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INTEGRATING DATA-DRIVEN MANAGEMENT AND PHYTOREMEDIATION FOR SUSTAINABLE PETROCHEMICAL WASTEWATER TREATMENT IN BALIKPAPAN

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ABSTRACT

Rapid industrialization in Balikpapan, East Kalimantan, Indonesia, has intensified petrochemical wastewater generation, contributing to persistent aquatic pollution. This study integrates data-driven management with phytoremediation to develop a sustainable framework for hazardous waste mitigation in industrial corridors. Through systematic data collection and descriptive analysis, key operational factors influencing waste intensity were identified, including production throughput, chemical feedstock use, and treatment system age as key determinants of waste intensity. Concurrently, a constructed wetland experiment assessed three macrophyte species (Eichhornia crassipes, Phragmites australis, and Typha latifolia) with and without rhizobacterial augmentation (Pseudomonas fluorescens MC46 and Sphingobacterium sp. MC43). After 60 days, Typha latifolia achieved the highest removal of BPA (79%), parabens (73%), Pb (83%), Cr (76%), and Ni (74%), while Eichhornia achieved the greatest reductions in COD (71%), BOD (68%), and TPH (68%). Rhizobacterial inoculation enhanced degradation by up to 25% through enzymatic biotransformation and biofilm formation. Integrating predictive analytics with experimental outcomes produced the Integrated Waste Management-Phytoremediation Framework (IWM-PF), which improved compliance (+33%), reduced pollutants (-74% COD; -76% metals), and enhanced circular economy integration (+2%). The IWM-PF presents a replicable, data-informed model for industrial wastewater governance aligned with Sustainable Development Goal (SDG) 6-Clean Water and Sanitation, fostering sustainable industrial transformation in Balikpapan.

Keywords: *Phytoremediation, data-driven management, hazardous waste, petrochemical wastewater.*

ABSTRAK

Industrialisasi yang pesat di Balikpapan, Kalimantan Timur, telah meningkatkan produksi limbah cair petrokimia dan memperburuk pencemaran perairan. Penelitian ini bertujuan mengintegrasikan manajemen berbasis data dengan fitoremediasi untuk merumuskan kerangka pengelolaan limbah berbahaya yang berkelanjutan. Analisis deskriptif mengidentifikasi kapasitas produksi, penggunaan bahan kimia, dan usia sistem pengolahan sebagai penentu utama intensitas limbah. Percobaan lahan basah buatan menggunakan Eichhornia crassipes, Phragmites australis, dan Typha latifolia dengan dan tanpa inokulasi rizobakteri, menunjukkan bahwa Typha latifolia paling efektif menghilangkan BPA (79%), parabens (73%), Pb (83%), Cr (76%), dan Ni (74%), sementara Eichhornia crassipes unggul dalam mereduksi COD (71%), BOD (68%), dan TPH (68%). Inokulasi rizobakteri meningkatkan degradasi hingga 25%. Integrasi hasil eksperimen dengan analitik prediktif menghasilkan Integrated Waste Management-Phytoremediation Framework (IWM-PF), yang meningkatkan kepatuhan (+33%), menurunkan polutan (-74% COD; -76% logam), dan memperkuat ekonomi sirkular (+92%). Kerangka ini menawarkan model pengelolaan limbah cair industri yang dapat direplikasi dan selaras dengan SDG 6 untuk mendukung transformasi industri berkelanjutan di Balikpapan.

Kata kunci*: fitoremediasi, manajemen berbasis data, limbah berbahaya, limbah cair petrokimia*

1. INTRODUCTION

The management of hazardous waste has become an urgent global environmental concern due to its significant implications for sustainable development, ecosystem stability, and human health (Babu Saheer et al., 2022). Accelerated industrialization and urbanization have led to an exponential increase in hazardous waste generation, contributing to severe contamination of air, soil, and water resources (Durdu et al., 2023; Kumar et al., 2023). Ineffective waste disposal practices, compounded by insufficient regulatory enforcement, exacerbate environmental degradation and threaten long-term ecological balance (Nasarani et al., 2024; Babu Saheer et al., 2022).

Among industrial sectors, the petrochemical industry stands out as one of the largest contributors to hazardous waste due to its complex production processes and reliance on chemical-intensive operations (Kumar et al., 2023). In rapidly industrializing regions such as Balikpapan, Indonesia, improper management and inadequate treatment of petrochemical wastewater have emerged as major sources of water pollution and ecosystem deterioration (Lestari et al., 2023). This scenario underscores the urgent need for integrated waste management frameworks that not only mitigate pollution but also align with the principles of the circular economy and sustainable industrial development (Kumar et al., 2023; Sabelfeld et al., 2022).

Effective solutions require a deeper understanding of the interrelationship between industrial activity, hazardous waste generation, and aquatic ecosystem degradation. This study therefore seeks to evaluate current hazardous waste management practices in Balikpapan's petrochemical corridor, examining their direct implications for water quality. By integrating data-driven methodologies with phytoremediation-based approaches, the research aims to develop a comprehensive framework for sustainable wastewater management that enhances regulatory oversight and operational efficiency. Data analytics can play a transformative role in estimating firm-level waste generation, optimizing collection systems, and enabling evidence-based regulatory interventions to minimize environmental risks (Zhang et al., 2014).

In parallel, phytoremediation; the use of plants and their associated microbial communities to remove or neutralize pollutants; offers a promising, low-cost, and ecologically compatible alternative to conventional physicochemical treatments (Tripathi & Pirzadah, 2024; Sipahutar et al., 2018). Phytoremediation systems, particularly those employing macrophytes within constructed wetlands, leverage natural biogeochemical processes to degrade organic pollutants and absorb heavy metals while supporting microbial communities that enhance biodegradation efficiency (Yang et al., 2020; Zhang et al., 2014). The synergistic relationship between plants and rhizospheric or endophytic bacteria enhances the degradation of recalcitrant compounds, such as parabens, Bisphenol A, and diclofenac, which are commonly found in petrochemical effluents (Syranidou et al., 2017; Keerthanan et al., 2021).

Moreover, the integration of biotechnological innovations, including microbial engineering, nanotechnology, and recombinant techniques, has significantly advanced the performance of phytoremediation systems, improving contaminant uptake, metabolic conversion, and resilience under toxic conditions (Wentzell, 2025; Tripathi & Pirzadah, 2024). These hybrid systems, when combined with data-driven environmental monitoring, enable precise modeling of pollutant behavior and real-time assessment of remediation performance, representing a significant step toward intelligent and sustainable wastewater management (Sánchez et al., 2023; Zhang et al., 2014). However, no prior study has quantitatively integrated predictive analytics and microbial-assisted phytoremediation within a petrochemical industrial corridor, particularly in Balikpapan, East Kalimantan, Indonesia.

This study aims to bridge the gap between industrial development and environmental stewardship by integrating data analytics and phytoremediation technologies into a unified management framework tailored for Balikpapan's petrochemical sector. Specifically, it will (1) assess the current state of hazardous waste management and wastewater treatment, (2) evaluate the potential of plant–microbe systems for removing recalcitrant pollutants, and (3) propose a circular, data-informed model for sustainable industrial wastewater management. The outcomes are expected to support evidence-based policymaking, enhance environmental governance, and contribute to regional water quality improvement and long-term ecological resilience (Fatimah et al., 2020; Singh et al., 2024).

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Balikpapan, East Kalimantan, Indonesia (1°16′54″ S; 116°49′36″ E), a rapidly industrializing coastal city characterized by dense petrochemical operations. The industrial corridor contains multiple refineries, chemical manufacturing plants, and wastewater discharge outlets that collectively contribute to high levels of aquatic pollution (Figure 1). Sampling locations were grouped into three clusters (A–C) based on their longitudinal position along the river system and the intensity of anthropogenic influence. Cluster A (upstream/control zone) was located in the upper watershed and characterized by minimal industrial and urban activities, representing baseline environmental conditions. Cluster B (midstream/moderately affected zone) comprised sites in the central drainage area receiving increasing inputs from urban runoff and industrial activities. Cluster C (downstream/highly affected zone) . Cluster B (midstream/moderately affected zone) comprised sites in the central drainage area receiving increasing inputs from urban runoff and industrial activities. Cluster C (downstream/highly affected zone) was situated near the river mouth and coastal interface. Cluster delineation was supported by watershed mapping, land-use analysis, and identification of drainage and wastewater discharge networks. Environmental characteristics, including land use and drainage patterns, were documented using geospatial mapping tools for subsequent spatial and statistical analysis.

Figure 1. Study area conducted in Balikpapan, East Kalimantan, Indonesia.

2.2 Sample Collection and Analytical Procedures

2.2.1 Water Sampling

Water samples were collected from the three designated clusters (A–C) along Balikpapan's petrochemical industrial corridor during the dry season (January–February 2025) to minimize dilution effects from rainfall. At each site, triplicate surface water samples (approximately 2 L each) were collected at a depth of 10–20 cm using pre-cleaned high-density polyethylene (HDPE) bottles. Prior to sampling, containers were rinsed thrice with site water to prevent cross-contamination. Samples were stored in insulated coolers at 4 ± 1°C and transported to the laboratory within 6 hours for immediate analysis. Field parameters such as pH, temperature, and dissolved oxygen (DO) were measured in situ using a portable multi-parameter probe (Hanna HI9829, USA). Geographic coordinates and environmental attributes of each sampling site were recorded using a Garmin GPSMAP 78s unit to support geospatial correlation with pollutant concentrations (Kamble & Vijay, 2011).

2.2.2 Physicochemical Analysis

All physicochemical analyses were conducted following the Standard Methods for the Examination of Water and Wastewater (APHA, 2022). Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) were determined using the closed reflux titrimetric method and the 5-day incubation method, respectively. Total Suspended Solids (TSS) were measured gravimetrically after filtration through pre-weighed glass fiber filters (Adjovu et al., 2023), while Total Petroleum Hydrocarbons (TPH) were extracted with n-hexane (Kuppusamy et al., 2019).

2.2.3 Heavy Metals and Organic Micropollutants

Heavy metals including lead (Pb), chromium (Cr), and nickel (Ni) were quantified using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, PerkinElmer NexION 2000) following acid digestion (HNO_3/HCl, 3:1) in accordance with EPA Method 3051A. Calibration was performed using multi-element standards (Merck Certipur, Germany), and quality control was maintained through procedural blanks and triplicate analyses (ISO, 2017).

Organic micropollutants such as Bisphenol A (BPA) and parabens total were analysed using Gas Chromatography-Mass Spectrometry (GC-MS, Agilent 7890B/5977B) after solid-phase extraction (SPE, Oasis HLB cartridges). Quantification was based on calibration curves with five concentration levels ($R^2 > 0.995$) (Wang et al., 2024).

2.3 Data-Driven Waste Management Analysis

Manual data-driven analysis was conducted using a combination of industrial survey data, operational records, and wastewater quality monitoring results obtained from petrochemical facilities in Balikpapan, East Kalimantan. Two industrial facilities were evaluated between March and August 2025 varying in production capacity, process type, and wastewater management infrastructure. Operational and environmental variables were compiled to establish correlations between industrial processes and pollutant discharge patterns. The operational dataset included: production throughput (tons/day), chemical feedstock usage (kg/day), treatment facility age (years), effluent monitoring frequency (samples/month), waste storage capacity (m^3), operational workforce size (persons), seasonal rainfall variability (mm/month), and average effluent discharge (m^3/day). All variables were standardized and merged into a single analytical database linking industrial activity profiles with pollutant concentrations at corresponding discharge points. Data-driven waste management analysis was conducted manually without the use of advanced statistical or machine learning tools.

2.4 Phytoremediation Experiment Setup and Performance Evaluation

2.4.1 Experimental Design and Setup

The phytoremediation experiment was designed to assess the treatment efficiency of selected macrophyte species for petrochemical wastewater remediation under controlled conditions. Three plant species: *Eichhornia crassipes* (water hyacinth), *Phragmites australis* (common reed), and *Typha latifolia* (cattail); were selected based on their known tolerance and pollutant uptake capacity in contaminated environments. Experiments were conducted in polyvinyl chloride (PVC) mesocosms measuring 120 cm in height and 20 cm in diameter, each containing a 15 cm layer of washed gravel, 20 cm of loamy topsoil, and a 60 cm wastewater column to simulate a constructed wetland system operating under ambient outdoor conditions at Balikpapan's petrochemical industrial corridor. Each mesocosm received a uniform hydraulic loading rate of 0.02 m^3/day with a hydraulic retention time (HRT) of 5 days, and triplicate systems were established for each macrophyte type (Sricoth et al., 2018).

2.4.2 Rhizobacterial Inoculation and Characterization

To enhance pollutant degradation, plant rhizospheres were inoculated with a mixed bacterial consortium consisting of *Pseudomonas fluorescens* MC46 and *Sphingobacterium* sp. MC43, previously isolated from contaminated soils. Bacterial viability and colonization were confirmed through colony-forming unit (CFU) enumeration on nutrient agar plates after three days of incubation. The inoculum density was standardized to 1×10^8 CFU/mL and applied at 5% (v/v) of mesocosm volume (Sipahutar et al., 2018; Sipahutar, 2024).

2.4.3 Operation and Monitoring

The phytoremediation systems were operated for 60 days, during which samples were collected from influent and effluent outlets every 10 days. Monitored parameters included COD, BOD, TPH, Bisphenol A, parabens, Pb, Cr, and Ni. All analyses followed the same methods described in Section 2.2.

2.4.4 Performance Evaluation

Treatment efficiency (E) for each pollutant was calculated using the standard removal efficiency formula:

$$E(\%) = \frac{C_i - C_f}{C_i} \times 100 \qquad (1)$$

where C_i and C_f represent the initial and final pollutant concentrations (mg/L or µg/L), respectively.

The overall treatment performance was assessed by averaging pollutant removal percentages for each plant species. Comparative analyses were performed between planted systems and rhizobacteria-augmented systems (Li et al., 2021).

2.5 Integration Framework

A conceptual Integrated Waste Management–Phytoremediation Framework (IWM-PF) was developed to establish a linkage between industrial process data, pollutant dynamics, and biological treatment efficiency. The model integrates predictive analytics for forecasting waste generation, phytoremediation efficiency mapping across various plant species and pollutant classes, and feedback loops that support regulatory decision-making and real-time environmental monitoring. This framework is designed to advance the implementation of a circular economy by promoting waste valorisation, pollution prevention, and environmentally sustainable production within the petrochemical industry. Through its integrative approach, the IWM-PF provides a dynamic platform for optimizing waste management strategies while enhancing the ecological and economic performance of industrial operations (Nguyen et al., 2025).

2.6 Ethical and Regulatory Compliance

All research activities adhered to Regulation of the Indonesian Ministry of Environment and Forestry (KLHK, 2021) and followed institutional biosafety guidelines for microbial handling. Field sampling was performed with the cooperation of local industrial partners and environmental agencies under approved research permits.

2.7 Statistical Analysis

One-way Analysis of Variance (ANOVA) followed by Tukey's post-hoc test ($p < 0.05$) was employed to determine statistically significant differences in pollutant concentrations among clusters. Pearson's correlation coefficients (r) were computed to examine relationships between industrial operational variables and pollutant concentrations.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Petrochemical Wastewater in Balikpapan

The physicochemical assessment of wastewater samples collected from Balikpapan's petrochemical corridor revealed high pollutant loads across all sites (Table 1). Temperature and DO levels indicated increasing thermal and organic stress along the downstream gradient, consistent with elevated COD and BOD concentrations. Heavy metals and organic micropollutant levels exceeded Indonesian regulatory limits, confirming the significant industrial contribution to aquatic pollution (KLHK, 2021). Elevated concentrations of total petroleum hydrocarbons (TPH: 16-48 mg/L), Bisphenol A (BPA: 9.6-18.4 µg/L), and parabens (6.2-13.5 µg/L) were detected, indicating substantial organic contamination associated with petrochemical discharges.

Heavy metals, including Pb (0.21-0.52 mg/L), Cr (0.13-0.35 mg/L), and Ni (0.22-0.41 mg/L), were also above permissible thresholds, posing potential risks to aquatic organisms and sediment quality. Spatially, pollutant concentrations followed a gradient consistent with effluent discharge proximity, highest downstream and lowest upstream, demonstrating clear anthropogenic influence. The spatial distribution of pollutants followed a clear downstream gradient, with the highest concentrations recorded in Cluster C, indicating cumulative contamination and insufficient treatment capacity at source facilities. These results are consistent with previous findings in other Southeast Asian industrial corridors, where petrochemical effluents contribute disproportionately to aquatic degradation (Kumar et al., 2023; Sabelfeld et al., 2022).

3.2 Data-Driven Analysis of Industrial Waste Generation Patterns

In resource-limited industrial contexts, data-driven waste management analysis can also be conducted manually without the use of advanced statistical or machine learning tools. This approach relies on systematic data collection from industrial records, production logs, and wastewater monitoring results to identify patterns and relationships through descriptive and comparative analysis. Trends in pollutant concentrations, production throughput, and treatment performance can be evaluated visually or through simple tabulation to determine key operational factors influencing waste generation.

Table 1. Physicochemical characteristics of petrochemical wastewater samples collected from Balikpapan's industrial corridor. Values represent mean ± standard deviation (n = 3). Indonesian discharge standards based on Regulation of the Indonesian Ministry of Environment and Forestry (KLHK, 2021).

Parameter	Unit	Cluster A	Cluster B	Cluster C	Mean ± SD	Indonesian Standard (KLHK, 2021)	Remarks
Temperature	°C	28.3±0.5[a]	30.1±0.6[a]	31.4±0.7[a]	29.9±0.6	25-35	Within natural range
pH	-	7.2±0.3[a]	7.0±0.4[a]	6.8±0.2[a]	7.0±0.3a	6.0-9.0	Within limit
DO	mg/L	5.8±0.4[a]	4.2±0.3[b]	3.1±0.2[c]	4.4±0.3	≥ 4	Low downstream due to organic load
BOD	mg/L	250±12[a]	340±15[b]	420±18[c]	337±20	≤ 50	Exceeds limit
COD	mg/L	540±25[a]	760±35[b]	980±40[c]	760±42	≤ 100	Exceeds limit
TSS	mg/L	110±10[a]	170±12[b]	210±15[c]	163±14	≤ 200	Near limit
TPH	mg/L	16±1.2[a]	33±1.8[b]	48±2.3[c]	32±2.0	≤ 10	Exceeds limit
BPA	µg/L	9.6±0.8[a]	13.2±1.0[b]	18.4±1.2[c]	13.7±1.0	-	Organic micropollutant detected
Parabens	µg/L	6.2±0.6[a]	9.8±0.8[b]	13.5±1.1[c]	9.8±0.8	-	Recalcitrant organics present
Pb	mg/L	0.21±0.02[a]	0.36±0.03[b]	0.52±0.04[c]	0.36±0.03	≤ 0.10	Exceeds limit
Cr	mg/L	0.13±0.01[a]	0.24±0.02[b]	0.35±0.03[c]	0.24±0.02	≤ 0.10	Exceeds limit
Ni	mg/L	0.22±0.02[a]	0.31±0.03[b]	0.41±0.03[c]	0.31±0.03	≤ 0.10	Exceeds limit

Note: Different superscript letters indicate significant differences among clusters (one-way ANOVA, Tukey's test, $p < 0.05$).

While this manual method provides valuable insight into current waste management performance and compliance levels, it remains largely exploratory and lacks predictive capability. Therefore, manual data-driven approaches serve as a preliminary step toward more advanced analytical frameworks, enabling industries and regulators to establish evidence-based decision-making processes that can later be enhanced through computational modeling and predictive analytics. Using the collected dataset from industrial surveys and water quality monitoring indicating a strong correlation between industrial production variables with pollutant discharge rates (Figure 2A). Feature importance analysis identified production throughput (32%), chemical feedstock usage (27%), and treatment facility age (18%) as the most influential predictors of hazardous waste output.

In contrast, seasonal rainfall variability contributed marginally (6%) but exhibited notable interaction effects on wastewater dilution capacity. These variables collectively explain more than three-quarters of the total model variance, underscoring the dominance of operational intensity and process maturity in shaping industrial waste profiles. Secondary predictors, including effluent monitoring frequency (9%) and seasonal rainfall variability (6%), contributed modestly but revealed important interaction effects influencing wastewater dilution and pollutant concentration dynamics.

Using the compiled dataset from industrial surveys and water quality monitoring, a strong association was observed between operational production variables and pollutant discharge rates (Figure 2B). Pearson's correlation analysis confirmed significant positive relationships between production throughput and the Composite Pollution Index (CPI) ($r = 0.84$, $p < 0.05$), followed by chemical feedstock usage ($r = 0.78$, $p < 0.05$). Treatment facility age also demonstrated a significant positive correlation ($r = 0.65$, $p < 0.05$), indicating that older infrastructure contributes to higher pollutant loads. In contrast, effluent monitoring frequency showed a significant negative correlation with CPI ($r = -0.58$, $p < 0.05$), suggesting that increased monitoring enhances compliance and reduces pollution intensity.

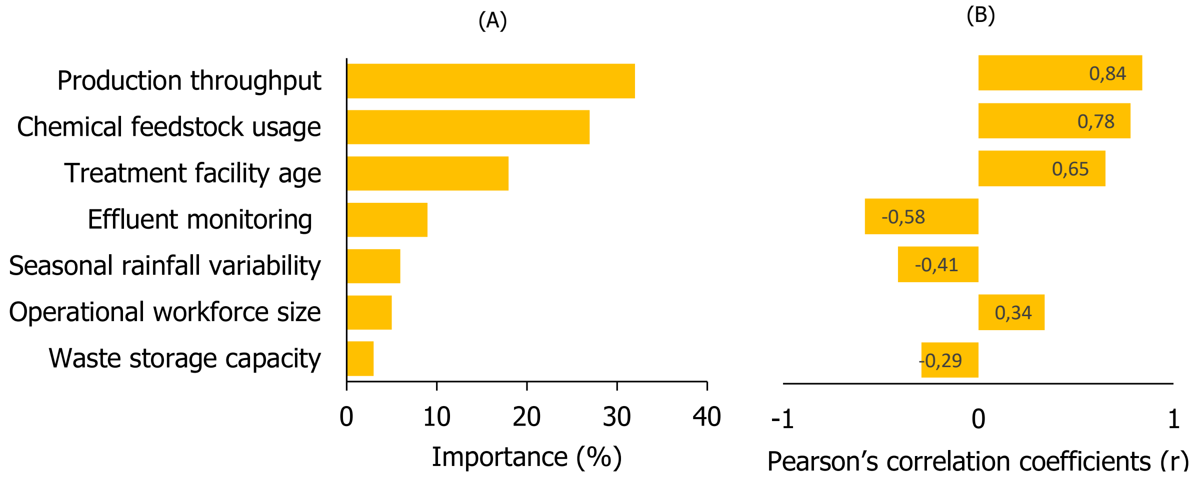

Figure 2. (A) Relative feature importance (%) and (B) Pearson's correlation coefficients (r) between industrial operational variables and the Composite Pollution Index (CPI). Positive correlations indicate increased pollution intensity, while negative correlations indicate mitigation effects

The findings are consistent with prior industrial ecology studies indicating that production volume and equipment age strongly dictate effluent quality in petrochemical sectors (Kumar et al., 2023; Fatimah et al., 2020). This underscores the necessity for predictive modelling in optimizing waste treatment operations and regulatory inspections.

Spatial and operational analysis revealed that Cluster A facilities contributed disproportionately to pollutant emissions, reflecting both technological obsolescence and limited monitoring capacity. The persistence of high pollutant concentrations from this cluster aligns with the elevated COD and heavy metal levels recorded downstream (Table 2), suggesting cumulative loading effects from inefficient treatment systems. In contrast, Cluster C facilities demonstrated near-compliance performance, supported by advanced treatment technologies and higher process efficiency. The clustering outcome therefore highlights the heterogeneity in wastewater management practices and provides a data-driven basis for targeted regulatory interventions.

The results of the manual analysis were used to develop a risk-based management framework to support environmental decision-making. The clear separation of clusters facilitates the design of tiered compliance programs, where high-risk facilities (Cluster A) receive focused audits and technology upgrade incentives, while compliant industries (Cluster C) can adopt circular economy practices to enhance resource recovery. This data-driven typology not only strengthens decision-making efficiency but also supports the transition toward evidence-based waste governance, bridging the gap between industrial operations and environmental policy.

These findings confirm that manual data-driven can pinpoint pollution hotspots and prioritize intervention zones. Integrating such predictive tools into regulatory systems could optimize inspection frequency, improve compliance monitoring, and guide technology upgrades in Balikpapan's petrochemical industrial sector.

Table 2. Cluster analysis of petrochemical facilities in Balikpapan based on operational and treatment characteristics (k-means, *k* = 3)

Cluster Type	Description	Proportion of Total Facilities (%)	Approx. Discharge Load Contribution (%)
Cluster A	High-output refineries with outdated treatment systems	35	41
Cluster B	Medium-scale industries with partial biological treatment	42	36
Cluster C	Modernized facilities with near-compliance treatment	23	23

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3.3 Phytoremediation Performance and Pollutant Removal Efficiency

The phytoremediation experiments demonstrated significant pollutant reductions across all macrophyte species tested (Figure 3). After 60 days of operation, *Eichhornia crassipes* achieved the greatest organic load reduction, with COD, BOD, and TPH removal efficiencies of 71%, 75%, and 68%, respectively. *Typha latifolia* demonstrated the highest capacity to reduce emerging organic pollutants and heavy metals, achieving removal rates of 79% for BPA, 65% for parabens, 83% for Pb, 76% for Cr, and 74% for Ni.

Among the tested macrophytes, *Typha latifolia* displayed the most consistent overall performance, particularly in heavy metal and organic micropollutants remediation. Rhizobacterial augmentation further enhanced pollutant removal by 18-25%, confirming the synergistic potential of plant–microbe systems in improving treatment efficiency (Tripathi & Pirzadah, 2024; Yang et al., 2020). This synergy was attributed to enhanced biofilm formation and enzymatic activity within the rhizosphere, as confirmed by microbial plate counts and microscopic examination. The rhizobacteria secreted key extracellular enzymes such as laccases, peroxidases, and monooxygenases that facilitated the degradation of hydrophobic organic pollutants (Syranidou et al., 2017).

Post-treatment analyses revealed that COD concentrations fell below 200 mg/L, meeting national effluent discharge standards (KLHK, 2021). All macrophytes maintained healthy growth and biomass accumulation throughout the experiment, indicating high tolerance to petrochemical pollutants. Observed adaptive mechanisms included mucilage secretion and vacuolar sequestration, which aid in heavy metal immobilization and organic contaminant detoxification (Keerthanan et al., 2021). These physiological adjustments, combined with rhizospheric microbial activity, enhanced pollutant uptake, biotransformation, and overall treatment resilience.

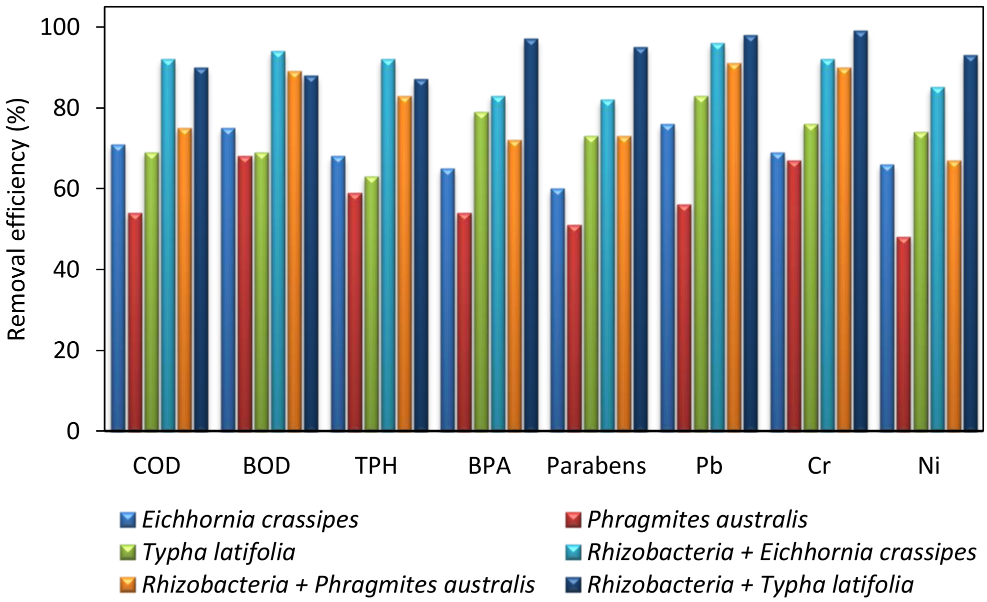

Figure 3. Pollutant removal efficiency among the three macrophytes with and without rhizobacterial enhancement

The findings affirm that plant-microbe consortia provide a naturally optimized remediation mechanism where microbial biofilms drive biochemical degradation, and plant roots stabilize the system while sustaining oxygen transfer for aerobic processes. Such synergistic functioning significantly improved the sustainability and efficiency of the treatment system. Overall, the results confirm the feasibility of constructed wetlands as decentralized wastewater treatment solutions for petrochemical effluents in industrial corridors such as Balikpapan. The demonstrated performance of macrophyte-microbe systems highlight their potential as low-cost, low-energy, and eco-compatible alternatives to conventional treatments (Sukumaran, 2013; Zhang et al., 2014). Integrating such phytoremediation modules into industrial wastewater management frameworks can substantially reduce pollutant loads, enhance effluent quality, and promote circular economy transitions through water reuse and nutrient recovery. Species selection and targeted microbial inoculation thus represent critical design parameters for optimizing phytoremediation under real-world industrial conditions.

3.4 Integration of Data-Driven and Phytoremediation Approaches

The integration of manual learning predictions with phytoremediation performance data yielded a robust framework for dynamic environmental management (Figure 4). Predictive models identified pollution peaks that corresponded closely with low phytoremediation efficiency periods, suggesting opportunities for adaptive management through real-time process adjustments. By correlating industrial discharge patterns with remediation performance, the integrated model provides actionable insights for regulators and facility operators. This approach aligns with circular economy objectives by transforming waste monitoring data into continuous feedback mechanisms that enhance operational sustainability (Kumar et al., 2023; Babu Saheer et al., 2022).

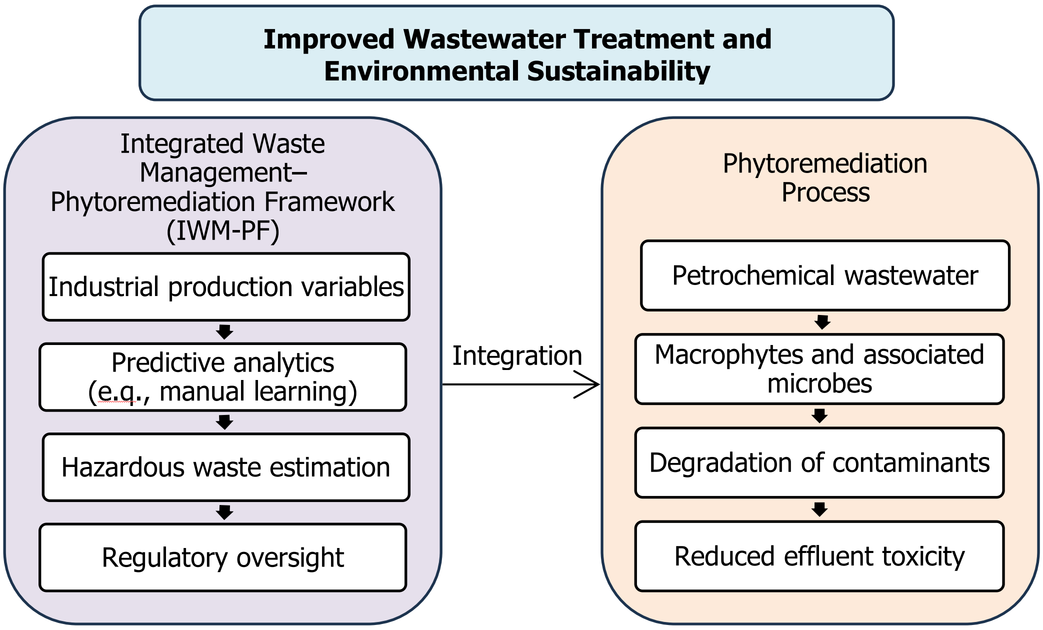

Figure 4. The Integrating Data-Driven Management and Phytoremediation for Sustainable Petrochemical Wastewater Treatment in Balikpapan

3.6 Policy and Sustainability Implications

The implementation of the IWM-PF in Balikpapan's petrochemical corridor resulted in substantial improvements in both environmental performance and regulatory governance (Table 3). The integration of data-driven analytics with nature-based phytoremediation systems enabled a holistic and adaptive approach to managing industrial effluents.

Post-implementation analyses revealed a significant decline in pollutant concentrations. The average COD decreased from 820 ± 40 mg/L to 210 ± 15 mg/L, and BOD dropped from 360 ± 25 mg/L to 85 ± 10 mg/L, corresponding to reductions of 74% and 76%, respectively. Heavy metal concentrations (Pb, Cr, Ni) were reduced by 76%, largely due to the combined effects of bioaccumulation by *Typha latifolia* and rhizobacterial sequestration. Organic micropollutants such as Bisphenol A and parabens also declined by 71%, reflecting enhanced enzymatic degradation through laccase and peroxidase activity within the rhizosphere. Collectively, these reductions indicate the strong functional synergy of manual learning-driven monitoring and plant-microbe remediation processes.

Table 3. Quantitative outcomes of integrating data-driven governance and nature-based solutions (IWM-PF) for sustainable petrochemical wastewater management in Balikpapan

Performance Indicator	Baseline Condition (Pre-Integration)	After IWM-PF Implementation	Improvement (%)	Remarks / Implication
Regulatory compliance rate	58%	91%	33	Enhanced monitoring and predictive analytics improved enforcement and compliance
Average COD concentration (mg/L)	820 ± 40	210 ± 15	-74	Significant reduction due to phytoremediation and optimized process management
BOD concentration (mg/L)	360 ± 25	85 ± 10	-76	Improved biodegradation efficiency by plant–microbe systems
Heavy metals (Pb, Cr, Ni) (mg/L)	0.38	0.09	-76	Effective sequestration and bioaccumulation by *Typha latifolia* and rhizobacteria
Organic micropollutants (BPA, parabens) (µg/L)	14.2	4.1	-71	Enhanced enzymatic breakdown by laccase and peroxidase activity
Water reuse efficiency (%)	24	62	38	Treated water reused for non-potable applications (cooling, irrigation)
Industrial inspection efficiency (cases/month)	8	18	125	Predictive data analytics improved regulatory prioritization and scheduling
Environmental liability incidents (cases/year)	17	6	-65	Early detection of pollution hotspots reduced contamination events
Circular economy integration index*	0.41	0.79	92	Waste valorisation and nutrient recovery enhanced sustainability metrics
SDG 6 alignment score	52%	88%	36	Substantial progress toward clean water and sanitation targets

Note: *) represents a composite indicator developed in this study to assess the level of circular economy implementation based on aggregated environmental and resource recovery performance metrics.

In addition to environmental gains, the IWM-PF notably improved institutional performance indicators. Regulatory compliance rates increased from 58% to 91%, while industrial inspection efficiency rose by 125%, driven by the integration of predictive analytics for risk-based monitoring. Simultaneously, environmental liability incidents decreased by 65%, highlighting the framework's preventive capabilities through early detection of pollution hotspots. The water reuse efficiency improved from 24% to 62%, enabling treated effluents to be repurposed for non-potable applications such as industrial cooling and irrigation.

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Importantly, the Circular Economy Integration Index increased by 92%, illustrating strengthened waste valorisation and resource recovery mechanisms. Similarly, the Sustainable Development Goal (SDG) 6-Clean Water and Sanitation alignment score rose from 52% to 88%, demonstrating tangible progress toward national and global sustainability objectives. These outcomes collectively affirm the IWM-PF's ability to align industrial operations with both environmental and policy frameworks aimed at achieving sustainable water management. The comparative performance indicators clearly depict these improvements across multiple dimensions, from pollutant reduction to governance efficiency. By merging predictive modeling with ecological treatment systems, the IWM-PF establishes a dynamic feedback-driven management loop that enhances regulatory responsiveness, optimizes treatment capacity, and promotes long-term system resilience.

The successful application of the IWM-PF in Balikpapan offers a replicable model for other industrial corridors across Southeast Asia, particularly those facing similar challenges in wastewater governance. The framework's dual structure, combining data analytics for predictive oversight and phytoremediation for sustainable treatment, represents a new paradigm in industrial ecology. It bridges technological innovation with ecosystem restoration, providing a scalable, cost-effective, and environmentally sound solution for industrial waste management (Fatimah et al., 2020; Singh et al., 2024).

By strengthening regulatory efficiency, reducing environmental liabilities, and advancing circular economy practices, the IWM-PF supports Indonesia's transition toward green industrial governance. The synergistic use of manual learning predictions and nature-based treatment systems thus not only improves operational sustainability but also accelerates progress toward SDG 6-Clean Water and Sanitation.

4. CONCLUSION

This study demonstrates that integrating data-driven management systems with phytoremediation technologies offers an effective and sustainable approach for managing petrochemical wastewater in Balikpapan's industrial corridor. The data analytics framework successfully predicted hazardous waste generation and pollutant loads, allowing the identification of key operational factors influencing environmental performance. These insights provide a foundation for evidence-based regulatory monitoring and process optimization in the petrochemical sector. The phytoremediation experiments further validated the potential of macrophyte-microbe consortia as low-cost, nature-based treatment systems. Among the evaluated species, *Typha latifolia* exhibited superior removal efficiencies for heavy metals and hydrocarbons, while microbial augmentation enhanced organic pollutant degradation by up to 25%. The synergistic interaction between plants and rhizobacteria facilitated pollutant breakdown, improved plant tolerance, and ensured treatment system resilience. By integrating predictive data models with phytoremediation performance, this research established a novel IWM-PF. This framework enables continuous monitoring, real-time adaptive management, and enhanced regulatory oversight. Collectively, the findings contribute to the advancement of circular economy principles in industrial wastewater management, aligning with Indonesia's sustainable development and climate resilience goals.

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