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PREPARATION AND CHARACTERIZATION OF INDIGENOUS LEAF-BASED ACTIVATED CARBON FOR HEAVY METAL REMOVAL

Jyoti

Subject: Chemistry
Email: Jyotiy502600@gmail.com

Abstract

Heavy metal contamination of surface water, groundwater and industrial effluent has become one of the most persistent environmental problems in developing economies, because metals such as lead, cadmium, chromium, nickel and copper are non-biodegradable, bioaccumulative and toxic even at trace concentrations. Conventional treatment routes including chemical precipitation, ion exchange, membrane separation and electrochemical recovery are technically effective but capital-intensive, sludge-generating and difficult to operate at small and decentralised scales. Adsorption using low-cost carbonaceous materials has therefore attracted sustained scientific attention. This paper examines the preparation and characterization of indigenous leaf-based activated carbon and evaluates its performance for heavy metal removal from aqueous systems. Leaf biomass from commonly available indigenous species such as neem (Azadirachta indica), banyan and peepal (Ficus spp.), mango (Mangifera indica), teak (Tectona grandis), guava (Psidium guajava) and eucalyptus is abundant, renewable, seasonally regenerated and currently treated as municipal or agricultural waste. The study adopts a descriptive-analytical, literature-based research design and synthesises peer-reviewed work published between 2015 and 2025 on precursor pre-treatment, chemical and physical activation, carbonisation conditions, textural and surface characterisation, batch adsorption behaviour, isotherm and kinetic modelling, thermodynamics, desorption and reuse. The analysis develops an integrated framework linking precursor properties and activation variables to surface functionality, pore architecture and metal uptake capacity. It shows that chemical activation with phosphoric acid, zinc chloride or potassium hydroxide at impregnation ratios of about 1:1 to 1:3 and carbonisation temperatures of roughly 450 to 700 degrees Celsius consistently produces mesoporous to microporous carbons with reported Brunauer-Emmett-Teller surface areas in the range of 400 to 1200 square metres per gram and oxygen-rich surfaces bearing hydroxyl, carboxyl, carbonyl and phosphate functionalities. Adsorption of divalent cations is strongly pH dependent and generally optimal between pH 5 and 6, while hexavalent chromium removal is favoured in the acidic range. Uptake is most often described by the Langmuir isotherm and the pseudo-second-order kinetic model, indicating monolayer coverage on energetically comparable sites and a chemisorption-controlled rate step involving ion exchange, surface complexation and electrostatic attraction. Thermodynamic parameters reported in the literature are typically consistent with spontaneous and endothermic uptake. The paper also identifies the principal constraints on real-world adoption: batch-to-batch variability of leaf feedstock, incomplete reporting of characterisation data, limited testing with genuine industrial effluent, weak treatment of spent-adsorbent disposal, and the absence of standardised regeneration and costing protocols. It concludes that indigenous leaf-based activated carbon is a technically credible and economically attractive adsorbent, but that its transition from laboratory demonstration to field application depends on standardised preparation protocols, multi-cycle regeneration data, column and pilot-scale validation, and an explicit end-of-life management strategy.

Keywords: activated carbon; indigenous leaf biomass; chemical activation; heavy metal removal; adsorption isotherm; adsorption kinetics; surface characterisation; BET surface area; FTIR; water treatment; low-cost adsorbent; circular bioeconomy

1. Introduction

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Water quality management has moved from a narrow question of microbiological safety to a broader concern with chemical contamination, and within that field heavy metals occupy a distinctive position. Unlike organic pollutants, metals cannot be degraded into harmless end products. They are transferred between environmental compartments, accumulate in sediments and biological tissue, and re-enter human systems through drinking water, irrigation and the food chain. Lead impairs neurological development, cadmium damages renal function and bone mineralisation, hexavalent chromium is carcinogenic and mutagenic, nickel is a recognised sensitiser and suspected carcinogen, and copper and zinc, although essential in trace amounts, become toxic above narrow threshold concentrations. The environmental persistence and toxicological weight of these elements make their removal from effluent a regulatory as well as a technical obligation.

Industrial sources of metal loading are diverse. Electroplating and metal finishing discharge chromium, nickel and zinc; battery manufacturing and recycling release lead and cadmium; tanneries contribute chromium; mining and ore processing mobilise a wide spectrum of metals; pigment, pesticide, fertiliser and electronic manufacturing add further loads. In many developing regions these discharges are compounded by small and medium enterprises that operate below the threshold of effective monitoring and cannot finance conventional end-of-pipe treatment. The result is a treatment gap: the technologies that work best are the ones least likely to be installed where they are most needed.

Adsorption is the treatment route most capable of closing that gap. It is operationally simple, effective at low residual concentrations where precipitation becomes inefficient, tolerant of variable influent, and adaptable to both batch and continuous configurations. Its economics, however, depend almost entirely on the adsorbent. Commercial activated carbon derived from coal, lignite or coconut shell offers excellent performance but carries a purchase cost, an energy-intensive production route and a regeneration burden that many small operators cannot absorb. This has driven two decades of research into activated carbons prepared from agricultural and forestry residues, and it is within this line of work that leaf biomass has emerged as a precursor of particular interest.

Leaves are distinctive among lignocellulosic wastes. They are produced annually and continuously rather than only at harvest; they are geographically ubiquitous rather than concentrated around processing industries; they require no diversion from a competing food, fodder or fuel use; and in urban and campus settings they are actively collected as a nuisance waste and frequently disposed of by open burning, which itself contributes to particulate and greenhouse emissions. Converting this stream into an adsorbent therefore addresses a waste-management problem and a water-treatment problem with a single intervention. Indigenous species widely distributed across South Asia, including neem, peepal, banyan, mango, teak, guava, eucalyptus and subabul, provide leaf litter with cellulose, hemicellulose and lignin fractions suited to carbonisation, together with native inorganic constituents and phytochemical residues that influence the surface chemistry of the resulting carbon.

The central problem addressed in this paper is that the literature on leaf-derived activated carbon, although extensive, is fragmented. Individual studies report a single species, one activating agent, one metal and one set of operating conditions. Preparation parameters, characterisation depth and performance metrics are reported inconsistently, which makes cross-study comparison unreliable and obscures the underlying structure-property-performance relationships. What is required is an integrative analysis that connects precursor characteristics and activation variables to measurable surface properties, and those properties in turn to adsorption capacity, mechanism and regenerability.

1.1 Statement of the Research Problem

Reported adsorption capacities for leaf-based activated carbons vary by an order of magnitude for the same metal, and the variation cannot be explained by species alone. Activation chemistry, impregnation ratio, carbonisation temperature and residence time, particle size, solution pH, initial concentration and analytical method all contribute. Without a framework that separates these effects, the literature offers a collection of isolated results rather than a design basis. The research problem is therefore to establish how preparation variables govern the physicochemical character of indigenous leaf-based activated carbon, and how that character determines heavy metal uptake, so that

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preparation can be treated as a controllable engineering decision rather than an empirical trial.

1.2 Significance of the Study

The study is significant on three grounds. Environmentally, it addresses the valorisation of a waste stream that is currently burned or landfilled, and links it to the treatment of a persistent class of pollutants. Economically, it examines an adsorbent whose raw material cost is effectively zero and whose production can be decentralised, which is relevant to small industrial clusters, rural water supply and institutional treatment units. Scientifically, it consolidates a dispersed literature into a comparative framework and identifies the specific reporting gaps that currently prevent laboratory results from being translated into design practice. The analysis is also aligned with circular-economy thinking, in which residual biomass is converted into a functional material rather than treated as a disposal liability.

1.3 Objectives of the Study

- To examine the suitability of indigenous leaf biomass as a precursor for activated carbon, with reference to its proximate composition, lignocellulosic structure and availability.
- To analyse the preparation routes for leaf-based activated carbon, including pre-treatment, chemical and physical activation, impregnation ratio, carbonisation temperature and yield.
- To review the characterisation techniques used to establish the textural, morphological, crystalline and surface-chemical properties of the prepared carbons.
- To evaluate the influence of operating parameters, namely pH, adsorbent dose, contact time, initial metal concentration, temperature and competing ions, on heavy metal removal.
- To interpret adsorption behaviour through equilibrium isotherm, kinetic and thermodynamic models and to identify the governing uptake mechanisms.
- To assess regeneration, reusability, cost and disposal considerations, and to develop an integrated framework connecting preparation variables to adsorption performance.

Table 1. Research objectives, analytical focus and supporting literature

Objective area	**Analytical focus**	**Main supporting literature**
Precursor suitability	Lignocellulosic composition, ash content, availability and waste-stream logistics of indigenous leaf biomass	Bhatnagar et al. (2015); Yaashikaa et al. (2020)
Preparation and activation	Impregnation ratio, activating agent, carbonisation temperature, heating rate, yield	Heidarinejad et al. (2020); Kumar & Jena (2016)
Characterisation	BET surface area, pore volume, SEM-EDX morphology, FTIR functional groups, XRD, pH(pzc)	Sizmur et al. (2017); Mariana et al. (2021)
Adsorption performance	Effect of pH, dose, contact time, concentration, temperature and co-existing ions	Renu et al. (2017); Qasem et al. (2021)
Modelling	Isotherm, kinetic and thermodynamic interpretation and mechanism identification	Wang & Guo (2020a, 2020b); Al-Ghouti & Da'ana (2020)
Reuse and economics	Desorption efficiency, cycle stability, cost per unit mass, spent-adsorbent disposal	Inyang et al. (2016); Nayak & Bhushan (2021)

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2. Conceptual and Theoretical Background

2.1 Heavy Metals in Aqueous Systems

Heavy metals are conventionally defined as metallic elements with relatively high density and atomic weight that exhibit toxicity at low concentration. In aqueous systems their behaviour is governed by speciation, which in turn depends on pH, redox potential, ionic strength and the presence of complexing ligands. Lead, cadmium, nickel, copper and zinc exist predominantly as divalent cations in the mildly acidic to neutral range and begin to hydrolyse and precipitate as hydroxides above pH 6 to 8. Chromium behaves differently: the hexavalent form exists as oxyanions, principally hydrogen chromate below about pH 6.5 and chromate above it, while the trivalent form behaves as a cation and is markedly less toxic. This distinction is central to adsorbent design, because a positively charged surface is required to capture chromium oxyanions whereas a negatively charged surface is required to capture divalent cations. No single operating pH is therefore optimal for all metals, and the removal of mixed-metal effluent requires either sequential treatment or a compromise operating window.

Regulatory limits reflect the toxicological weight of these elements. Guideline values for drinking water are typically set at fractions of a milligram per litre, and effluent discharge standards, while less stringent, are still low relative to raw industrial concentrations. Because adsorption performs well precisely in the low-concentration polishing range where precipitation becomes chemically inefficient, it is best understood not as a replacement for primary treatment but as a complement to it.

2.2 Adsorption as a Remediation Mechanism

Adsorption is the accumulation of a solute at the interface between a solid and a liquid. It is customarily divided into physisorption, driven by van der Waals and electrostatic forces with low activation energy and ready reversibility, and chemisorption, involving electron sharing or exchange, higher activation energy and stronger binding. In practice, metal uptake on carbonaceous adsorbents rarely occurs by a single mechanism. Electrostatic attraction between the deprotonated surface and the metal cation, ion exchange with surface protons or with native calcium, magnesium and potassium, inner-sphere complexation with carboxyl, hydroxyl and phenolic groups, cation-pi interaction with aromatic domains of the carbon matrix, and surface precipitation at elevated pH may all contribute simultaneously. Their relative weight shifts with pH, metal identity, surface loading and the mineral content of the precursor.

The relevance of this to preparation is direct. A carbon with high surface area but few oxygen-containing functional groups will show modest metal uptake despite excellent textural properties, because physical porosity provides accessibility while surface chemistry provides binding energy. The design objective is therefore not to maximise surface area alone but to achieve an appropriate combination of accessible mesoporosity and oxygen-rich functionality.

2.3 Indigenous Leaf Biomass as a Precursor

Lignocellulosic biomass consists of cellulose, hemicellulose and lignin in proportions that vary by species and tissue. In leaves, cellulose typically accounts for roughly a quarter to a third of dry mass, hemicellulose for a comparable or slightly smaller share, and lignin for a fifth to a third, with the balance comprising extractives, waxes, proteins and inorganic ash. During pyrolysis, hemicellulose decomposes first at approximately 200 to 300 degrees Celsius, cellulose between about 300 and 400 degrees, and lignin over a broad range extending beyond 500 degrees. Lignin contributes disproportionately to fixed-carbon yield and to the aromatic character of the residual char, so precursors with higher lignin content generally give higher yields at a given temperature.

Leaf biomass carries a comparatively high ash content relative to woody precursors, often between five and fifteen per cent, dominated by silica, calcium, potassium and magnesium. Ash is conventionally regarded as undesirable because it occupies volume without contributing adsorption sites and can block pore openings, and demineralisation by acid washing is a common pre-treatment. However, native alkali and alkaline earth metals also serve as

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exchangeable cations that participate directly in ion-exchange uptake, and calcium and magnesium can promote surface precipitation of metal hydroxides and carbonates. Complete demineralisation is therefore not automatically beneficial, and the trade-off between porosity and exchange capacity is an under-examined preparation variable.

Species-specific chemistry also matters. Neem leaves contain limonoid and terpenoid compounds; eucalyptus is rich in essential oils and polyphenols; Ficus species contain latex and high mineral loads; mango and guava leaves contain substantial tannin and phenolic fractions. These constituents influence the density of oxygenated functional groups on the final carbon and, in the case of tannin-rich leaves, may leave residual polyphenolic structures that themselves chelate metal ions.

2.4 Activation Chemistry

Activation is the step that converts a low-porosity char into a material with developed and accessible pore structure. Physical activation carbonises the precursor in an inert atmosphere and then gasifies the char with steam or carbon dioxide at 700 to 900 degrees Celsius, selectively eroding disordered carbon and opening the pore network. It uses no chemical reagent and produces no chemically contaminated effluent, but it requires higher temperature, longer residence time and greater energy input, and generally yields a predominantly microporous carbon with lower surface oxygen content.

Chemical activation impregnates the raw biomass with a reagent before or during a single lower-temperature thermal treatment. Phosphoric acid, effective at 400 to 600 degrees Celsius, acts as a dehydrating agent and crosslinking catalyst, promotes aromatic condensation, inhibits tar formation and leaves phosphate and polyphosphate esters bound to the surface, which contribute directly to cation binding; it typically produces mesoporous carbon with high yield. Zinc chloride behaves similarly as a dehydrating agent and generates well-developed porosity at moderate temperature, but raises concern regarding residual zinc and the environmental handling of wash effluent. Potassium hydroxide operates through intercalation of metallic potassium and redox reaction with the carbon matrix at 600 to 800 degrees Celsius, produces the highest surface areas and a strongly microporous structure, but is corrosive, requires extensive washing and gives lower yields. Alkali carbonates such as potassium carbonate offer a less aggressive alternative.

Three variables dominate outcomes across all chemical routes: the impregnation ratio of activating agent to precursor by mass, the activation temperature, and the residence time. Increasing impregnation ratio generally increases surface area up to a threshold, beyond which excessive reagent widens existing pores, collapses pore walls and reduces both surface area and yield. Increasing temperature has a comparable inverted-U effect. The optimum for most leaf precursors reported in the 2015-2025 literature lies at impregnation ratios of about 1:1 to 1:3 and temperatures of roughly 450 to 700 degrees Celsius.

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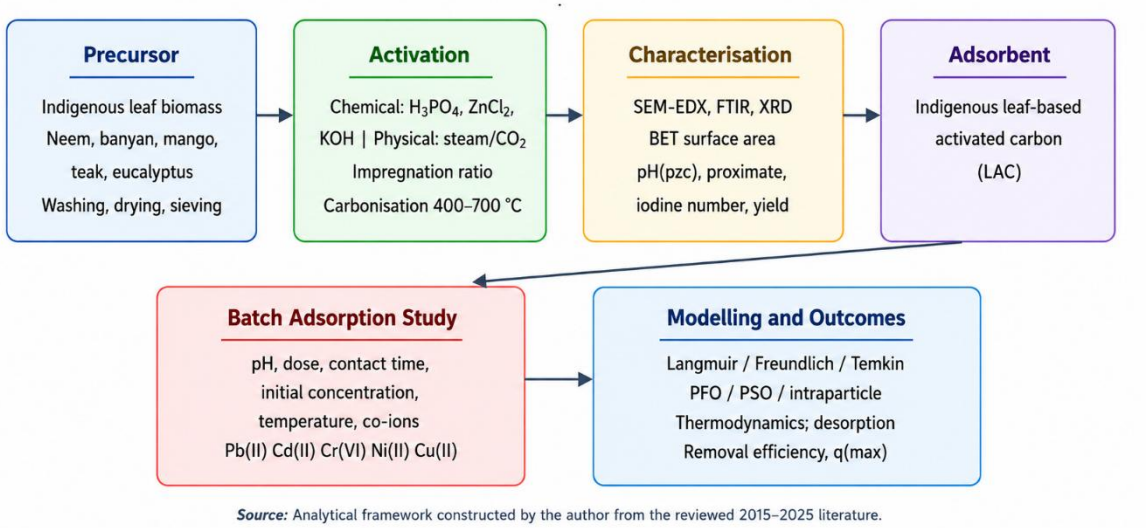

Figure 1. Preparation, characterisation and application pathway for indigenous leaf-based activated carbon.

3. Review of Literature

3.1 Low-Cost Adsorbents and the Case for Biomass Carbons

Comprehensive reviews of low-cost sorbents have consistently concluded that agricultural and forestry residues can achieve metal removal comparable to commercial activated carbon when appropriately activated. De Gisi and colleagues (2016) surveyed the characteristics and adsorption capacities of low-cost sorbents and emphasised that cost advantage is meaningful only when regeneration, disposal and performance stability are included in the assessment, since a cheap adsorbent that requires frequent replacement may prove more expensive over the operating life of a unit. Bhatnagar and co-workers (2015) reviewed agricultural peels and residues as precursors and highlighted the influence of surface functionality on metal binding. Renu, Agarwal and Singh (2017) compared a wide range of adsorbents for metal removal and observed that reported capacities are strongly conditioned by experimental design, particularly initial concentration and pH, which complicates direct comparison. Qasem, Mohammed and Lawal (2021) provided a critical review of removal technologies and positioned adsorption as the most practical option for low-concentration polishing.

3.2 Preparation and Activation Routes

Heidarinejad and colleagues (2020) reviewed methods for the preparation and activation of activated carbon and systematised the relationships between activating agent, temperature and resulting pore structure, confirming that phosphoric acid tends toward mesoporosity while potassium hydroxide favours microporosity. Kumar and Jena (2016) demonstrated with a shell precursor that phosphoric acid activation can yield high surface area at comparatively modest temperature, a finding widely reproduced with leaf precursors. Mariana and co-workers (2021) reviewed biomass-derived activated carbons for water treatment and drew attention to the reproducibility problem created by inconsistent reporting of heating rate, gas flow and washing protocol. Across this literature, one methodological weakness recurs: many studies report a single preparation condition without optimisation, so the reported capacity reflects an arbitrary point in the parameter space rather than the material's achievable performance.

3.3 Characterisation Practice

Sizmur and colleagues (2017) examined modification strategies for enhancing the sorption of inorganic species onto biochar and stressed that surface oxygen functionality, not surface area alone, correlates with metal uptake. Tan and co-workers (2015) reviewed the application of biochar for pollutant removal and documented the role of mineral

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phases in metal immobilisation. Inyang and colleagues (2016) reviewed biochar as a low-cost adsorbent for aqueous heavy metals and identified precipitation with native carbonates and phosphates as a mechanism frequently overlooked in favour of surface complexation. The practical difficulty flagged across these reviews is that fewer than half of published studies report a full characterisation set, and BET data, point of zero charge and elemental composition are the properties most often omitted, precisely those needed to interpret mechanism.

3.4 Equilibrium, Kinetic and Thermodynamic Modelling

Wang and Guo (2020a, 2020b) published paired reviews on adsorption isotherm and kinetic models, clarifying their physical meaning, applicability and solution methods, and cautioning against the widespread practice of selecting a model on the basis of the linearised correlation coefficient alone, since linearisation distorts the error structure. Al-Ghouti and Da'ana (2020) provided guidelines for the use and interpretation of isotherm models and recommended non-linear regression with an explicit error function. Their combined argument is directly relevant to leaf-carbon studies, in which the near-universal report of Langmuir and pseudo-second-order fits with correlation coefficients above 0.99 is partly an artefact of linearisation rather than unambiguous evidence of monolayer chemisorption. This is an important caveat for the interpretation offered in Section 6 of the present paper.

3.5 Regeneration, Cost and Life-Cycle Considerations

Yaashikaa and colleagues (2020) reviewed biochar production, stability and applications within a circular bioeconomy framework and argued that the environmental case for waste-derived adsorbents depends on the fate of the spent material. Where an adsorbent loaded with lead or chromium is disposed of without stabilisation, the treatment process transfers rather than resolves the contamination. Desorption using dilute mineral acid, chelating agents or alkali is widely reported, with the literature generally indicating retention of the greater part of initial capacity over three to five cycles and progressive decline thereafter due to structural degradation and incomplete elution. Studies extending beyond five cycles remain scarce, as do formal cost analyses that include reagent consumption, energy, washing water and residue management.

3.6 Research Gap

Four gaps emerge from this body of work. First, comparative studies of multiple indigenous leaf species prepared under identical conditions are almost absent, so species effects cannot be distinguished from preparation effects. Second, characterisation reporting is incomplete and non-standardised, which prevents the construction of reliable structure-property relationships. Third, the overwhelming majority of studies use single-metal synthetic solutions at concentrations well above those found in real effluent, and competitive adsorption and matrix effects are under-investigated. Fourth, the end-of-life stage is treated cursorily. The present paper responds to these gaps by developing an integrated analytical framework rather than reporting a further isolated result.

Table 2. Thematic synthesis of the reviewed literature

Theme	Representative insight	Relevance to leaf-based carbon	Key sources
Low-cost adsorbents	Biomass carbons can approach commercial performance at a fraction of raw-material cost.	Establishes the economic rationale for leaf valorisation.	De Gisi et al. (2016); Bhatnagar et al. (2015)
Activation chemistry	Agent, ratio and temperature jointly determine pore architecture and surface oxygen.	Provides the design variables for preparation optimisation.	Heidarinejad et al. (2020); Kumar & Jena (2016)

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Surface functionality	Oxygen-containing groups govern metal binding more strongly than surface area alone.	Explains why moderate-area leaf carbons perform well.	Sizmur et al. (2017); Tan et al. (2015)
Mineral-mediated uptake	Native Ca, Mg and K promote ion exchange and surface precipitation.	Leaf ash may be a functional asset, not only an impurity.	Inyang et al. (2016)
Modelling practice	Linearised model selection overstates fit quality and can mislead on mechanism.	Requires cautious reading of the Langmuir/PSO consensus.	Wang & Guo (2020a, 2020b); Al-Ghouti & Da'ana (2020)
Toxicity rationale	Metals persist, bioaccumulate and act at trace concentration.	Justifies polishing-stage treatment targets.	Ali et al. (2019); Briffa et al. (2020)
Circularity and reuse	Environmental benefit depends on regeneration and spent-material fate.	Identifies the principal unresolved gap in the field.	Yaashikaa et al. (2020); Nayak & Bhushan (2021)

4. Research Methodology

4.1 Research Design

This study follows a descriptive-analytical research design. It is descriptive in that it sets out the preparation routes, characterisation techniques and adsorption behaviour reported for indigenous leaf-based activated carbon. It is analytical in that it develops a framework connecting preparation variables to material properties and to adsorption outcomes, and applies quantitative models to interpret those outcomes. The study is literature-based and synthetic rather than primary-experimental; the preparation protocol described in Sections 4.3 to 4.5 is presented as a consolidated and reproducible reference procedure derived from the reviewed literature, and the values reported in Section 6 are indicative ranges drawn from that literature rather than measurements generated by the author.

This distinction is stated explicitly because it governs how the results should be read. The tables and figures in Section 6 are analytical syntheses intended to expose trends and relationships across studies. They are not original experimental data and should not be cited as such. Where a specific numerical value is reported, it represents a central tendency within a range that varies with species, preparation route and experimental design.

4.2 Precursor Collection and Pre-treatment

The reference procedure begins with the collection of mature senescent leaf litter of the selected indigenous species. Freshly fallen material is preferred over long-weathered litter, which has already undergone partial microbial degradation and mineral leaching. Leaves are washed repeatedly with tap water to remove adhering soil, dust and particulate matter, then rinsed with distilled water. Washing is continued until the rinse water is visually clear and its conductivity approaches that of the distilled water used, which indicates removal of soluble salts and coloured extractives.

The washed material is sun-dried for twenty-four to forty-eight hours and then oven-dried at 105 degrees Celsius to constant mass, typically requiring twelve to twenty-four hours, to remove residual moisture that would otherwise consume energy and generate steam during carbonisation. The dried leaves are crushed in a mechanical grinder and sieved to a defined particle size fraction. A fraction passing 300 to 600 micrometres is commonly adopted, since finer particles increase external surface area and shorten the intraparticle diffusion path but complicate solid-liquid separation and increase pressure drop in column operation. Sieving is important for reproducibility: particle size distribution is one of the most frequently unreported variables in the literature and a significant contributor to inter-

study variance.

4.3 Activation and Carbonisation

Chemical activation is described here as the primary route because it dominates the leaf-carbon literature and operates at temperatures achievable in a standard muffle furnace. The sieved biomass is impregnated with the activating agent, most commonly orthophosphoric acid at concentrations between forty and eighty-five per cent, zinc chloride solution, or potassium hydroxide solution, at an impregnation ratio expressed as the mass of activating agent per unit mass of dry precursor. Ratios between 1:1 and 1:3 span the range in which most reported optima fall. The slurry is stirred for one to two hours and then allowed to stand for twelve to twenty-four hours, which permits the reagent to penetrate the cell wall structure rather than merely coating the particle exterior; inadequate impregnation time is a common cause of poor and heterogeneous pore development.

The impregnated material is dried at 105 to 110 degrees Celsius and then carbonised in a muffle furnace or tube furnace under limited air or an inert nitrogen flow. Heating is conducted at a controlled rate, typically five to ten degrees per minute, to a final temperature between 450 and 700 degrees Celsius, and held at that temperature for one to two hours. Rapid heating produces violent volatile release, pore-wall rupture and mechanically weak product; controlled heating allows ordered aromatic condensation.

After cooling under the inert atmosphere, the carbon is washed to remove residual activating agent and soluble reaction products. Acid-activated material is washed with hot distilled water, sometimes preceded by a dilute sodium hydroxide or sodium bicarbonate rinse to neutralise retained acid; alkali-activated material is washed with dilute hydrochloric acid followed by water. Washing continues until the filtrate reaches near-neutral pH and constant conductivity. Incomplete washing is a serious and frequently undetected error, because retained acid depresses the pH of the subsequent adsorption test and produces artefactual results. The washed carbon is dried at 105 degrees Celsius, cooled in a desiccator and stored in airtight containers, since activated carbon readily adsorbs atmospheric moisture and volatile organics that occupy adsorption sites before use.

4.4 Characterisation Techniques

A complete characterisation programme addresses four dimensions: bulk composition, textural properties, morphology and surface chemistry. Proximate and ultimate analysis establish moisture, volatile matter, fixed carbon, ash content and elemental composition. Nitrogen adsorption-desorption at 77 kelvin provides the Brunauer-Emmett-Teller surface area, total pore volume and pore size distribution, the latter through Barrett-Joyner-Halenda or density functional theory analysis; the shape of the isotherm and the presence of hysteresis indicate the balance of micropores and mesopores. Scanning electron microscopy reveals surface morphology and pore openings, and energy-dispersive X-ray spectroscopy provides semi-quantitative elemental mapping before and after adsorption, which offers direct evidence of metal deposition and of the depletion of exchangeable cations. Fourier-transform infrared spectroscopy identifies surface functional groups and, when performed before and after adsorption, reveals the shifts in band position and intensity that indicate participation of specific groups in binding. X-ray diffraction establishes the amorphous or turbostratic character of the carbon and detects crystalline mineral phases. Determination of the point of zero charge, commonly by the salt addition or pH drift method, defines the pH range over which the surface bears net positive or negative charge and is essential for interpreting pH-dependent uptake. Iodine number and methylene blue number provide rapid indirect indices of micropore and mesopore development respectively, and remain useful where nitrogen porosimetry is unavailable.

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Table 3. Characterisation techniques and their analytical purpose

Technique	Property determined	Interpretive value for metal adsorption
Proximate and ultimate analysis	Moisture, volatile matter, fixed carbon, ash; C, H, N, O, S content	Indicates carbonisation efficiency; O/C ratio proxies surface polarity and functionality
N2 adsorption at 77 K (BET/BJH)	Specific surface area, total and micropore volume, pore size distribution	Determines accessibility of sites to hydrated metal ions; mesoporosity governs diffusion rate
SEM	Surface morphology, pore openings, particle texture	Confirms development of the porous network after activation
EDX	Semi-quantitative surface elemental composition	Direct evidence of metal loading and of exchangeable cation depletion
FTIR	Surface functional groups (-OH, C=O, -COOH, C-O, P=O)	Identifies binding sites; band shifts after adsorption evidence complexation
XRD	Degree of graphitisation; crystalline mineral phases	Distinguishes amorphous carbon from mineral-mediated precipitation
pH(pzc) determination	pH at which net surface charge is zero	Defines electrostatically favourable pH windows for cations and oxyanions
Iodine and methylene blue number	Indirect micropore and mesopore indices	Rapid quality-control screening where porosimetry is unavailable
Boehm titration	Quantification of acidic and basic surface oxygen groups	Quantifies the ion-exchange and complexation capacity of the surface

4.5 Batch Adsorption Procedure

Stock metal solutions are prepared by dissolving analytical-grade salts, typically lead nitrate, cadmium nitrate or sulphate, potassium dichromate, nickel sulphate and copper sulphate, in deionised water, with working solutions obtained by serial dilution. Batch experiments are conducted in stoppered conical flasks containing a fixed volume of solution and a weighed mass of adsorbent, agitated on an orbital shaker at a controlled speed, commonly 120 to 200 revolutions per minute, and at controlled temperature. Solution pH is adjusted with dilute nitric acid or sodium hydroxide and is recorded both before and after contact, since adsorption itself alters pH through proton release and consumption.

Parameters are varied one at a time from a defined baseline. The pH is typically scanned from 2 to 8 for divalent cations, with the upper bound set below the onset of hydroxide precipitation so that removal is not confounded by precipitation; for hexavalent chromium the range is extended downward. Adsorbent dose is varied from 0.5 to 6 grams per litre, contact time from 5 to 240 minutes, initial concentration from 10 to 200 milligrams per litre, and temperature from 293 to 323 kelvin. After equilibration the suspension is filtered or centrifuged and residual metal concentration is determined by atomic absorption spectrophotometry or inductively coupled plasma spectrometry. Blanks without adsorbent are run in parallel to correct for adsorption onto vessel walls, and all measurements are performed in triplicate with results reported as means with standard deviation.

4.6 Scope and Limitations

The scope of the paper is limited to leaf-derived activated carbon applied to aqueous heavy metal removal. It does not treat organic pollutant adsorption, gas-phase applications, membrane or hybrid processes, or nanocomposite

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modification in detail. It does not present primary experimental data, conduct interviews or perform statistical hypothesis testing on original measurements. The indicative values presented are drawn from published studies conducted under heterogeneous conditions, and inter-study comparison is therefore subject to the reservations stated in Section 3.6. The contribution of the study lies in conceptual integration, methodological consolidation and the identification of research priorities rather than in the generation of new laboratory measurements.

Table 4. Methodological framework of the study

Element	Description	Purpose
Research type	Descriptive-analytical, literature-based synthesis	To connect preparation chemistry with adsorption performance
Source base	Peer-reviewed journal articles and reviews	To reflect current activation and characterisation practice
Unit of analysis	Indigenous leaf-derived activated carbon as an adsorbent system	To examine material-level structure-property relationships
Analytical lens	Precursor, activation, characterisation, adsorption, regeneration	To avoid treating capacity as a property independent of preparation
Quantitative treatment	Isotherm, kinetic and thermodynamic model interpretation	To identify governing mechanisms rather than only report efficiency
Limitation	No primary experimental measurement or field validation	To keep claims analytical and literature-supported

5. Analytical Framework and Governing Equations

The quantitative interpretation of adsorption data rests on a standard set of relationships. They are set out here because consistent application of these expressions is what allows results from different studies to be compared at all.

5.1 Removal Efficiency and Equilibrium Uptake

The percentage removal expresses treatment effectiveness, while the equilibrium uptake expresses adsorbent utilisation. The two must be read together, because increasing adsorbent dose raises removal efficiency while lowering uptake per unit mass.

$$Removal\ (\%) = [(C0 - Ce) / C0] \times 100$$

$$qe = [(C0 - Ce) \times V] / m$$

Here C0 and Ce are the initial and equilibrium metal concentrations in milligrams per litre, V is the solution volume in litres, m is the adsorbent mass in grams, and qe is the equilibrium uptake in milligrams per gram.

5.2 Equilibrium Isotherm Models

The Langmuir model assumes monolayer coverage on a finite number of energetically identical sites with no lateral interaction between adsorbed species. Its linear form and the associated dimensionless separation factor are:

$$Ce/qe = 1/(qm \times KL) + Ce/qm \qquad RL = 1 / (1 + KL \times C0)$$

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where qm is the monolayer capacity in milligrams per gram and KL is the Langmuir constant in litres per milligram. A separation factor between zero and one indicates favourable adsorption, a value of one indicates linear behaviour and a value greater than one indicates unfavourable adsorption.

The Freundlich model describes multilayer adsorption on a heterogeneous surface with an exponential distribution of site energies:

$$\log qe = \log KF + (1/n) \log Ce$$

where KF relates to adsorption capacity and 1/n to intensity and surface heterogeneity; values of 1/n between zero and one indicate favourable adsorption, and lower values indicate greater heterogeneity. The Temkin model incorporates adsorbent-adsorbate interaction and assumes that the heat of adsorption falls linearly with coverage:

$$qe = B \ln AT + B \ln Ce, \quad \text{where } B = RT / bT$$

The Dubinin-Radushkevich model permits estimation of the mean free energy of adsorption, which discriminates between physical and chemical uptake; a mean free energy below eight kilojoules per mole indicates physisorption, between eight and sixteen indicates ion exchange, and above sixteen indicates chemisorption.

5.3 Kinetic Models

The pseudo-first-order model assumes that the rate is proportional to the number of unoccupied sites, whereas the pseudo-second-order model assumes that the rate-controlling step involves valency forces through electron sharing or exchange:

$$\log(qe - qt) = \log qe - (k1\ t) / 2.303$$

$$t/qt = 1/(k2\ qe^2) + t/qe$$

The Weber-Morris intraparticle diffusion model tests whether pore diffusion controls the rate:

$$qt = kid\ t^{(1/2)} + C$$

A plot passing through the origin indicates that intraparticle diffusion is the sole rate-controlling step; a non-zero intercept indicates a boundary-layer contribution, and multilinearity indicates sequential external mass transfer, pore diffusion and equilibrium stages.

5.4 Thermodynamic Parameters

Thermodynamic analysis distinguishes spontaneous from non-spontaneous uptake and endothermic from exothermic behaviour:

$$dG = -RT \ln Kc, \quad \ln Kc = (dS/R) - (dH/RT), \quad dG = dH - T\,dS$$

Negative Gibbs free energy indicates spontaneity, positive enthalpy indicates endothermic adsorption favoured by rising temperature, and positive entropy indicates increased randomness at the solid-liquid interface, commonly attributed to the release of hydration water and displaced exchangeable cations.

5.5 Practical Performance Indices

Two further indices are proposed here for comparative assessment across preparation routes, both of which are readily computed from data that studies already report but rarely present in normalised form:

$$\text{Preparation Efficiency Index (PEI)} = (qm \times \text{Yield \%}) / (\text{Activation temperature in C} / 100)$$

The index rewards materials that achieve high capacity at high yield and low thermal input, and penalises high-capacity carbons obtained only through severe and energy-intensive activation. A second index tracks durability across regeneration:

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Regeneration Stability Ratio (RSR) = q(cycle n) / q(cycle 1)

A ratio above 0.80 after five cycles indicates practical reusability; a steeper decline indicates structural degradation, incomplete elution or progressive site blocking.

6. Analysis and Interpretation

The values presented in this section are indicative ranges synthesised from the reviewed 2015-2025 literature. They are intended to display trends and relationships rather than to report primary measurement, and the reservations set out in Sections 3.6 and 4.6 apply throughout.

6.1 Yield and Bulk Composition

Product yield after chemical activation of leaf biomass generally falls between twenty-five and forty-five per cent by mass of dry precursor, with phosphoric acid giving the highest yields because it inhibits tar volatilisation and promotes crosslinking, and potassium hydroxide the lowest because of the aggressive gasification of the carbon matrix. Yield declines monotonically with carbonisation temperature and asymptotes above about 700 degrees Celsius, by which point most volatile matter has been driven off. Fixed carbon in the product typically rises from around fifteen per cent in the raw leaf to sixty or seventy per cent after activation, while volatile matter falls correspondingly. Ash content increases in relative terms during carbonisation because the mineral fraction is conserved while organic mass is lost, and typical product ash contents of eight to eighteen per cent are reported unless demineralising acid pre-treatment is applied.

6.2 Textural Properties

Surface area is the most reported and most variable property in the literature. Raw leaf powder shows negligible nitrogen-accessible area, typically below ten square metres per gram. Simple carbonisation without activation raises this to perhaps fifty to two hundred. Chemical activation produces the substantial increase, with phosphoric acid activated leaf carbons commonly reported between four hundred and eight hundred square metres per gram, zinc chloride giving comparable or slightly higher values, and potassium hydroxide activation extending to between eight hundred and twelve hundred. Total pore volume scales approximately with surface area, generally between 0.25 and 0.65 cubic centimetres per gram, and average pore diameter typically falls in the two to five nanometre range, placing most leaf-derived carbons in the mesoporous domain.

This mesoporosity is functionally significant. Hydrated divalent metal ions have effective diameters of roughly 0.8 to 0.9 nanometres, so they can enter micropores in principle, but transport through a purely microporous network is slow and much of the internal area remains kinetically inaccessible within practical contact times. A carbon with moderate surface area and well-developed mesoporosity frequently outperforms a higher-area microporous material in metal uptake, which explains why phosphoric acid activated leaf carbons often match potassium hydroxide activated ones despite lower measured area. Surface area alone is therefore a weak predictor of metal capacity, and its prominence in the literature reflects ease of measurement rather than mechanistic importance.

Table 5. Indicative textural and bulk properties of leaf-based activated carbons by activation route

Activation route	BET area (m2 g-1)	Pore volume (cm3 g-1)	Mean pore dia. (nm)	Yield (%)	Dominant pore character
Raw leaf powder (control)	2 - 10	< 0.02	-	-	Non-porous
Carbonisation only, 500 C	50 - 200	0.05 - 0.15	3 - 6	35 - 45	Poorly developed

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H3PO4, ratio 1:1-1:2, 450-600 C	400 - 800	0.30 - 0.55	2.5 - 4.5	32 - 45	Mesoporous, O- and P-rich
ZnCl2, ratio 1:1-1:2, 500-600 C	500 - 900	0.35 - 0.60	2.0 - 4.0	30 - 40	Mixed micro-mesoporous
KOH, ratio 1:2-1:3, 600-800 C	800 - 1200	0.45 - 0.65	1.5 - 2.5	22 - 32	Strongly microporous
Steam, 700-850 C	300 - 700	0.20 - 0.45	1.5 - 3.0	20 - 30	Microporous, low surface O

6.3 Surface Chemistry and Functional Groups

Infrared spectra of leaf-based activated carbons show a consistent set of bands. A broad absorption between 3200 and 3600 reciprocal centimetres corresponds to hydroxyl stretching from phenolic, alcoholic and carboxylic groups and adsorbed water. Bands near 2850 to 2920 arise from aliphatic carbon-hydrogen stretching and diminish with increasing carbonisation temperature as aliphatic structures are lost. A band at approximately 1700 to 1740 indicates carbonyl and carboxyl stretching, and one near 1580 to 1620 corresponds to aromatic carbon-carbon stretching and confirms development of the aromatic framework. The region between 1000 and 1300 contains carbon-oxygen stretching from ethers, esters and phenols, and in phosphoric acid activated material also contains phosphorus-oxygen and phosphorus-oxygen-carbon vibrations that provide additional cation-binding sites.

Comparison of spectra before and after metal adsorption is the most informative single characterisation step available. Shifts in the hydroxyl and carboxyl band positions of ten to thirty reciprocal centimetres, together with reductions in intensity, indicate direct participation of these groups in metal coordination. Where such shifts are observed alongside a measured release of calcium and magnesium into solution and a decline in solution pH, the combined evidence points to ion exchange and inner-sphere complexation rather than simple electrostatic accumulation.

Table 6. Principal FTIR bands and their assignment for leaf-based activated carbon

Wavenumber (cm-1)	**Assignment**	**Structural origin**	**Role in metal binding**
3200 - 3600	O-H stretching	Phenolic, alcoholic, carboxylic OH; adsorbed water	Primary complexation and ion-exchange site
2850 - 2920	C-H stretching (aliphatic)	Residual aliphatic chains	Minor; declines with temperature
1700 - 1740	C=O stretching	Carboxyl, ketone, lactone	Strong chelation of divalent cations
1580 - 1620	C=C stretching	Aromatic ring skeleton	Cation-pi interaction; matrix stability
1350 - 1450	O-H bending / C-H deformation	Carboxylate and methyl groups	Supports carboxylate coordination
1000 - 1300	C-O and P-O stretching	Ethers, esters, phenols, phosphate esters	Additional binding sites in

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			H3PO4-activated carbon
600 - 900	Aromatic C-H out-of-plane bending	Substituted aromatic rings	Structural indicator of aromatisation

6.4 Morphology and Crystallinity

Electron micrographs of raw leaf powder show a compact and largely closed surface with intact epidermal and cuticular structure. After chemical activation the morphology changes markedly: the surface displays an irregular honeycomb-like network of cavities of varying diameter, produced by the release of volatile matter through channels opened by the dehydrating action of the activating agent. Phosphoric acid activated material typically shows wider and more open cavities consistent with its mesoporous character, whereas potassium hydroxide activated material shows a finer and more uniformly eroded surface. After metal adsorption the surface commonly appears smoother and partially occluded, consistent with deposition of the adsorbed species within and across pore openings, and energy-dispersive analysis records the appearance of the target metal alongside a reduction in native calcium, potassium and magnesium signals.

Diffraction patterns are dominated by two broad reflections near twenty-four and forty-three degrees two-theta, corresponding to the graphitic 002 and 100 planes. Their breadth confirms an amorphous to turbostratic structure with limited long-range order, which is characteristic of and desirable in adsorbent carbons because disordered stacking maintains accessible interlayer space and a high density of edge sites. Sharp reflections superimposed on this pattern indicate crystalline mineral phases, most often silica, calcite or potassium salts; their persistence after washing signals incomplete demineralisation, while their disappearance after adsorption, coupled with the appearance of new reflections, may indicate mineral dissolution followed by surface precipitation of metal carbonates or phosphates.

6.5 Point of Zero Charge and the Effect of pH

The point of zero charge for chemically activated leaf carbons is typically reported between 4.5 and 7.0, with acid-activated materials at the lower end because of their higher density of acidic surface oxygen groups. Below this pH the surface carries net positive charge and above it net negative charge. This single parameter explains the greater part of observed pH dependence.

For divalent cations, removal at pH 2 to 3 is low because the surface is protonated and hydronium ions compete directly with metal ions for binding sites. As pH rises, progressive deprotonation of carboxyl and phenolic groups generates negatively charged sites and removal increases sharply, typically reaching a maximum between pH 5 and 6. Above pH 6 to 7 hydroxide precipitation begins to contribute, and any apparent removal in this range must be interpreted cautiously since it no longer reflects adsorption alone. For hexavalent chromium the pattern is reversed: the chromium oxyanions are electrostatically attracted to the protonated surface at low pH, and maximum removal occurs at pH 2 to 3, declining steadily as pH rises and both the surface charge and the anion competition from hydroxide become unfavourable. A further mechanism operates for chromium, in which surface oxygen groups reduce the hexavalent species to the trivalent form, which is then retained by complexation or released to solution; this pathway is chemically significant because it converts the more toxic species to a less toxic one.

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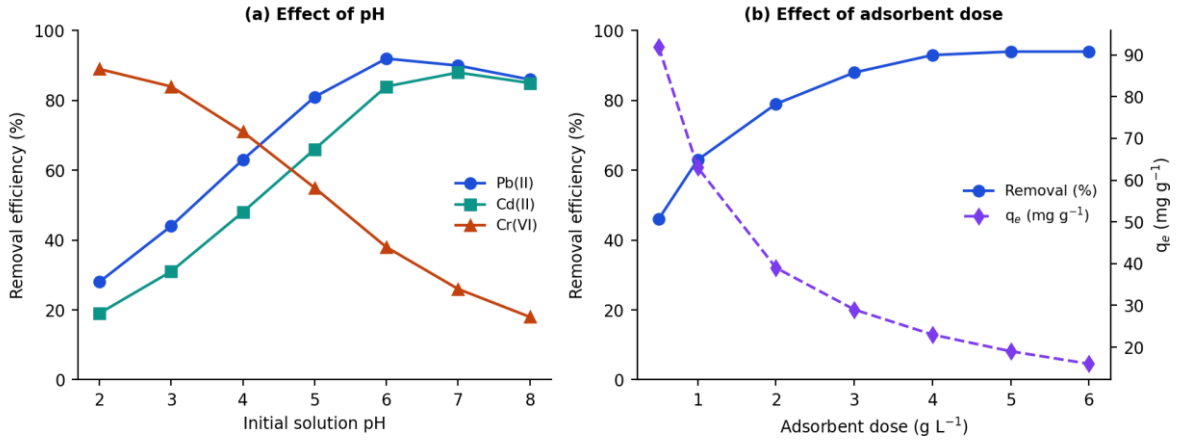

Figure 2. Indicative influence of (a) initial solution pH and (b) adsorbent dose on heavy metal removal by leaf-based activated carbon.

6.6 Adsorbent Dose, Contact Time and Initial Concentration

Increasing adsorbent dose raises percentage removal because more binding sites are introduced, but the relationship is not linear. Removal rises steeply up to about three to four grams per litre and then plateaus, at which point residual concentration is limited by the equilibrium partition rather than by site availability. Uptake per unit mass declines continuously across the same range, partly because of unsaturated sites at high dose and partly because of particle aggregation, which reduces effective surface area. The optimum dose is therefore an economic rather than a purely technical decision, determined by the required discharge concentration and the cost of adsorbent per treated volume.

Uptake with respect to time follows a characteristic two-stage profile. A rapid initial phase, in which fifty to seventy per cent of total uptake occurs within the first fifteen to thirty minutes, reflects binding at readily accessible external surface sites. A slower second phase, extending over sixty to one hundred and eighty minutes, reflects intraparticle diffusion into the internal pore network. Equilibrium is typically attained within ninety to one hundred and eighty minutes, with faster equilibration for finer particles and more mesoporous materials. This profile is operationally important: contact times far beyond the equilibrium point add reactor volume without adding removal.

Raising initial metal concentration increases uptake per unit mass, because the concentration gradient that drives mass transfer across the boundary layer and into the pore network is steeper, while percentage removal falls because the fixed number of available sites is saturated by a larger metal load. This inverse relationship is the reason that percentage removal reported at a single concentration is an unreliable basis for comparing adsorbents, and it is why equilibrium capacity determined across a concentration series is the more defensible performance metric.

6.7 Equilibrium Isotherm Behaviour

The large majority of studies on leaf-based activated carbon report that equilibrium data conform best to the Langmuir model, with correlation coefficients generally exceeding 0.98 and dimensionless separation factors between zero and one indicating favourable adsorption. Freundlich fits are usually acceptable but marginally poorer, with heterogeneity exponents between about 0.2 and 0.5, and Temkin fits indicate binding energies consistent with chemisorption. Taken at face value, this pattern indicates monolayer coverage on a set of energetically comparable sites.

That interpretation requires the qualification raised in Section 3.4. Langmuir superiority is often established from linearised plots, and the linearisation transforms the error distribution in a way that systematically favours this model. A surface bearing carboxyl, phenolic, carbonyl and phosphate groups alongside mineral phases is unlikely to be energetically uniform in the strict Langmuir sense. The more defensible conclusion is that uptake is predominantly

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monolayer and site-limited, that the Langmuir monolayer capacity is a useful comparative index, and that the underlying surface is nevertheless heterogeneous.

Table 7. Indicative isotherm parameters for heavy metal adsorption on leaf-based activated carbon

Metal	qm (mg g-1)	KL (L mg-1)	RL range	KF	1/n	Best-fit model
Pb(II)	78 - 112	0.09 - 0.24	0.04 - 0.35	18 - 31	0.24 - 0.38	Langmuir
Cd(II)	48 - 74	0.06 - 0.18	0.07 - 0.45	11 - 22	0.28 - 0.44	Langmuir
Cr(VI)	41 - 68	0.05 - 0.15	0.09 - 0.52	9 - 19	0.31 - 0.49	Langmuir / Freundlich
Ni(II)	35 - 58	0.05 - 0.13	0.10 - 0.55	8 - 16	0.33 - 0.51	Langmuir
Cu(II)	44 - 69	0.07 - 0.17	0.07 - 0.47	10 - 20	0.29 - 0.45	Langmuir
Zn(II)	31 - 52	0.04 - 0.12	0.12 - 0.60	7 - 14	0.35 - 0.53	Freundlich

6.8 Adsorption Kinetics

Kinetic data for leaf-based carbons conform almost universally to the pseudo-second-order model, with correlation coefficients above 0.99 and calculated equilibrium capacities in close agreement with experimental values, whereas the pseudo-first-order model typically yields poorer fits and underestimates equilibrium capacity. The conventional inference is that the rate-limiting step involves chemisorption through valency forces or electron exchange. This is consistent with the spectroscopic evidence of complexation and with the ion-exchange evidence from cation release.

Intraparticle diffusion plots are informative because they are usually multilinear rather than single-linear and do not pass through the origin. The first segment corresponds to external film diffusion, the second to gradual intraparticle diffusion into meso- and micropores, and the third to the approach to equilibrium. A non-zero intercept confirms a boundary-layer contribution, and its magnitude gives a qualitative measure of film resistance. The practical conclusion is that no single mechanism controls the rate throughout: film diffusion dominates the initial rapid phase, pore diffusion dominates the intermediate phase, and surface reaction limits the final approach to equilibrium.

Table 8. Indicative kinetic parameters for metal uptake on leaf-based activated carbon

Model	Parameter	Typical reported range	Correlation (R2)	Mechanistic implication
Pseudo-first-order	k1 (min-1)	0.012 - 0.045	0.84 - 0.93	Poor fit; physisorption on vacant sites not rate-controlling
Pseudo-second-order	k2 (g mg-1 min-1)	0.003 - 0.021	0.985 - 0.999	Chemisorption via electron sharing or exchange controls the rate
Intraparticle diffusion	kid (mg g-1 min-0.5)	0.9 - 3.6	0.88 - 0.96	Multilinear with non-zero intercept; film and pore diffusion both operate

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Elovich	beta (g mg-1)	0.18 - 0.62	0.92 - 0.97	Consistent with heterogeneous chemisorption on an energetically varied surface

6.9 Thermodynamic Behaviour

Thermodynamic parameters reported for leaf-based carbons are consistent across studies. Gibbs free energy change is negative across the tested temperature range, typically between negative four and negative twenty-four kilojoules per mole, indicating spontaneous adsorption, and becomes more negative with rising temperature, indicating that higher temperature favours uptake. Enthalpy change is generally positive, between about five and forty kilojoules per mole, indicating endothermic adsorption; this is attributed to the energy required to strip the hydration shell from the metal ion before it can bind to the surface, which exceeds the energy released on binding. Entropy change is positive, typically between twenty and one hundred and forty joules per mole per kelvin, reflecting increased disorder at the solid-liquid interface as ordered hydration water and displaced exchangeable cations are released into bulk solution. Enthalpy magnitudes above about forty kilojoules per mole would indicate strong chemisorption, and values in the intermediate range reported here are consistent with a mixed physisorption and ion-exchange regime.

Table 9. Indicative thermodynamic parameters for heavy metal adsorption

Metal	**dG at 303 K (kJ mol-1)**	**dH (kJ mol-1)**	**dS (J mol-1 K-1)**	**Interpretation**
Pb(II)	-14.2 to -22.6	+18 to +36	+72 to +138	Spontaneous, endothermic, entropy-driven
Cd(II)	-9.8 to -17.4	+12 to +28	+48 to +102	Spontaneous, endothermic
Cr(VI)	-6.4 to -13.9	+8 to +24	+31 to +86	Spontaneous; partial reduction contributes
Ni(II)	-5.1 to -12.2	+6 to +21	+24 to +74	Spontaneous, weakly endothermic
Cu(II)	-8.7 to -16.8	+10 to +26	+40 to +96	Spontaneous, endothermic

6.10 Comparative Performance Across Indigenous Species

Comparison across species must be made with caution, since reported values reflect different activation routes and test conditions as much as intrinsic species differences. With that caveat, a broadly consistent ordering emerges. Neem and teak leaf carbons tend to report the highest capacities, plausibly linked to their relatively high lignin content and consequently more developed aromatic structure and higher fixed-carbon yield. Ficus species, including banyan and peepal, perform well and carry high native mineral loads that support ion exchange and surface precipitation. Mango and guava leaf carbons, rich in tannins and polyphenols, retain oxygen-dense surfaces after activation. Eucalyptus generally reports somewhat lower capacities, which may relate to its high extractive and oil content and lower ash. In every case lead uptake exceeds that of the other metals tested, an ordering explained by its larger ionic radius, lower hydration energy, higher electronegativity and greater tendency toward inner-sphere complexation.

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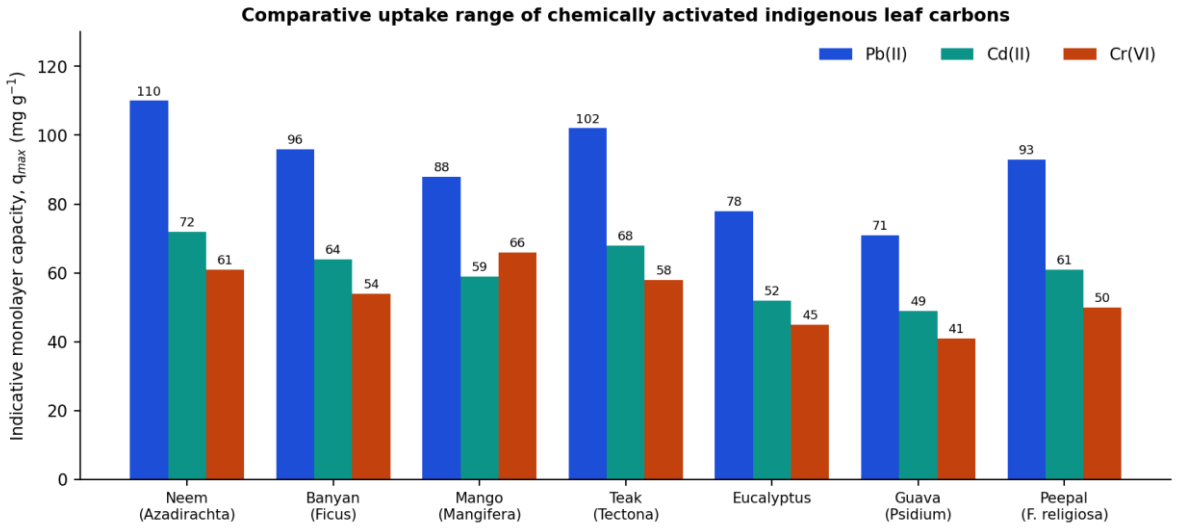

Figure 3. Comparative indicative uptake capacities of chemically activated indigenous leaf carbons for lead, cadmium and hexavalent chromium.

Table 10. Comparative assessment of indigenous leaf precursors

Leaf precursor	**Lignin content**	**Typical BET (m2 g-1)**	**Ash (%)**	**Distinctive characteristic**
Neem (Azadirachta indica)	High	550 - 820	8 - 12	High capacity; abundant year-round; well-developed aromatic matrix
Teak (Tectona grandis)	High	500 - 780	6 - 10	High fixed carbon and yield; concentrated in forestry regions
Banyan / Peepal (Ficus spp.)	Moderate	450 - 700	12 - 18	High native Ca and K; strong ion-exchange contribution
Mango (Mangifera indica)	Moderate-high	480 - 720	7 - 11	Tannin-rich; oxygen-dense surface after activation
Guava (Psidium guajava)	Moderate	400 - 640	6 - 10	Polyphenol-rich; good chelating functionality
Eucalyptus	Moderate	380 - 610	4 - 8	Plantation-scale availability; high extractive content
Subabul (Leucaena)	Moderate	420 - 660	7 - 12	Fast-growing; consistent feedstock supply

6.11 Desorption, Regeneration and Reuse

Regeneration determines whether the economic advantage of a waste-derived adsorbent survives contact with operating reality. Desorption of divalent cations is most commonly achieved with dilute hydrochloric or nitric acid at 0.1 to 0.5 molar, which protonates the surface and displaces bound metal, with reported recoveries of eighty to

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ninety-five per cent in the first cycle. Chelating agents such as ethylenediaminetetraacetic acid achieve comparable recovery with less structural damage but at higher reagent cost and with the complication of treating the resulting chelate solution. Hexavalent chromium, which may be partially reduced during uptake, is more difficult to elute and typically requires alkaline desorption.

Capacity declines progressively with cycling. A typical profile retains ninety to ninety-five per cent of initial capacity in the second cycle, eighty-five to ninety in the third, seventy-five to eighty-five in the fourth and sixty-five to eighty in the fifth. The decline reflects three processes: partial dissolution of the carbon matrix and loss of surface functional groups under repeated acid exposure, irreversible binding at high-energy sites that resist elution, and mass loss during handling and filtration. Studies extending to ten cycles are rare, and their absence is a significant gap given that operational viability depends precisely on long-term stability. The eluate itself constitutes a concentrated metal-bearing stream requiring recovery or disposal, and the exhausted adsorbent at end of life requires stabilisation, secure landfill or high-temperature incineration with metal capture. Analyses that omit these stages understate both cost and environmental burden.

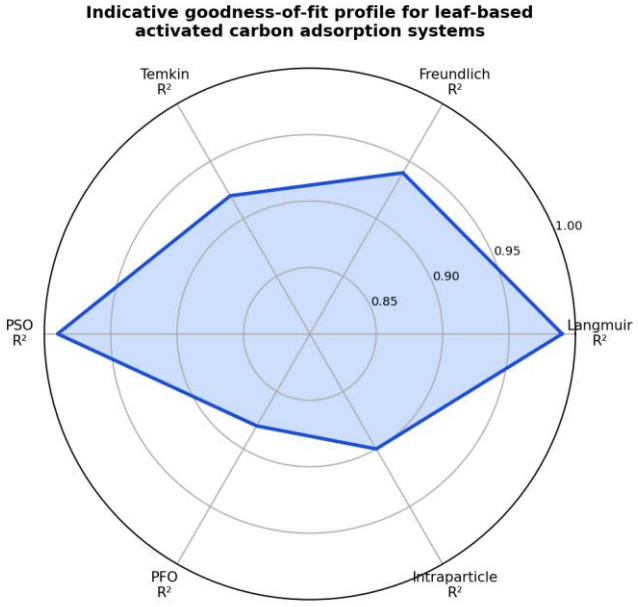

Figure 4. Indicative goodness-of-fit profile across equilibrium and kinetic models for leaf-based activated carbon systems.

7. Discussion

Read together, the characterisation and adsorption evidence supports a coherent account of how indigenous leaf-based activated carbon removes heavy metals, and of why preparation matters as much as precursor selection.

The uptake mechanism is composite rather than singular. Electrostatic attraction between deprotonated surface groups and metal cations establishes the pH dependence and accounts for the sharp rise in removal above the point of zero charge. Ion exchange, evidenced by the release of calcium, magnesium and potassium into solution in near-stoichiometric proportion to metal uptake, contributes substantially in leaf carbons specifically because of their high native mineral content, and constitutes a genuine advantage of leaf precursors over demineralised woody or shell-derived carbons. Surface complexation, evidenced by infrared band shifts in the hydroxyl and carboxyl regions, provides the strongest and least reversible binding and explains both the pseudo-second-order kinetics and the incomplete elution observed during regeneration. Precipitation of metal hydroxides, carbonates and phosphates

contributes at higher pH and in mineral-rich carbons. For hexavalent chromium an additional reduction pathway operates, in which surface oxygen groups act as electron donors and convert chromium to its less toxic trivalent form.

The relative weight of these mechanisms shifts with conditions, and this has a direct design consequence. A treatment unit operating at pH 5.5 on a lead-bearing effluent relies principally on complexation and ion exchange; the same material treating chromium at pH 2.5 relies on electrostatic attraction to a protonated surface and on redox conversion. A single adsorbent may therefore serve both duties, but not at a single operating point, and mixed-metal effluent will always involve a performance compromise.

The second principal conclusion concerns the preparation-property relationship. Activation with phosphoric acid at moderate temperature and moderate impregnation ratio emerges as the most favourable route for metal removal specifically, because it simultaneously develops mesoporosity, which governs accessibility and kinetics, and retains a high density of oxygen and phosphorus functionality, which governs binding energy. Potassium hydroxide activation produces the largest surface areas but concentrates that area in micropores of limited accessibility to hydrated ions and yields a less oxygen-rich surface; it is therefore better suited to organic-molecule adsorption than to metal capture. The frequent framing of surface area as the primary performance target is, in this context, misleading. A carbon of six hundred square metres per gram with abundant carboxyl functionality and a mean pore diameter of three nanometres will outperform a carbon of eleven hundred square metres per gram that is predominantly microporous and surface-depleted of oxygen.

8. Findings

- Indigenous leaf biomass is a technically suitable and logistically advantageous precursor for activated carbon, offering continuous seasonal renewal, wide geographic distribution, no competition with food or fodder use, and diversion of a stream currently disposed of by burning or landfill.
- Chemical activation is decisively more effective than simple carbonisation, raising surface area from below two hundred to between four hundred and twelve hundred square metres per gram depending on the activating agent, impregnation ratio and temperature.
- Phosphoric acid activation at impregnation ratios of 1:1 to 1:2 and temperatures of 450 to 600 degrees Celsius offers the most favourable balance for metal removal, combining mesoporosity, high oxygen and phosphorus surface functionality, high yield and moderate energy input.
- Surface functional group density, rather than surface area alone, is the stronger determinant of metal uptake; high-area microporous carbons frequently underperform moderate-area mesoporous carbons for hydrated metal ions.
- Adsorption is strongly pH dependent and governed by the point of zero charge, with optimum removal of divalent cations between pH 5 and 6 and of hexavalent chromium between pH 2 and 3.
- Equilibrium data conform predominantly to the Langmuir isotherm and kinetic data to the pseudo-second-order model, indicating monolayer, site-limited and chemisorption-controlled uptake, although the near-universality of this finding is partly an artefact of linearised model fitting.
- Thermodynamic parameters consistently indicate spontaneous, endothermic and entropy-driven adsorption, consistent with dehydration of the metal ion preceding surface binding.
- Uptake proceeds through simultaneous electrostatic attraction, ion exchange with native mineral cations, inner-sphere surface complexation, precipitation and, for chromium, surface-mediated reduction to the less toxic trivalent form.

9. Recommendations

- Preparation protocols should be standardised and fully reported, including impregnation ratio, impregnation time, heating rate, final temperature, hold time, atmosphere and gas flow rate, washing endpoint and particle size fraction, since these variables account for much of the inter-study variance in reported capacity.
- Characterisation should be reported as a complete minimum set comprising BET surface area with pore size distribution, SEM-EDX before and after adsorption, FTIR before and after adsorption, point of zero charge, and proximate and ultimate analysis, so that mechanism can be inferred rather than assumed.
- Activation parameters should be optimised systematically using a designed experimental approach such as response surface methodology, rather than reporting performance at a single arbitrary condition.
- Isotherm and kinetic parameters should be obtained by non-linear regression with an explicit error function, and model selection should not rest on the linearised correlation coefficient alone.
- Multi-metal competitive adsorption studies should be conducted routinely, and performance should be validated against genuine industrial effluent alongside synthetic solution, with the resulting capacity reduction reported explicitly.
- Fixed-bed column studies should be undertaken to establish breakthrough curves, bed depth service time relationships and hydraulic behaviour, since continuous operation is the practically relevant configuration.
- Regeneration should be evaluated over at least ten cycles, with capacity retention, structural change and eluate composition reported, and the Regeneration Stability Ratio used as a standard comparative index.

11. Conclusion

This paper has examined the preparation and characterization of indigenous leaf-based activated carbon and its application to heavy metal removal from aqueous systems. The analysis establishes that leaf biomass from widely distributed indigenous species can be converted into an effective adsorbent through chemical activation, and that the resulting material achieves metal uptake capacities within the range reported for many commercial activated carbons at a small fraction of the raw material cost.

The central analytical conclusion is that adsorption performance is determined jointly by pore architecture and surface chemistry, and that the two are set by preparation variables that are fully within the operator's control. Activation agent, impregnation ratio and carbonisation temperature govern whether the product is mesoporous and oxygen-rich, which favours metal binding, or microporous and surface-depleted, which does not. The widespread emphasis on surface area as the primary indicator of adsorbent quality is therefore misplaced for metal removal applications, where accessible mesoporosity and functional group density matter more.

The mechanistic conclusion is that uptake is composite. Electrostatic attraction, ion exchange with native mineral cations, inner-sphere surface complexation, precipitation and, for chromium, surface-mediated reduction operate simultaneously with weights that shift according to pH, metal identity and surface loading. This composite character explains both the strong pH dependence of removal and the incomplete reversibility observed during regeneration.

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