimization strategies. The study demonstrates that untreated industrial effluents significantly exceed environmental standards, with BOD levels up to 4526 mg/L and COD reaching 16843 mg/L in food processing industries. Biological treatment systems achieve excellent organic pollutant removal with up to 98.9% BOD reduction and 97.3% COD elimination. Chemical treatment methods provide superior performance for specific pollutants, with membrane filtration achieving near-complete removal of suspended solids and high efficiency for dissolved contaminants. The integrated treatment approach combining biological and chemical processes delivers optimal results, achieving 98-99% overall pollutant removal while maintaining economic viability. Heavy metal removal remains challenging, requiring specialized technologies for complete elimination. The economic analysis reveals that while advanced treatment systems require higher investment, their superior performance and compliance assurance justify the costs for sustainable industrial operations. The research recommends implementation of integrated treatment systems for large industrial complexes, biological treatment for organic-rich effluents, and specialized heavy metal removal technologies where required. Regular monitoring and adaptive management strategies are essential for maintaining treatment efficiency and environmental compliance. Future research should focus on emerging contaminants, energy-efficient treatment technologies, and resource recovery systems to support sustainable industrial development in the region.

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