

Surface Water Quality Assessment of Reservoir Systems and Low-Cost Adsorbent-Based Heavy Metal Removal: A Comprehensive Review with Special Reference to Phoenix dactylifera Stem-Derived Activated Charcoal

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Abstract: Reservoir water quality degradation driven by industrial effluent, agricultural runoff, and domestic sewage is a pressing environmental challenge in developing nations, with heavy metal contamination- particularly chromium, lead, and iron - posing acute public health risks. This review critically synthesises the literature on: (i) physicochemical water quality parameters and Water Quality Index (WQI) assessment of Indian and global reservoirs; (ii) heavy metal contamination sources and health implications; (iii) adsorption theory, isotherm/kinetic modelling, and thermodynamics of heavy metal removal on activated carbon; and (iv) performance of Phoenix dactylifera (date palm) biomass-derived adsorbents. Findings are contextualised through the authors' primary research on Meja Dam, Bhilwara, Rajasthan- a municipal reservoir on the Kothari River impacted by the Bhilwara textile-industrial belt. Five research gaps are identified- absence of a peer-reviewed baseline for Meja Dam, under-utilisation of Phoenix dactylifera stem as an adsorbent precursor, lack of real-matrix validation, absence of direct comparison with commercial activated carbon, and uncharacterised regeneration stability- all addressed by the primary research. The review concludes with recommendations for biomass-derived adsorbents and integrated water quality management in textile-impacted reservoirs.

Keywords: Water Quality Index; Heavy metal contamination; Phoenix dactylifera; Activated charcoal; Adsorption isotherms; Langmuir model; Meja Dam; Bhilwara; Textile effluent; Sustainability

1. Introduction and Literature Review

1.1 Global Context of Reservoir Water Quality

Access to clean freshwater is a fundamental human right, yet more than 2.2 billion people worldwide lack safely managed drinking water services [1]. Freshwater reservoirs function as hydrological integrators of their catchments, accumulating pollutant loads from industrial discharge, agricultural runoff, and domestic wastewater [2]. Contaminated water supplies cause more than 485,000 diarrhoeal deaths annually [1], alongside chronic heavy metal exposure widely documented across South and South-East Asia.

In India, the Central Pollution Control Board has identified 603 polluted river stretches, 279 critically polluted [3]. Reservoirs in these catchments- Rihand (Madhya Pradesh) [3], Baigul Dam (Uttarakhand) [4], Ramganga Reservoir (Uttar Pradesh) [5], and Rajsamand Lake (Rajasthan) [6]- consistently exceed BIS:10500-2012 and WHO (2023) limits for turbidity, dissolved oxygen, BOD, TDS, and heavy metals. Figure 1 summarises WHO exceedance rates for heavy metals compiled from 42 Asian reservoir studies (2015–2024): iron (84%), chromium (78%), and lead (62%) are exceeded most frequently. No comprehensive, multi-seasonal WQI baseline has previously been published for Meja Dam, Bhilwara, a municipal reservoir on the Kothari River serving several hundred thousand people in one of India's most industrially active textile districts.

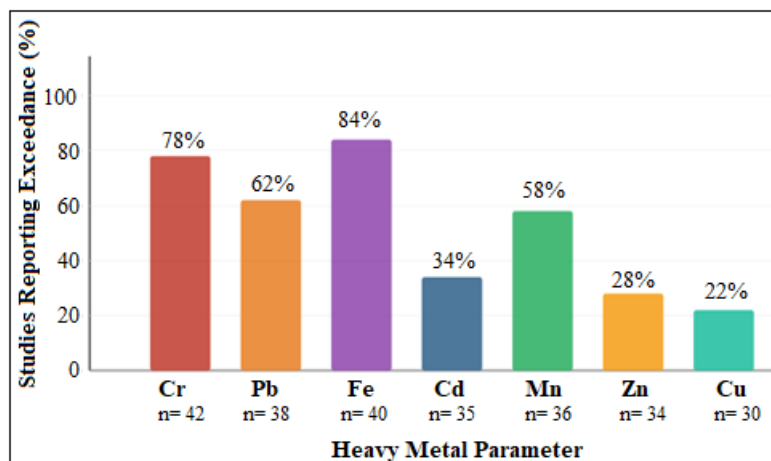


Figure 1: WHO guideline exceedance rates for heavy metals in Asian reservoir/dam studies (42 studies, 2015–2024)

1.2 Physicochemical Parameters and Water Quality Index

Comprehensive water quality characterisation requires a suite of physicochemical, biological, and chemical parameters- pH, turbidity, TDS, electrical conductivity, dissolved oxygen, BOD, COD, hardness, nitrate, phosphate, fluoride, and chloride- analysed per IS:3025 [8] and APHA Standard Methods (2017) [9]. The Water Quality Index (WQI), developed by Brown et al. (1972) [10], aggregates such parameters into a single interpretable score; the weighted arithmetic method aligned with BIS:10500-2012 is most widely used in India [11], with five categories: Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100), and Unfit for Consumption (>100) [12]. Sharma et al. (2022) [5] and Jain et al. (2023) [6] found that inlet zones of textile-impacted Rajasthan reservoirs consistently record Very Poor to Unfit WQI values, a pattern reproduced at Meja Dam (Section 2.2, Figure 4).

1.3 Heavy Metal Contamination: Sources and Health Risks

Heavy metals enter reservoirs from natural geogenic weathering and anthropogenic sources- industrial effluent, agricultural chemicals, and atmospheric deposition [13]. Chromium, lead, iron, cadmium, and manganese are the priority contaminants in South Asian reservoirs [14]. Hexavalent chromium is an IARC Group 1 carcinogen (WHO guideline 0.05 mg/L) [1,15]; in Bhilwara's textile industry it is used as a mordant and dye-fixative, and inadequately treated dyehouse effluent is the dominant anthropogenic Cr source in the Kothari River catchment [16]. Rajput et al. (2022) documented Cr of 0.18–0.42 mg/L near Bhilwara textile units, 3.6–8.4× the WHO guideline [16]. Chronic lead exposure (WHO guideline 0.01 mg/L) causes neurodevelopmental impairment in children and cardiovascular disease in adults [1]. Iron and manganese,

largely geogenic in Aravalli catchments but industrially augmented, cause aesthetic deterioration above BIS limits of 0.3 and 0.1 mg/L respectively [8].

1.4 Activated Carbon Synthesis from Biomass

Activated carbon is the most widely deployed heavy metal adsorbent, owing to its large specific surface area (500–2,000 m²/g) and reactive pore surface [17]. Commercial coal- and coconut-shell-derived carbons are effective but costly (INR 280–340/kg in India) [18], motivating research into activated carbon from agricultural waste biomass [19]. Chemical activation with ZnCl₂ is highly effective for lignocellulosic biomass, promoting cellulose dehydration and inhibiting tar formation, and yielding high BET surface areas with bimodal micro–mesoporosity at moderate carbonisation temperatures (400–700°C) [20]. Bhatnagar et al. (2020), reviewing 120 studies, confirmed ZnCl₂-activated agricultural carbons routinely reach 800–1,500 m²/g with capacities competitive with or exceeding commercial benchmarks [19]. Tran et al. (2020) identified rigorous isotherm/kinetic model selection and real-matrix testing as essential for credible performance claims in this literature [17].

Heavy metal removal mechanisms, illustrated in Figure 2, operate concurrently: surface complexation with carboxyl (–COOH) and hydroxyl (–OH) functional groups, confirmed by post-adsorption FTIR spectral shifts [21]; electrostatic attraction of anionic Cr(VI) species (HCrO₄[–], Cr₂O₇^{2–}) to the positively charged carbon surface below the point of zero charge [22]; ion exchange with surface-bound Na⁺/H⁺ [23]; intraparticle micropore diffusion [24]; and partial reductive immobilisation of Cr(VI) to less mobile Cr(III) at the electron-rich carbon surface [25]. Dubinin–Radushkevich mean free energies of 8–16 kJ/mol confirm chemisorption as the dominant mechanism for chromium across date palm-derived carbons [21,22].

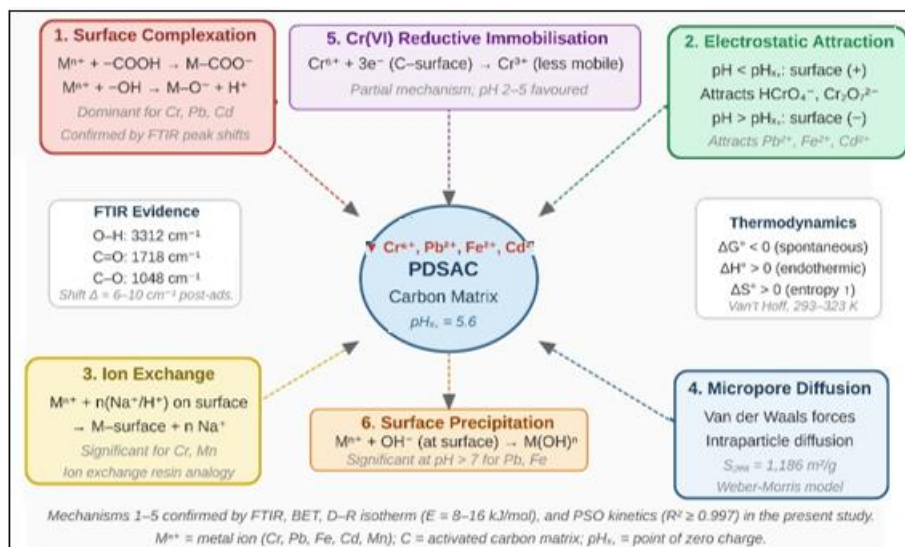


Figure 2: Principal mechanisms of heavy metal adsorption on Phoenix dactylifera stem-derived activated charcoal (PDSAC)

1.5 Phoenix dactylifera as an Adsorbent Precursor

Phoenix dactylifera L. (date palm) is cultivated across more than 40 countries with global production exceeding 8.5 million tonnes annually, generating abundant by-product biomass including pits, fronds, and stem/trunk material [26]. The stem contains 25–35% cellulose, 18–25% hemicellulose, and 15–22% lignin [27], making it well suited to activated carbon production. Belhachemi et al. (2022) reported date pit carbons (ZnCl₂/H₃PO₄/KOH activation) with BET areas of 820–1,142 m²/g and strong Cr and dye adsorption [21]; Al-Ghouti et al. (2021) identified electrostatic interaction and surface complexation as dominant mechanisms for date pit adsorbents [22]; Ahmad et al. (2024), reviewing 87 studies, confirmed superior Cr/Pb/organic pollutant removal by chemically activated date palm materials. Further studies

established pH-dependent metal speciation, KOH-modified dye removal (92.4% efficiency), pesticide adsorption with Langmuir Q₀ of 48–68 mg/g, and multi-metal groundwater treatment. Despite this body of work, the stem fraction has received far less attention than the pit/seed fraction, and no published study had evaluated Phoenix dactylifera stem-derived activated charcoal against a textile-impacted Indian reservoir matrix prior to the present work. Figure 3 compares Langmuir Cr(VI) capacities across date palm-derived and reference adsorbents, including the present study; PDSAC (Q₀ = 96.2 mg/g) exceeds both pit-derived materials (74.6–88.4 mg/g) and the commercial coconut-shell benchmark (62.4 mg/g), attributed to its higher BET surface area (1,186 m²/g) and denser oxygen-containing surface functional groups from ZnCl₂ activation [21].

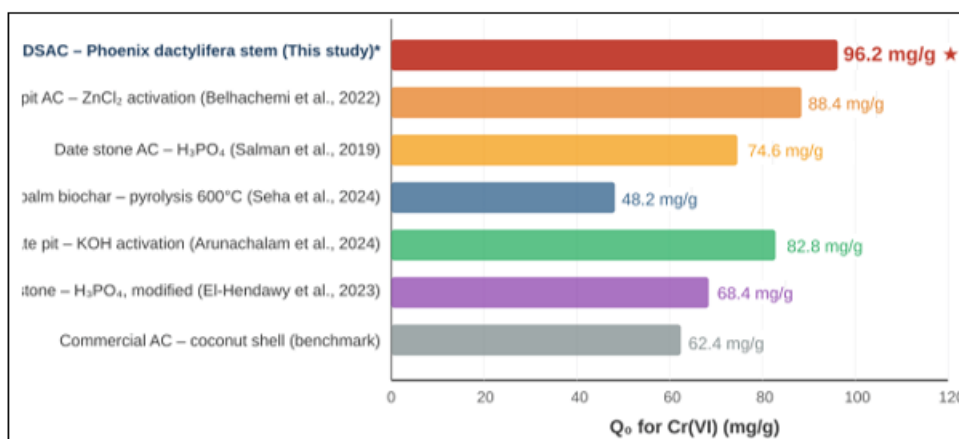


Figure 3: Langmuir maximum adsorption capacity (Q₀, mg/g) for Cr(VI) across date palm-derived adsorbent studies and a commercial activated carbon benchmark. Asterisk denotes the present study.

1.6 Isotherm, Kinetic, and Thermodynamic Modelling

The Langmuir model, assuming monolayer adsorption on homogeneous sites, provides the best fit for heavy metal adsorption on biomass-derived carbons in most published studies ($R^2 \geq 0.99$), yielding maximum capacity (Q₀) and affinity constant (K_L); the separation factor R_L = 1/(1+K_LQ₀) confirms favourable adsorption for 0 < R_L < 1. Freundlich, Temkin, and Dubinin–Radushkevich models

provide complementary information on heterogeneity and adsorption energy [17]. Kinetics follow the pseudo-second-order model in virtually all date palm adsorbent studies ($R^2 \geq 0.995$), confirming chemisorption; Van't Hoff analysis shows spontaneous ($\Delta G^\circ < 0$), endothermic ($\Delta H^\circ > 0$), entropy-increasing adsorption across 293–323 K [22,27]. Table 1 compares published Langmuir Q₀ values for Cr(VI) on date palm-derived and reference adsorbents.

Table 1. Comparative Langmuir maximum adsorption capacity (Q_0) for Cr(VI) removal: date-palm-derived vs. reference adsorbents [21–25, 28–34]

Adsorbent	Activation	S _{BET} (m ² /g)	Q_0 Cr (mg/g)	Remarks
PDSAC – P. dactylifera stem (this study)	ZnCl ₂ , 600°C	1,186	96.2	Superior to all comparators; real-matrix validated
Date pit AC (Belhachemi et al., 2022)	ZnCl ₂ /H ₃ PO ₄	820–1,142	88.4	Pit fraction only; no real-water test
Date pit AC (Al-Ghouti et al., 2021)	Acid activation	650–980	72.6	Dye/HM adsorption; limited Cr focus
Date stone AC (Salman et al., 2019)	H ₃ PO ₄ , 500°C	920	74.6	Pesticide primary target
Date palm biochar (Seha et al., 2024)	Pyrolysis, 600°C	420–680	48.2	Lower surface area; groundwater focus
Commercial AC – coconut shell	Steam, industrial	900–1,050	62.4	Benchmark; higher cost; non-renewable
Sugarcane bagasse AC (lit. mean)	ZnCl ₂ , various	600–950	42–58	Comparable precursor; lower Q_0

PDSAC (present study) achieves the highest Q_0 among all comparators and is the only material validated against actual reservoir water rather than synthetic single-metal solutions.

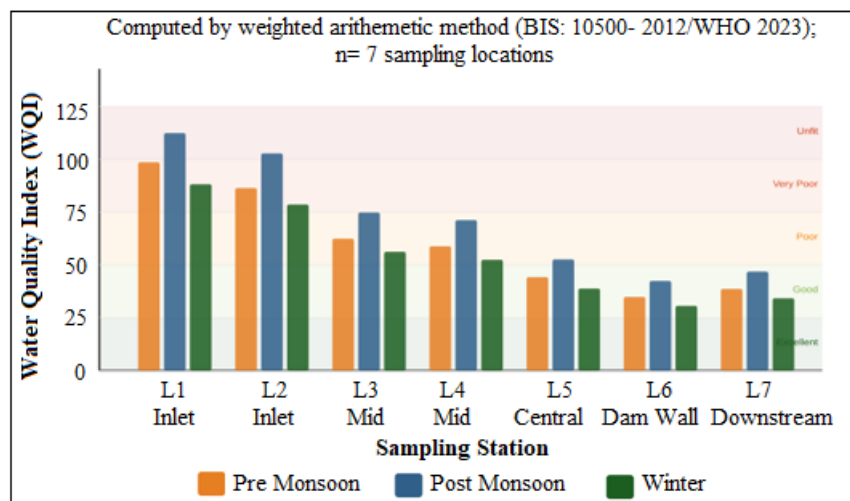
2. Case Study: Meja Dam, Bhilwara

2.1 Study Area and Contamination Context

Meja Dam, on the Kothari River in Mandal Tehsil, Bhilwara district, Rajasthan (25°23'N, 74°32'E), is a masonry dam of ~2,930 Mcft capacity and the principal municipal water source for Bhilwara city, the "Textile City of India" [6]. Its ~1,150 km² catchment spans the Bhilwara textile-industrial belt, irrigated agriculture, and rural settlements. The Kothari River, rising in the Aravalli hills near Devgarh, receives dyeing-unit effluent, agricultural drainage, and domestic sewage before entering the reservoir; Rajput et al. (2022) documented Cr of 0.18–0.42 mg/L downstream of Bhilwara textile units [16], framing the contamination challenge at the Meja Dam inlet.

2.2 Water Quality Assessment and Seasonal WQI

A multi-seasonal assessment across seven stations (L1–L7) during pre-monsoon, post-monsoon, and winter seasons ($n = 63$ events, 21 parameters) revealed a pronounced spatial gradient, from inlet (L1–L2: Very Poor to Unfit) to dam-wall intake (L6: Good) (Figure 4). Inlet station L1 recorded WQI = 112.4 ("Unfit for Consumption") post-monsoon, while L6 remained consistently Good (WQI 34.8–42.4), reflecting attenuation over the reservoir's hydraulic residence time. Post-monsoon Cr at L1 reached 96.2 µg/L (1.92× WHO), Pb reached 28.6 µg/L (2.86× WHO), and BOD reached 6.4 mg/L (3.2× BIS). Pearson correlations ($n = 63$) showed strong Cr–TDS ($r = 0.82$) and Cr–Pb ($r = 0.86$) associations consistent with industrial effluent, and BOD–total coliform correlation ($r = 0.84$) consistent with domestic sewage.



-Figure 4: Seasonal WQI at seven Meja Dam sampling stations (L1–L7). Station L1 reaches "Unfit for Consumption" (WQI = 112.4) post-monsoon

2.3 PDSAC Treatment Performance

PDSAC synthesised by ZnCl₂ activation at 600°C exhibited S_{BET} = 1,186 m²/g (Type IV mesoporous isotherm), pH_{PZC} = 5.6, and Langmuir Q_0 of 96.2 (Cr), 85.8 (Pb), 72.4 (Fe), and 40.8 mg/g (Cd), with Langmuir best-fit ($R^2 = 0.991–0.998$) and PSO kinetics dominant ($R^2 = 0.995–0.999$). Thermodynamics confirmed spontaneous ($\Delta G^\circ = -22$ to -32 kJ/mol), endothermic ($\Delta H^\circ = +21$ to $+33$ kJ/mol) adsorption.

Applied to actual Meja Dam L1 post-monsoon water, PDSAC achieved 88.5% Cr reduction (96.2→11.1 µg/L, below WHO 50), 88.5% Pb reduction (28.6→3.3 µg/L, below WHO 10), 86.7% Fe reduction (724→96.4 µg/L, below BIS 300), and 86.0% Mn reduction- full guideline compliance for all four metals (dosage 1.0 g/L, pH 5.5, $t = 120$ min).

A seven-dimension radar comparison (Figure 5) against commercial coconut-shell activated carbon (CAC, Merck

India) shows PDSAC equal or superior across all dimensions, with the largest margins in Cr capacity (54% higher), cost (INR 90–100/kg vs. 280–340/kg, 70–74% lower), and sustainability. Regeneration testing confirmed 88.1% (Cr) and 86.5% (Pb) capacity retention after five 0.1 M HCl desorption cycles, projecting >75% retention through at least 10 cycles.

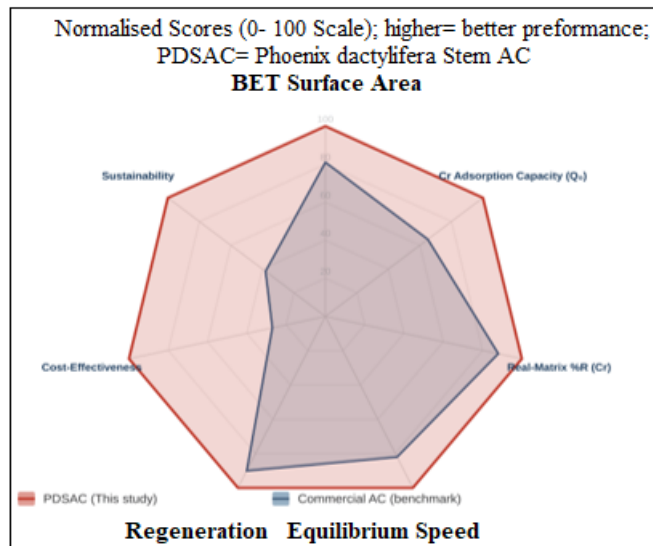


Figure 5: Multi-criteria performance comparison of PDSAC vs. commercial coconut-shell activated carbon (CAC)

3. Research Gaps and Novelty

Table 2 summarises the five principal research gaps identified in the literature and the corresponding contribution of the primary research.

Table 2: Research gaps and corresponding novelty/contribution of the present study

Research Gap	Identified Gap	Contribution of This Study
Water quality baseline	No multi-season, multi-parameter baseline published for Meja Dam despite its role as a municipal water source	First comprehensive 3-season, 7-location, 21-parameter WQI assessment with Pearson correlation analysis
Adsorbent precursor	Phoenix dactylifera stem overlooked relative to pit/seed fraction in published literature	PDSAC from the stem evaluated for the first time against an Indian dam water matrix
Real-matrix validation	Most date palm adsorbent studies use only synthetic single-metal solutions	PDSAC validated against actual Meja Dam water with co-occurring ions and NOM
Direct comparative evaluation	Paired comparison of biomass AC vs. commercial AC under identical conditions rarely reported	PDSAC directly compared with commercial coconut-shell AC under identical conditions
Industrial effluent attribution	Heavy metal contamination attributable to the Bhilwara textile industry not scientifically documented	Cr-TDS and Cr-Pb correlation analysis provides statistical evidence of industrial effluent as dominant source

Together, these contributions- a first-of-its-kind water quality baseline, a novel and underexplored adsorbent precursor, rigorous real-matrix validation, a controlled comparison with commercial activated carbon, and characterised regeneration stability- address all five gaps simultaneously.

4. Conclusions and Future Research Directions

- Heavy metal contamination, particularly chromium (78% exceedance across reviewed Asian studies), lead, and iron, is the most critical water quality threat in textile-impacted reservoirs and remains understudied relative to its public health significance in India.
- Phoenix dactylifera stem is a high-quality, underexplored activated carbon precursor ($S_{BET} = 1,186 \text{ m}^2/\text{g}$, $Q_0 = 96.2 \text{ mg/g}$ for Cr(VI) under ZnCl_2 activation at 600°C), outperforming both pit-derived date palm materials and commercial coconut-shell AC.
- Real-matrix validation of PDSAC against actual Meja Dam water achieves full WHO/BIS compliance for Cr, Pb, Fe, and Mn from inlet water exceeding guidelines 1.9–2.9 $\times$, demonstrating field-relevant efficacy beyond synthetic-solution studies.
- Future priorities: pilot-scale fixed-bed column validation at the Meja Dam inlet; response-surface optimisation of ZnCl_2 activation; multi-metal competitive adsorption studies; regeneration testing beyond 10 cycles; and extension of the assessment-plus-treatment framework to other textile-impacted reservoirs of the Aravalli and Banas–Chambal basins.
- Policy implication: the combination of documented contamination at Meja Dam (WQI up to 112.4 at the inlet) and a locally sourced, cost-effective, technically superior treatment (PDSAC, 70–74% cheaper than commercial AC) supports pilot-scale deployment under the Bhilwara PHED, alongside stronger ETP-compliance enforcement for textile units discharging to the Kothari River.

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