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Assessment of Industrial Effluent Impacts on the Vaigai River (Madurai, India) Using Physicochemical Indicators, Water Quality Index, and Bench-Scale Carbon Adsorption

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Abstract

Industrial wastewater discharges severely alter receiving surface water ecosystems, creating localized zones of extreme ecological degradation. This study evaluated spatial variations in physicochemical quality along an industrially influenced stretch of the Vaigai River in Madurai District, Tamil Nadu, India. Five strategic sites representing an upstream control location and zones receiving tyre-manufacturing and powder-coating effluents were monitored for pH, turbidity, total dissolved solids (TDS), total hardness, biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD). While pH remained near-neutral (7.2–7.7), industrial outfalls induced severe spikes in turbidity (up to 221 NTU), BOD_5 (up to 36 mg/L), and COD (up to 120 mg/L). Application of the weighted arithmetic Water Quality Index (WQI) yielded site-specific scores ranging from 1,137.70 to 13,409.18, categorizing all sites as unsuitable for human consumption without multi-stage treatment. Turbidity and organic load accounted for over 96% of the aggregated index severity. Bench-scale activated carbon adsorption demonstrated 100% apparent removal of COD (reducing levels below detection limits) but only a 9.25% reduction in TDS (335 to 304 mg/L). These results demonstrate that while adsorption effectively mitigates organic pollutants, comprehensive river remediation requires integrated treatment trains combining adsorption with membrane processes to reduce dissolved inorganic salts.

1. Introduction

Surface water bodies act as primary sources for agricultural, domestic, and industrial activities globally [1]. However, rapid urbanization and expanding manufacturing activities frequently release partially treated or untreated wastewater into riverine networks[2,3].Industrial discharges introduce complex mixtures [3] of suspended solids, biodegradable organics, refractory chemical compounds, and dissolved inorganic ions [3].

The Vaigai River is an essential freshwater artery[4,5] in southern Tamil Nadu, flowing through dense municipal and industrial zones in the Madurai region [4,5]. Industrial operations adjacent to the river—specifically automotive tyre manufacturing and industrial powder-coating units—contribute continuous effluent streams containing synthetic polymers, heavy metals, surfactants, and organic dyes [6].Evaluating the ecological impact of these points requires both individual parameter testing and aggregated environmental indexing [7].

Water Quality Indices (WQIs) simplify complex water datasets into a single numerical expression reflecting overall quality status [8-10]. While traditional physicochemical monitoring identifies specific contaminant spikes, adsorption technologies—particularly Granular Activated Carbon (GAC)—are widely applied as tertiary remediation techniques to sequester refractory organic pollutants [11,12].

The main objectives of this investigation are:

1. To evaluate spatial variations in key physicochemical parameters across industrially impacted stretches of the Vaigai River.
2. To quantify composite water suitability using a mathematically verified Weighted Arithmetic Water Quality Index (WQI).
3. To evaluate the bench-scale remediation performance of granular activated carbon (GAC) for treating high-load organic and inorganic constituents.

2. Materials and Methods

2.1 Study Area and Sampling Sites

"Five monitoring stations were established along the Vaigai River in Madurai District: Site I (Control), Site II (Pre-Tyre), Site III (Post-Tyre), Site IV (Pre-Powder Coating), and Site V (Post-Powder Coating)."

- **Site I (Control):** Upstream reference location prior to major industrial outfalls.
- **Site II (Pre-Tyre):** Location immediately upstream of tyre-manufacturing discharge.
- **Site III (Post-Tyre):** Direct receiving zone for tyre-manufacturing effluent.
- **Site IV (Pre-Powder Coating):** Location prior to industrial powder-coating outfall.
- **Site V (Post-Powder Coating):** Direct receiving zone for powder-coating process effluent.

Water samples were gathered in pre-cleaned high-density polyethylene (HDPE) bottles, preserved at 4°C, and analyzed within prescribed holding periods according to standard protocols [13]

2.2 Analytical Methods

Testing adhered to APHA (23rd Edition) Standard Methods and BIS standards [13,14].

- **pH:** Potentiometrically using a calibrated digital pH meter (APHA 4500-H^+ B).
- **Turbidity:** Nephelometrically using a digital turbidity meter calibrated with standard formazin suspensions (APHA 2130 B).
- **Total Dissolved Solids (TDS):** Gravimetric analysis post-evaporation at 180°C (APHA 2540 C).
- **Total Hardness:** EDTA complexometric titration using Eriochrome Black T indicator (APHA 2340 C).
- BOD_5**:** 5-day incubation at 20°C followed by dissolved oxygen measurement (APHA 5210 B).
- **COD:** Closed micro-dichromate digestion followed by ferrous ammonium sulfate titration (APHA 5220 D).

2.3 Water Quality Index (WQI) Calculation

The Weighted Arithmetic WQI method was applied [9,15]. The quality rating (Q_i) for each parameter was computed as:

$$Q_i = 100 \times \left(\frac{V_i - V_0}{S_i - V_0}\right)$$

Where V_i is the measured parameter value, S_i is the prescribed BIS drinking standard, and V_0 is the ideal value in pure water (7.0 for pH; 0 for all other parameters) (BIS, 2012)[14] .

The unit weight (W_i) was derived as:

$$W_i = \frac{K}{S_i} \quad \text{where} \quad K = \frac{1}{\sum(1/S_i)}$$

The aggregate index was calculated via:

$$\text{WQI} = \frac{\sum Q_i W_i}{\sum W_i}$$

Note: Standard values (S_i) adopted from BIS (IS 10500:2012) were: pH = 8.5, Turbidity = 1 NTU, TDS = 500 mg/L, Hardness = 200 mg/L, and BOD = 2 mg/L. A benchmark value of 10 mg/L was applied for COD as a study-defined modeling benchmark [16].

2.4 Activated Carbon Batch Adsorption

Batch remediation trials were performed using commercial granular activated carbon (GAC; surface area ~ 950 m^2/g, mesh size 12 × 40). High-load river water (100 mL) from Site III was agitated with 1.0 g of GAC at 150 rpm for 120 minutes at room temperature (28 ± 2°C) [17].Removal efficiency ($E\%$) was determined via:

$$E(\%) = \left(\frac{C_0 - C_e}{C_0}\right) \times 100$$

Where C_0 and C_e represent initial and equilibrium concentration values (mg/L), respectively.

3. Results and Discussion

3.1 Spatial Physicochemical Trends

The analytical findings reveal severe spatial degradation downstream of industrial outfalls [16]

Table 1: Physicochemical characteristics of river water across Sites I–V.

Parameter	Site I (Control)	Site II (Pre-Tyre)	Site III (Post-Tyre)	Site IV (Pre-Powder)	Site V (Post-Powder)	Regulatory Benchmark (Si)
pH	7.2	7.5	7.7	7.4	7.3	6.5–8.5
Turbidity (NTU)	19	185	221	140	85	1
TDS (mg/L)	290	335	320	310	305	500
Hardness (mg/L)	180	206	195	202	198	200
BOD (mg/L)	2	20	36	15	10	2
COD (mg/L)	10	80	120	60	40	10*

*Study-defined modeling benchmark.

Figure 1: Spatial variations in pH across sampling sites.

Figure 2: Spatial variations in Turbidity (NTU) across sampling sites.

Figure 3: Spatial variations in TDS (mg/L) across sampling sites.

Figure 4: Spatial variations in Hardness (mg/L) across sampling sites.

Figure 5: Spatial variations in COD (mg/L) across sampling sites.

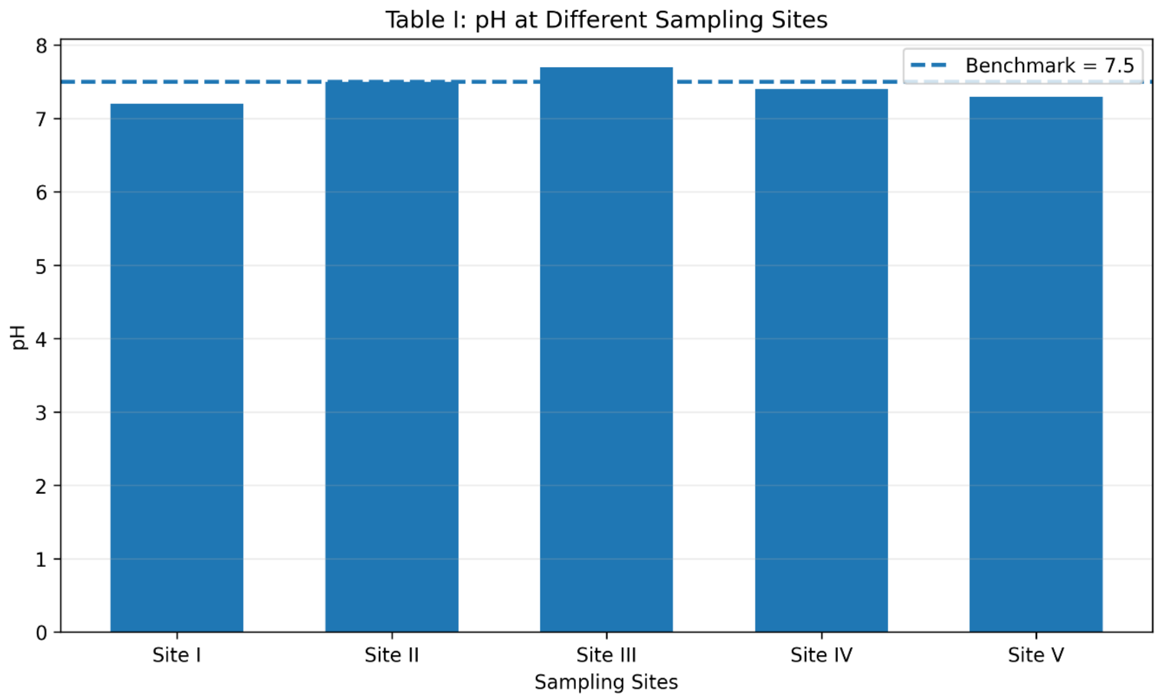

Figure 1: Spatial variations in pH across sampling sites.

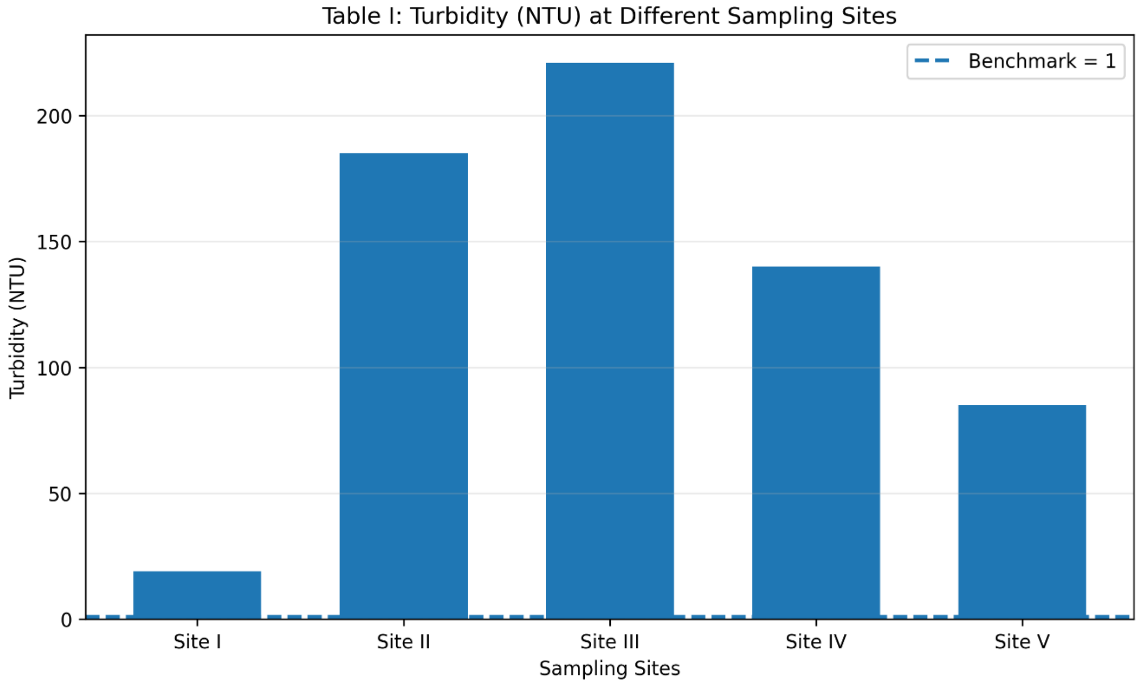

Figure 2: Spatial variations in Turbidity (NTU) across sampling sites.

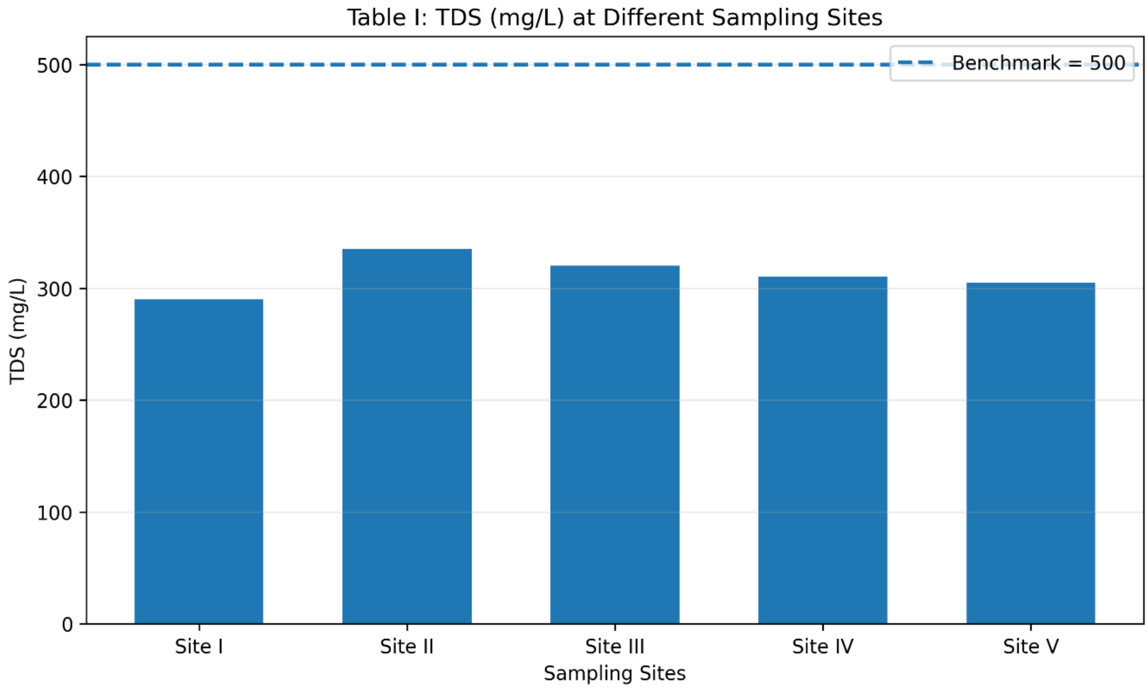

Figure 3: Spatial variations in TDS (mg/L) across sampling sites.

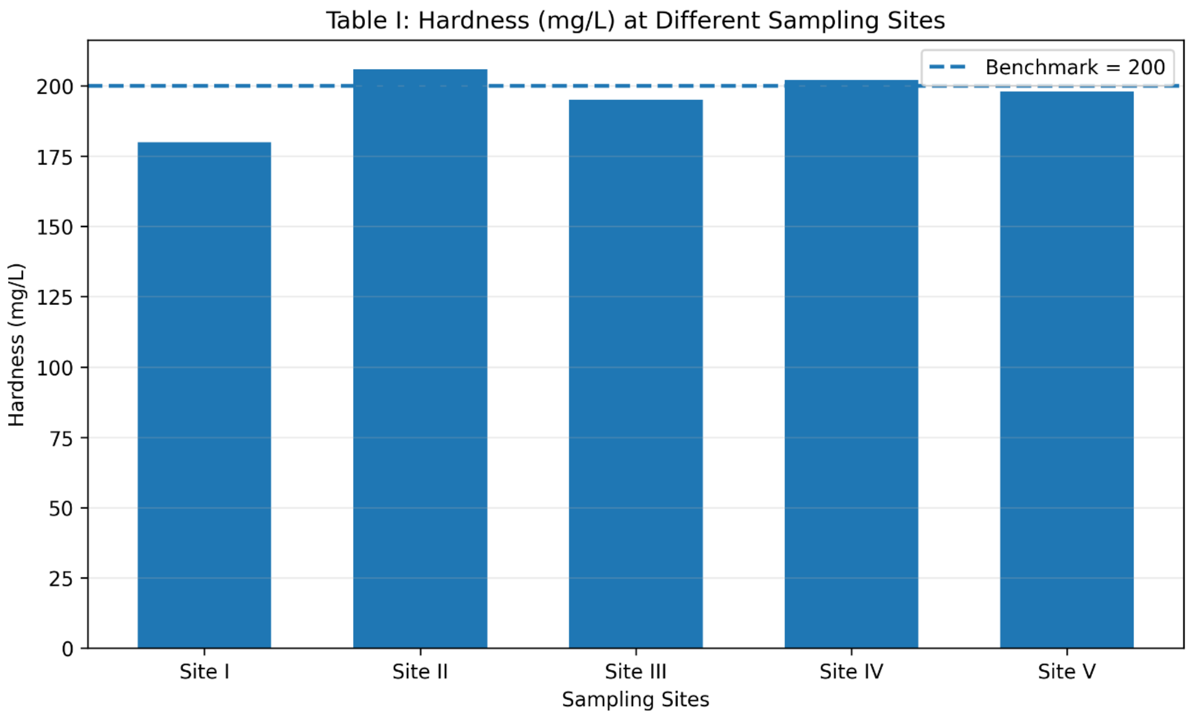

Figure 4: Spatial variations in Hardness (mg/L) across sampling sites.

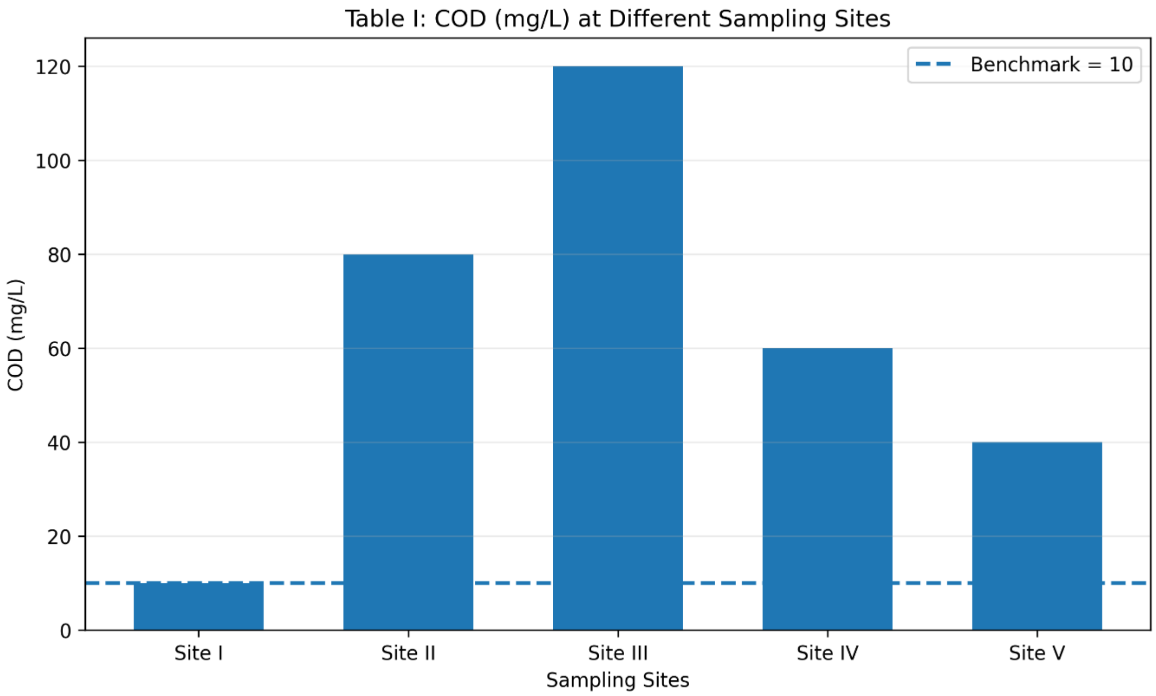

Figure 5: Spatial variations in COD (mg/L) across sampling sites.

Organic & Chemical Load: BOD_5 spiked from 2 mg/L (Control) to 36 mg/L at Site III, while COD increased from 10 mg/L to 120 mg/L. This 12-fold increase highlights heavy inputs of chemically oxidizable compounds and organic polymers from tyre-processing facilities [6]

Physical & Inorganic Indicators: Turbidity increased sharply from 19 NTU (Control) to a peak of 221 NTU at Site III. Hardness hovered near the 200 mg/L permissible threshold, while TDS remained below the 500 mg/L drinking limit across all stations (BIS, 2012)[14].

3.2 Spatial Water Quality Index (WQI) Evaluation

Applying the weighted arithmetic formula across each individual sampling location reveals extreme spatial variation [7]

Table 2: Site-wise calculated WQI scores.

Sampling Location	Calculated WQI Score	Quality Classification
Site I (Control)	1,137.70	Unsuitable for Drinking
Site II (Pre-Tyre)	11,065.78	Unsuitable for Drinking
Site III (Post-Tyre)	13,409.18	Severely Polluted / Unsuitable
Site IV (Pre-Powder)	8,372.01	Unsuitable for Drinking
Site V (Post-Powder)	5,098.42	Unsuitable for Drinking

"The dataset mean WQI is **7,236.93**. Turbidity ($Q_i W_i = 6{,}957.95$) accounts for **96.1%** of the total index value due to the strict 1 NTU benchmark. BOD_5 contributed an additional 240.63 to the sub-index. All five sampling points fall far beyond the threshold of 100, proving the water is completely unsafe for domestic use without extensive treatment" [10].

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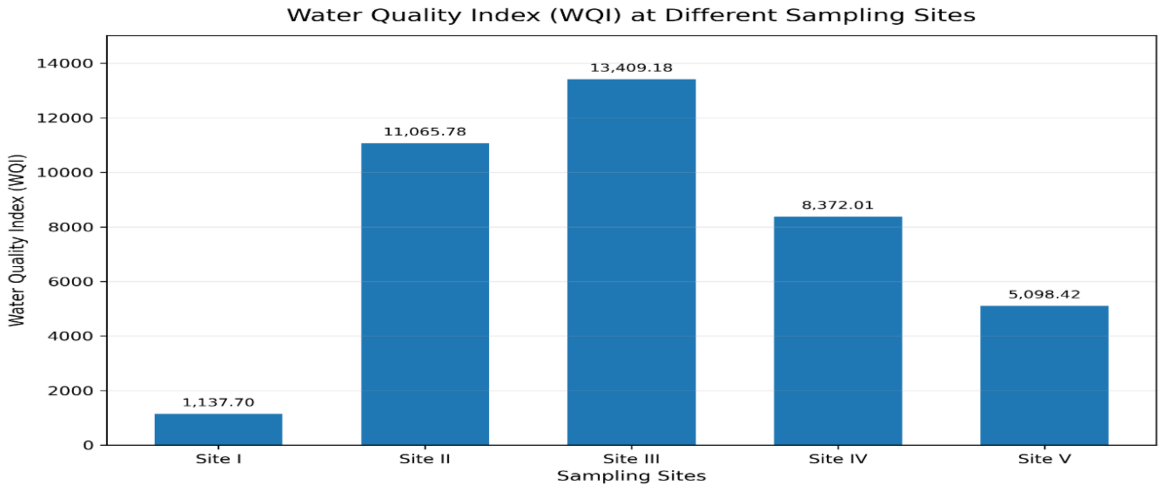

Figure 6: Water Quality Index (WQI) scores across different sampling sites.

3.3 Carbon Adsorption Treatment Performance

Bench-scale GAC treatment demonstrated significant performance differences between organic and inorganic parameters [17]

Table 3: Remediation efficiency of Granular Activated Carbon (GAC) batch treatment

Parameter	Initial (C_0)	Post-Treatment (Ce)	Removal Efficiency (E%)	Mechanism
COD	120 mg/L	< Detection Limit	**100.0%** (Apparent)	Hydrophobic attraction & π-π electron interactions in GAC micropores
TDS	335 mg/L	304 mg/L	**9.25%**	Weak electrostatic interaction of small hydrated ions (Ca^{2+}, Mg^{2+}, Cl^{-})

Adsorption Performance:

"GAC's non-polar porous network effectively traps complex organic molecules responsible for COD via $\pi - \pi$ interactions and van der Waals forces [11,12]. However, small hydrated inorganic ions (Ca^{2+}, Mg^{2+}, Cl^{-}) pass through GAC unhindered, explaining the minimal TDS removal (9.25%) [18].

Organic Pollutants (COD): GAC achieved complete (100%) organic load reduction because non-polar organic molecules adsorb strongly to porous carbon surfaces.

Inorganic Salts (TDS): GAC failed to remove dissolved salts (only 9.25% reduction) because small, highly hydrated inorganic ions pass directly through activated carbon pores.

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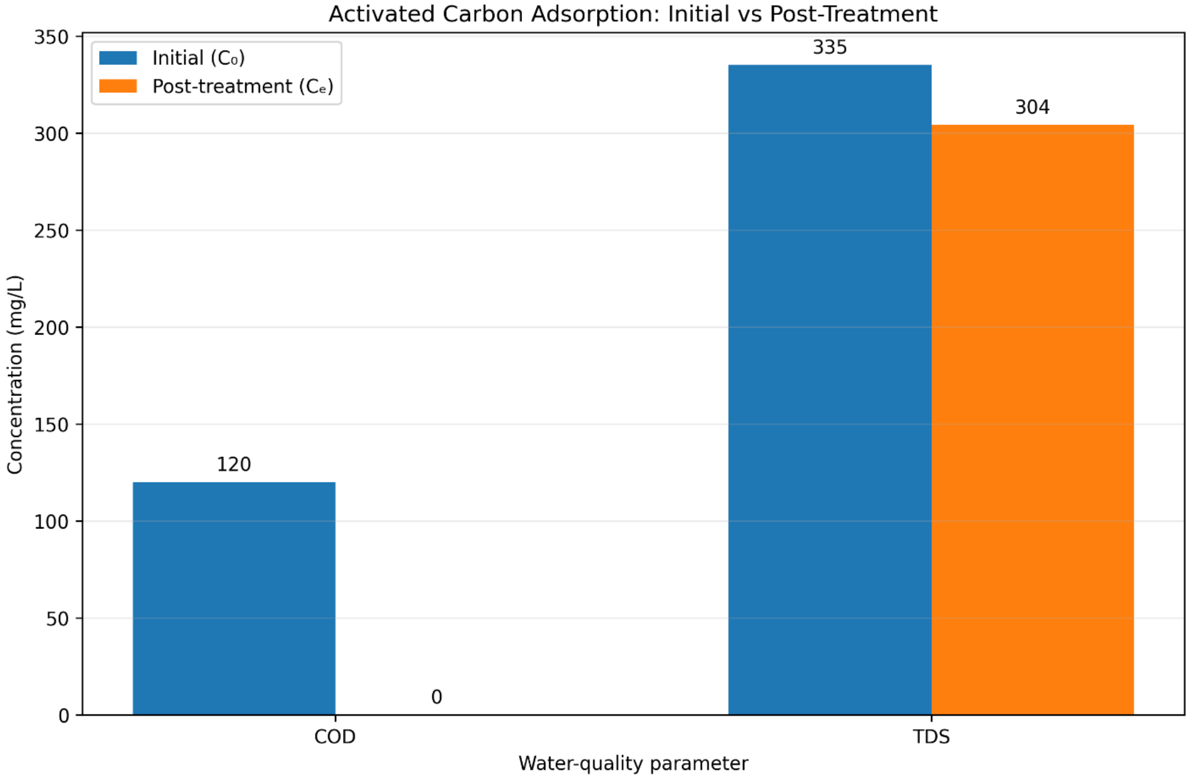

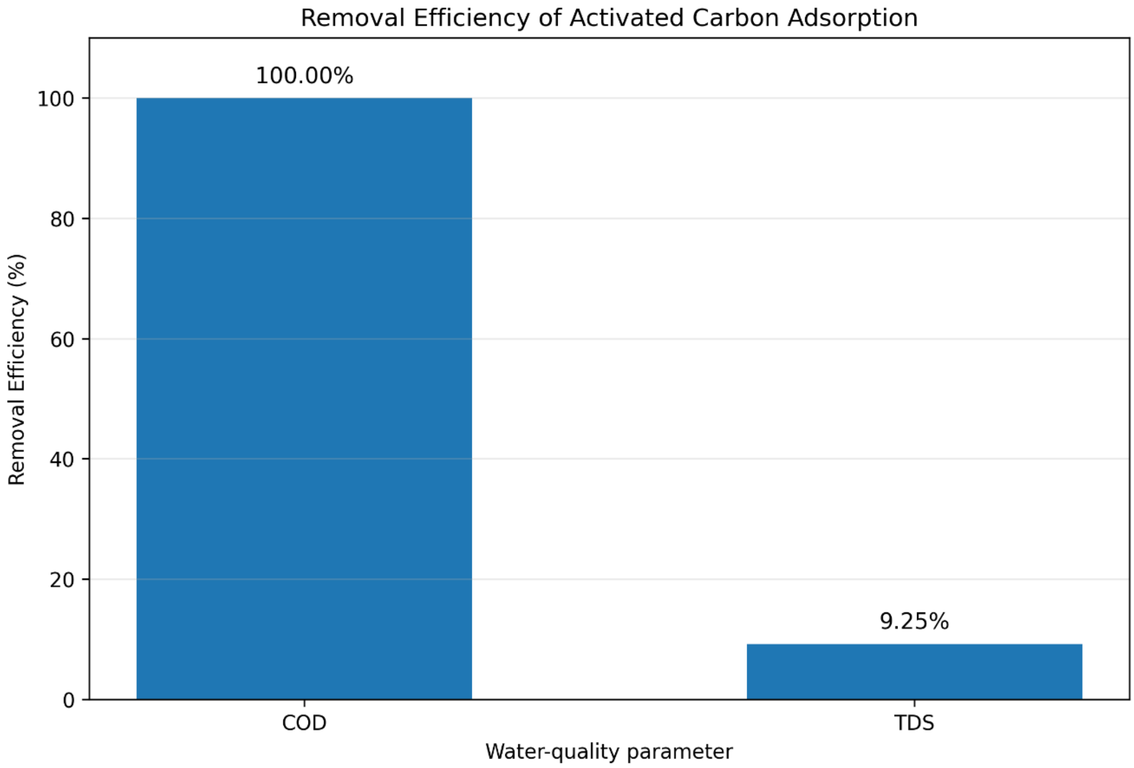

4. Conclusions and Policy Recommendations

Tertiary river remediation requires combining GAC adsorption with membrane filtration (such as Reverse Osmosis or Nanofiltration) to remove both organic and inorganic fractions effectively.

1. **Severe Degradation:** Untreated industrial outfalls from tyre-manufacturing and powder-coating operations significantly degrade the Vaigai River, causing acute spikes in turbidity (221 NTU), BOD (36 mg/L), and COD (120 mg/L).
2. **Index Severity:** The overall WQI score (7,236.93) confirms that the water is completely unsuitable for direct human use.
3. **Remediation Bottlenecks:** Granular activated carbon achieves complete organic COD removal (100%) but fails to remove dissolved inorganic salts (TDS reduction < 10%).
4. **Policy Requirements:** Regional environmental regulatory authorities must enforce mandatory **Multi-Stage Effluent Treatment Plants (ETPs)** combining activated carbon adsorption with Reverse Osmosis (RO) or nanofiltration to achieve total effluent remediation prior to river discharge [18].

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