Low-Cost Adsorbents for Landfill Leachate Treatment: A Systematic Review

Aparna Srivastava[1], Shafaque Aziz[2], Suman Kumari[1], Abhay Kumar[3]
[1]*Department of Civil Engineering, Rashtrakavi Ramdhari Singh Dinkar College of Engineering, Begusarai, Bihar India*
[2]*Department of Computer Engineering, Government Engineering College Samastipur Bihar India*
[3]*Department of Civil Engineering, Government Engineering College Samastipur Bihar India*

***Abstract*—Landfill leachate is among the most complex and hazardous wastewater streams generated by municipal solid waste disposal, carrying heavy metals, recalcitrant organic matter, ammonia nitrogen, and intense colour. Conventional treatments such as activated carbon adsorption, membrane filtration, and advanced oxidation are effective but often economically prohibitive for developing regions and small-to-medium landfills, which has driven interest in low-cost adsorbents derived from natural minerals, agricultural and industrial by-products, and waste materials. We conducted this systematic review to synthesize the evidence on low-cost adsorbents for leachate treatment and to benchmark them against commercial activated carbon. Six databases and search engines were searched, two independent reviewers screened records, and 75 studies were included. Zeolites, natural and modified, were most effective for ammoniacal nitrogen; carbonaceous materials, including activated carbons and biochars, dominated colour and COD removal; and engineered or modified clays, metal oxides, and biopolymer composites delivered the highest heavy metal capacities. Commercial activated carbon often achieves higher capacity per unit mass, but several low-cost alternatives reached comparable removals under optimized conditions at lower cost. Integrated treatment trains that couple oxidative, coagulation, or biological stages with adsorption outperformed stand-alone adsorption. However, reported optimal conditions are inconsistent, regeneration and long-term performance data are limited, techno-economic assessments are largely absent, and few studies reach pilot scale. Standardized protocols, techno-economic and life cycle analyses, and pilot-scale validation of hybrid treatment trains are priorities for future research.**

***Index Terms*—Landfill leachate treatment, low-cost adsorbents, natural and waste-derived materials, contaminant removal, systematic review.**

I. INTRODUCTION

Landfill leachate is generated when precipitation, surface runoff, and the inherent moisture of municipal solid waste percolate through the waste mass, dissolving and suspending a wide spectrum of organic and inorganic constituents [1]. It is widely regarded as one of the most complex and hazardous wastewater streams, with elevated concentrations of dissolved organic matter, ammonia nitrogen, heavy metals, xenobiotic organic compounds, and inorganic salts [1]. Its composition evolves over the life of a landfill, from an acidic, high-strength acetogenic phase dominated by volatile fatty acids to a methanogenic phase characterized by recalcitrant humic and fulvic substances, lower BOD/COD ratios, and persistently high ammonia [2]. Waste composition, climate, hydrogeology, and operating practice add further variability, so that leachate treatment defies uniform solutions [3]. The consequences of inadequate management are severe: migration into groundwater can introduce lead, cadmium, chromium, and arsenic into drinking water sources, while surface water contamination causes eutrophication, oxygen depletion, and toxicity to aquatic organisms [4]. Ammonia nitrogen, often present at several thousand mg/L in mature leachate, is directly toxic to fish and contributes to carcinogenic disinfection by-products when chlorination is applied downstream [5], and endocrine-disrupting compounds and pharmaceutical residues raise further concerns about chronic effects [6]. Tightening discharge standards now mandate treatment beyond simple biological processes [7].

Conventional treatment combines biological, physical-chemical, and membrane processes.

Biological treatment remains the cornerstone for BOD and nitrogen removal, but its efficacy declines for mature leachate in which the biodegradable fraction is low and recalcitrant humic substances dominate [8]. Reverse osmosis and nanofiltration achieve high rejection of organic and inorganic contaminants but generate concentrated retentate and incur substantial capital and operating costs [9]. Advanced oxidation processes (Fenton oxidation, ozonation, photocatalysis) destroy recalcitrant organics but entail high chemical consumption, sludge production, and energy demand [10]. Adsorption onto activated carbon is one of the most versatile polishing steps [11], yet the cost of commercial activated carbon, from several hundred to several thousand dollars per ton, is a significant barrier for small-to-medium landfills and for regions with constrained waste management budgets [12].

This barrier has catalyzed research into low-cost alternatives derived from agricultural residues, industrial by-products, natural minerals, and wastes, including zeolites, clay minerals, biochars, chitosan, fly ash, blast furnace slag, and shell and sludge wastes, which offer comparable performance at a fraction of the cost [13]. Many are locally available, need minimal processing, and valorize waste streams in line with circular economy principles [14]. Biochar from agricultural residues has tunable surface chemistry and porosity [15], natural zeolites such as clinoptilolite are highly selective for ammonium through ion exchange [16], and clay minerals show enhanced affinity for cationic and anionic pollutants after functionalization with surfactants or metal oxides [17].

Despite this growth, the field remains fragmented. Experimental protocols, leachate sources, adsorbent preparation, and reporting formats vary widely, complicating comparison across studies [18]. Many investigations use synthetic or diluted leachate, which questions transferability to real matrices with competing ions and dissolved organic matter [19]. Most work is confined to laboratory batch experiments, with limited attention to continuous-flow performance, regeneration, and techno-economic feasibility [20], and standardized performance metrics and cost data are rarely reported [21]. This systematic review therefore consolidates and critically evaluates the dispersed evidence to show which materials perform best under which conditions, where the key gaps lie, and where future effort should be concentrated, with particular relevance to developing countries and resource-limited settings. Section 2 describes the methodology; Section 3 presents research trends, an overview of included studies, and detailed syntheses of natural and waste-derived adsorbents for organic and nutrient removal, engineered and modified adsorbents for heavy metals and micropollutants, and integrated and hybrid systems; Section 4 discusses implications, limitations, and future directions; and Section 5 concludes.

II. METHODOLOGY

2.1 Review Protocol and Search Strategy

This review was conducted and reported in accordance with the PRISMA guidelines [22], using a protocol developed a priori that specified the research question, search strategy, eligibility criteria, data extraction fields, and quality assessment. The question was framed with the PICO framework: which low-cost adsorbents (Intervention) have been investigated for the treatment of landfill leachate (Population), and how effective are they in removing heavy metals, organic matter, ammonia nitrogen, and color (Outcomes) compared with conventional adsorbents (Comparison), considering adsorption capacity, optimal conditions, regeneration potential, and cost-effectiveness.

Six sources were searched: Scopus (primary database; broad coverage of environmental engineering, materials science, and water treatment, with citation analysis), Web of Science (high-impact journals and citation networks), ScienceDirect (Elsevier full texts), SpringerLink (Springer's environmental science portfolio), PubMed (environmental health and toxicological outcomes), and Google Scholar (supplementary: grey literature, preprints, and forward citation tracking). The core search string was: ("landfill leachate" OR "municipal solid waste leachate" OR "solid waste leachate") AND (treatment OR remediation OR removal OR adsorption OR "adsorptive removal" OR purification) AND ("low-cost adsorbent" OR "low cost adsorbent" OR "cheap adsorbent" OR "inexpensive adsorbent" OR bioadsorbent OR biosorbent OR "agricultural waste" OR "industrial by-product" OR "natural material" OR "waste material" OR "activated carbon" OR zeolite OR clay OR "fly ash" OR "red mud" OR chitosan OR biochar) NOT ("review" OR "systematic review" OR

"meta-analysis" OR "survey"). It was adapted to each database's syntax and field codes (TITLE-ABS-KEY in Scopus, TS in Web of Science, title/abstract/keyword fields in ScienceDirect and SpringerLink, and a simplified string with MeSH terms where applicable in PubMed). In Google Scholar the first 200 results sorted by relevance were screened. No publication year restrictions were applied, the search ran up to the date of manuscript preparation, and backward and forward citation tracking of included studies was performed.

2.2 Analytical Framework

Included studies were classified along three dimensions. The first was the nature and origin of the adsorbent, separating natural and waste-derived materials from engineered and modified ones; within the former, studies targeting organic matter and nutrients were distinguished from those targeting heavy metals and micropollutants, because the governing mechanisms differ (hydrophobic interactions and ion exchange versus complexation, precipitation, and redox reactions). The second was the treatment configuration, separating stand-alone adsorption from adsorption integrated with biological treatment, coagulation, or advanced oxidation; studies that fit neither, such as production optimization or surface chemistry without direct leachate application, formed a residual category. The third was experimental scale and reporting completeness: batch, column, or pilot scale; reporting of dosage, contact time, pH, initial concentration, and temperature; and use of real versus synthetic leachate.

2.3 Eligibility Criteria

Studies were included if they investigated landfill leachate treatment using low-cost adsorbents (naturally occurring, agricultural or industrial by-product, or waste-derived materials that are economically viable), provided sufficient methodological detail on adsorbent preparation, characterization, and experimental conditions, reported quantitative removal results, and addressed at least one PICO element. Eligible designs were original experimental, pilot-scale, and field studies; reviews, meta-analyses, and conference proceedings were considered only where they offered substantial original data or synthesis. Peer-reviewed articles and preprints on recognized platforms (e.g., arXiv) were eligible if they met the quality criteria, and only English-language studies were included. Studies were excluded for significant methodological flaws (no replicates, no control experiments, inadequate adsorbent characterization); for non-low-cost adsorbents (e.g., activated carbon from non-waste sources, synthetic resins) or wastewaters other than landfill leachate; for lack of quantitative performance results; for non-English language (owing to translation constraints); for being opinion pieces, editorials, letters, or conference abstracts without full papers; for unobtainable full texts; and for publication in predatory journals or as non-peer-reviewed preprints lacking credibility. Where several publications reported the same data, only the most comprehensive or recent was kept.

2.4 Study Selection, Extraction, and Quality Assessment

Records were exported to reference management software and de-duplicated. Two independent reviewers screened titles and abstracts, resolving disagreements by discussion with a third reviewer as arbiter. Full texts were sought through institutional access, interlibrary loan, and author contact; those that could not be obtained were documented and excluded. A standardized extraction form, piloted on a subset of studies, captured adsorbent type and preparation, leachate characteristics, experimental conditions, removal efficiencies, adsorption capacities, isotherm and kinetic fits, regeneration performance, and cost information. Study quality was assessed with a customized checklist covering clarity of objectives, adequacy of adsorbent characterization, experimental design, reporting of key parameters, replicates and controls, statistical analysis, and transparency about limitations. Scores reflected the number of criteria met and were used to weight findings and flag studies for sensitivity analysis, not to exclude studies.

As shown in Figure 1, the searches returned 1,564 records. After removing 637 duplicates and 2 records for other reasons, 925 records were screened by title and abstract and 636 were excluded, leaving 289 reports sought for retrieval. Of these, 124 could not be retrieved, primarily owing to access restrictions or unavailable full texts, and 165 were assessed for eligibility. Ninety were excluded for insufficient data, methodological flaws, irrelevant focus, or language limitations, and the final 75 studies were included.

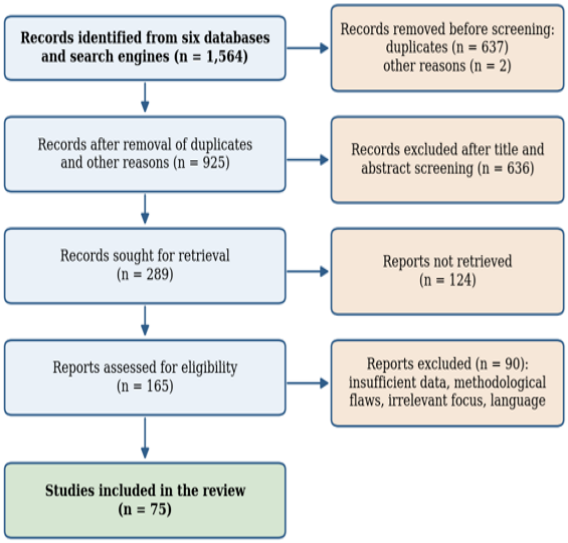


Figure 1. Flow diagram of the study selection process, from database searches through screening and eligibility assessment to the 75 included studies.

Several limitations of the selection process warrant acknowledgment. Publication bias may overestimate effectiveness, since positive results are more likely to be published. Excluding non-English publications may have omitted relevant work from developing countries where leachate problems are acute and local adsorbents abundant. The 124 unretrieved reports may differ systematically from those analyzed, and heterogeneity in protocols, leachate sources, and reporting complicated quantitative synthesis and quality assessment. We mitigated these through transparent reporting, dual-reviewer screening, and sensitivity analyses where feasible.

III. RESULTS

3.1 Research Trends

Of the 75 included studies, 27 (36%) were published before 2016, reflecting early recognition of low-cost adsorbents as alternatives to commercial activated carbon and establishing many of the fundamental material classes, notably natural zeolites, clay minerals, and agricultural by-products.

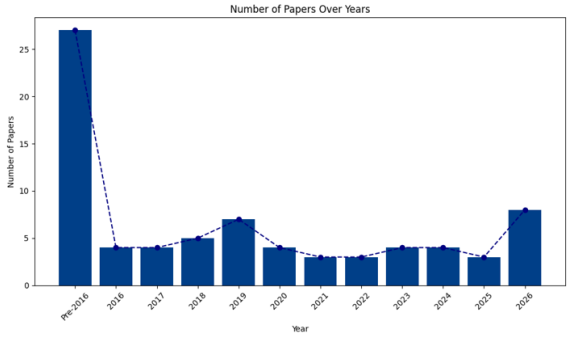


Figure 2. Temporal distribution of publications on low-cost adsorbents for landfill leachate treatment, showing the number of studies published before 2016 and in each year from 2016 to 2026.

From 2016 onward, annual output fluctuated between three and eight studies with no monotonic upward trend: 2019 and 2026 were the most productive years with seven and eight studies respectively (2026 alone accounting for nearly 11% of the corpus), whereas 2021, 2022, and 2025 each yielded only three. The absence of the exponential growth seen in some emerging environmental technologies may signal a plateau of incremental refinement or persistent barriers to scaling laboratory findings to pilot and full scale, but steady output in every recent year confirms that the topic remains active.

3.2 Overview of Included Studies

Table 1 summarizes the main characteristics of the included studies: adsorbent material and origin, target pollutants, leachate type, treatment configuration, and maximum removal efficiency where reported. Blank cells indicate information not reported in the extracted data. The studies differ widely in materials, targets, and configurations, which provides important context for interpreting heterogeneity across the evidence base.

Table 1. Characteristics of Included Studies

Study ID	Adsorbent Material	Adsorbent Origin	Target Pollutants	Leachate Type	Treatment Configuration	Maximum Removal Efficiency
[23]	Feldspar (FE), zeolite (ZE), activated carbon (AC), and cockle shells (CS) mixtures	-	Chemical Oxygen Demand (COD) and Ammonia Nitrogen (NH3-N)	Stabilised leachate	-	-

[24]	Composite sorbent of sludge coated with iron oxide (FeO) nanoparticles combined with organically modified bentonite	Sludge and bentonite	Cadmium ions (Cd (II)), dissolved organic components (DOC), and ammonia nitrogen (NH3-N)	Synthetic sanitary landfill leachate (model acetogenic leachate)	Batch and column experiments; permeable reactive barrier	over 85% (batch tests exceeded 90%)
[25]	palm, coconut and banana fiber	natural fibers, often part of waste discarded	Chemical Oxygen Demand (COD), Turbidity, Color	landfill leachate	natural fibers intercropped with advanced oxidation processes, laboratory scale	COD removals between 67.9% and 90.9%, Turbidity between 88.0% and 99.7%, Color between 67.4% and 90.4%
[26]	red mud waste	Bayer process	Cd2+, Zn2+, Ni2+, As	leachate from an abandoned mine	-	more than 99% Cd, Ni, Zn and As
[27]	Pressmud ash	Sugar mill, Malaysian Sugar Manufacturing (MSM) Sdn Bhd, Seberang Perai, Pulau Pinang	Heavy metals, COD, ammonia, colour	Stabilized landfill leachate from municipal solid waste (MSW) Pulau Burung Sanitary Landfill (PBSL)	-	COD: 60.76%, ammonia: 64.37%, colour: 35.78%
[28]	crushed brick, steel slag	-	Zn, Cu, Pb	leachate	pilot-scale constructed wetland (CW1 with Phragmites australis and crushed brick; CW2 with Typha latifolia and steel slag)	-
[29]	smectite-rich clayey rock (raw AYD clay)	El Hamma area, Tunisia	copper and nickel	Jebel Chakir landfill leachate	batch and column methods	
[30]	palm bark powder (PBP)	palm bark	chemical oxygen demand (COD), color, turbidity, biological oxygen demand (BOD5)	landfill leachate from Casablanca city	coagulation-flocculation coupled with adsorption	turbidity 99%, COD 59%, color 90%
[31]	Natural bentonite clay	Nador, eastern Morocco	Ammonium, nitrate, and nitrite ions	Synthetic leachate	-	Ammonium: 48%, nitrate: 40%, nitrite: 85% at 35°C; ammonium: 40%, nitrate: 15%, nitrite: 25% at 25°C
[32]	Activated carbon made from sewage sludge and straw	Activated sludge and straw	Organic matter (COD)			69.63% COD removal
[33]	diatomite		COD and ammonia nitrogen	fresh landfill leachate	integrated KMnO4 oxidation and diatomite adsorption	98% for COD and 90% for ammonia nitrogen
[34]	Activated carbon	Coffee waste	Chemical oxygen demand, ammonia, total chlorine, bromine, copper	Landfill leachate	Stirrer system (batch adsorption)	51.0% chemical oxygen demand, 32.8% ammonia, 66.0% total chlorine, 81.0% bromine, 97.1% copper

[35]	aluminosilicate		ammonia nitrogen	distilled old landfill leachate	adsorption	
[36]	Zeolite (ZE) and moringa oleifera leaf powder (MP) mixture		COD and ammoniacal nitrogen (NH3-N)	Stabilised leachate		COD: 70.14%; NH3-N: 86.94%
[37]	Waste paper sludge (WPS) and activated carbon (AC)	Waste paper sludge is produced by the paper industry during the wastewater treatment process of paper production	Ammonia nitrogen (NH3-N) and chemical oxygen demand (COD)	Stabilized landfill leachate	Batch adsorption study	COD: 85.9%, NH3-N: 49.3%
[38]	cockle shells		chemical oxygen demand (COD)	stabilized landfill leachate		
[39]	Waste green mussel shell (WGMS)	Seafood waste	Chemical oxygen demand (COD) and ammoniacal nitrogen (NH3-N)	Stabilized landfill leachate	Static batch experiment	COD: 58%, NH3-N: 48%
[40]	Activated Carbon (AC)	Coconut shell	pH, TSS, Ammonia-Nitrogen, heavy metals (zinc, sulphide)	Landfill leachate	Filtration process (with AC adsorption); hybrid technique using electrolysis process with AC adsorption	
[41]	Activated carbon	Oat hulls	Organic matter (COD and color)	Synthetic leachate and real landfill leachate	Adsorption batch tests	Color completely removed; COD removal up to 90%
[42]	Activated carbon and limestone mixture		Colour, COD, iron, ammoniacal nitrogen	Anaerobic landfill leachate	Batch and column studies	86% colour, 86% COD, 95% iron, 48% ammoniacal nitrogen (batch study)
[43]	fly ash		COD	stabilized leachate	combined coagulation-adsorption process (coagulation using alum followed by adsorption using fly ash)	82% overall COD removal (28% COD removal by fly ash adsorption for alum pretreated stabilized leachate)
[44]	perlite, powdered activated carbon (PAC)		COD, heavy metals	landfill leachate (LFL)	sequence batch reactors (SBRs)	over 81% (PAC), over 72% (perlite)
[45]	walnut-shell		COD	landfill leachate	coagulation-flocculation with lime and bio-sorption	
[46]	Kaolinite, Illite, Montmorillonite, sand and calcium-saturated clays		K, NH4, Mg, Si, Fe, Pb, Cd, Hg, Zn, Cr, Cu, As, Se	Municipal solid waste landfill leachate	Laboratory column study and batch studies	
[47]	granular activated carbon (GAC) and waste metal hydroxide (WMH) sludge			landfill leachate of Çorlu (non-regulated, municipal and industrial wastes)	combined process of coagulation-flocculation and adsorption	
[48]	mullock		CODCr, ammonia nitrogen	landfill leachate	Potassium Ferrate oxidation followed by mullock adsorption	CODCr removal above 98%, ammonia nitrogen removal 99%

[49]	rice husk composite adsorbent	rice husk ash waste	ammonia and chemical oxygen demand (COD)	synthetic leachate		
[50]	sodium bentonite and mixture bentonite-lime	Maghnia (Algeria)	nitrates	leachate of a technical burying centre (Boumergued/Algeria)		45% for sodium bentonite; 96% for bentonite-lime mixture
[51]	Chitosan combined with TiO_2	Red kurisi fish scales (Nemipterus virgatus)	Lead (Pb)	Landfill leachate from Batu Terang, Bantaeng Regency		
[52]	Biochar (BC) and commercial activated carbon (AC)	Wheat straw	Nitrogen (ammonium chloride solution and landfill leachate)	Landfill leachate (LLCH)		95.08% (BC from NH4Cl); 93.11% (AC from NH4Cl)
[53]	Composite adsorbent from activated carbon (AC) and calcite with alginate as binder	Activated carbon and calcite	COD and Fe2+	Stabilized landfill leachate from semi-aerobic sanitary landfill at Pulau Burung, Penang, Malaysia	Batch experimental study	54.6% for COD and 68.06% for Fe2+ at mixing ratio of 7:3
[54]	activated carbon derived from oil palm empty fruit bunches (EFBAC)	oil palm empty fruit bunches	organic and inorganic pollutants	municipal solid waste (MSW) leachate	batch adsorption	
[55]	Activated carbon derived from Colocasia esculenta	Colocasia esculenta (L.) Schott (taro)	Chemical oxygen demand (COD) and iron (Fe)	Landfill leachate	Constructed wetlands and batch adsorption experiments	46.37 % COD removal and 84.62 % Fe removal
[56]	biochar	municipal solid waste (MSW)	benzene	landfill leachate		
[57]	sawdust, pine bark, fibre sludge ash, peat, shrimp shells, seaweed	waste products from forest industries (sawdust, pine bark, fibre sludge ash) and biological materials (peat, shrimp shells, seaweed)	heavy metals (Cu, Pb, Zn, Cr, Cd, Ni) and petroleum hydrocarbons (diesel oil, n-alkanes C16 and C12)	contaminated leachates from an industrial landfill	batch and column experiments	
[58]	clay and clay-synthetic zeolite substrates		lead	municipal landfill leachate	percolating leachate in the soil	
[59]	sandy loam, synthetic zeolite NaP1, and their mixtures	sandy loam sampled in Chotyłów, Poland; synthetic zeolite NaP1	Al, P, Mn, Fe, Sn, Ba	municipal landfill leachate	column method	
[60]	iron-modified biochar (Fe-BC) nanocomposites	Pinus forestry waste		landfill leachate	heterogeneous Fenton-like CWPO system	
[61]	rice husk ash	rice husk	COD, ammoniacal nitrogen (NH3-N)	leachate generated from Perungudi semi-urban solid waste dumping site		
[62]	Granulated activated carbons (AG and BA-10) and biochar (BC)		COD and selected metals	Landfill leachate	Static conditions (batch sorption)	COD removal: 60% (AG), 53% (BC), 40% (BA-10); Metals removal: 84% to 96%
[63]	mixture of peat and carbon-containing ash			industrial landfill leachate	full-scale on-site vertical-flow biofilter with a 500 m3 equalization	

					pond prior to the filter-system	
[64]	ZnCl2-impregnated Parkia speciosa (Petai) pods activated carbon (PPAC-Z)	Parkia speciosa (Petai) pods	COD	pre-treated stabilised landfill leachate	batch mode	87.5%
[65]	bentonite		bisphenol A	landfill leachate	landfill liner material	
[66]	geosynthetic clay liner (GCL)		cations and organics	landfill leachate		
[67]	zeolite		ammoniacal nitrogen, chemical oxygen demand (COD), heavy metals (aluminium, vanadium, chromium, magnesium, cuprum, plumbum)	landfill leachate	aerobic sequencing batch reactor (ASBR) combined with zeolite adsorption	96% ammoniacal nitrogen, 43% COD
[68]	natural zeolite and NaCl-modified zeolite		ammonium	landfill leachates, livestock wastewaters or effluents from anaerobic digestion tanks of livestock manure		
[69]	clinoptilolite zeolites		ammonia nitrogen (NH3-N) and colour	landfill leachate	Integrated Electrocoagulation (EC) - zeolite adsorption	93% for NH3-N and 95% for colour
[70]	Zeolite	Natural zeolite	COD, TSS, N-total, organic compounds, heavy metals	Landfill leachate	Electrocoagulation-adsorption	COD 91.70%, TSS 71.61%, N-total 62.53%
[71]	wasted biosolids containing dead fungal biomass (Phanerochaete chrysosporium)	biomass produced from laboratory experiments for bioconversion of wastewater for lignin peroxydase production	cadmium, copper, zinc, iron	municipal landfill leachate		45.56% for iron from leachate
[72]	Red mud		COD and ammonia-nitrogen	Landfill leachate from a landfill in the suburbs of Beijing		
[73]	sawdust/bentonite		COD and ammonia nitrogen (NH3-N)	landfill leachate	sequencing batch reactor (SBR)	99.28% for COD and 95.41% for NH3-N
[74]	Powdered activated carbon and powdered zeolite		Fe, Mn, Ni, Cd	Landfill leachate	Sequencing batch reactor (SBR) augmented with powdered activated carbon (PAC-SBR) or powdered zeolite (PZE-SBR)	Fe: 65.65%, Mn: 61.56%, Ni: 63.41%, Cd: 60.44%
[75]	oyster shells, pumice stone, sand, zeolite	Powerstown landfill, Carlow, Ireland	ammonia, phosphate, nitrate	landfill leachate	fixed-bed column	
[76]	three different natural clays	natural	Cu (II) and Zn (II)	urban solid waste leachates	batch tests	
[77]	Calcined paper mill sludge (PMS-A), montmorillonite (Mt), and calcined PMS–Mt composite	Paper mill sludge and montmorillonite	Refractory dissolved organic matter (measured as COD) and color	Mature landfill leachate	Batch experiments	PMS-A: 98% color and 92% COD; PMS–Mt composite: 96% color and 76% COD; Mt:

						50% color and 60% COD
[78]	natural silica sand	Pulau Burung landfill site (PBLS) in Penang, Malaysia	ammoniacal nitrogen, iron, zinc	semi-aerobic stabilized landfill leachate		51% ammoniacal nitrogen, 44.4% iron, 39.2% zinc
[79]	banana peel, coconut fiber, corn cob, rice husk, and sawdust	agro-waste materials (AWMs)	TSS, heavy metals (Fe, Cu, Cr, Pb), organic indicators (BOD, COD), pH	raw leachate from the Talumelito landfill in Gorontalo, Indonesia	modular column filtration system operated under continuous-flow conditions	Cr Guard achieved complete chromium removal (100%); BOD, Pb, and Cr were completely removed by all formulations
[80]	Composite adsorbent composed of washed sea sand (WSS), dewatered alum sludge (DAS), zero-valent iron (ZVI), and granular activated carbon (GAC)	Washed sea sand, dewatered alum sludge, zero-valent iron, and granular activated carbon	Organic compounds (COD), total nitrogen (TN), total phosphorus (TP)	Landfill leachate	Batch sorption experiments	COD: 79.93 ± 1.95%; TN: 84.9%; TP: 97.4%
[81]	Activated carbon obtained from fish scales	Fish scales	Organic matter (colour and chemical oxygen demand, COD)	Landfill leachate	Batch adsorption process	60.1% colour and 37.3% COD
[82]	Perlite and Bentonite		Conductivity, Turbidity, BOD, COD	Municipal solid waste landfill leachate (Borg El Arab landfill, Alexandria)	Aerobic treatment using coagulation-flocculation with Alum coagulant and accelerator additives	Perlite: 86.7% conductivity, 87.4% turbidity, 89.9% BOD, 92.8% COD; Bentonite: 83.5% conductivity, 85.0% turbidity, 86.5% BOD, 85.0% COD
[83]	natural zeolite clinopteliolit		lead and cadmium	leachate of waste materials		
[84]	peat soil and compost	two compost sources and a peat soil	boron	landfill leachate	batch adsorption test	
[85]	Iron oxide (Fe2O3) nanoparticles	Iron ore	Chemical oxygen demand (COD), color, ammoniacal nitrogen (NH3-N)	Landfill leachate		
[86]	activated bio-char	sea mango	chemical oxygen demand (COD), color, ammoniacal nitrogen (NH3-N)	landfill leachate		color: 95.1%, COD: 84.94%, NH3-N: 95.77%
[87]	Natural clay (palygorskite)			Leachate mixed wastewater (diluted leachate, DL ≈ L: WW = 1:4)	Bioelectrochemical system (BES) followed by natural clay adsorption	
[88]	Titanium oxide–loaded activated		Ammoniacal nitrogen (NH3-N)	Leachate sample		75.8%

	carbon (TiO2 nanocomposite)					
[89]	Fly ash		Ammonia nitrogen (NH4+-N)	Landfill leachate from Huainan city		close to 100% under low concentration; 80.24% at initial NH4+-N concentration of 16 mg/L
[90]	Chitosan-modified banana peel biochar (CMBC)	Banana peel	Heavy metals (Zn, Fe, Pb, Ni, Cu, As, Cr)	Landfill leachate from Pulau Burung Sanitary Landfill, Malaysia		100% Zn, 66.2% Fe, 45.8% Pb, and 33.9% Ni removal (8:2 formulation, S2-CMBC)
[91]	natural Turkish zeolite	Turkey	NH4-N	landfill leachate	adsorption process	
[92]	biologically activated carbon (mesopore active carbon)	orange peel	macromolecular contaminants	landfill leachate		
[93]	Iron oxide-coated gravel		Fe (II), Ni (II), Zn (II)	Synthetic leachate	Continuous fixed bed column	58.24% for Zn (II), 47.71% for Fe (II), 39.45% for Ni (II)
[94]	oil palm frond-activated carbon (OPF-AC)	oil palm frond	COD, color, Fe	landfill leachate	batch experiment	COD: 77%, color: 75%, Fe: 69%
[95]	wood-derived biochar (BC), pulverized (PWB) and crushed (CWB)	wood	Pb, Mn, and Cu	landfill leachate		

*Studies whose corresponding information was not available has been left blank

3.3 Natural and Waste-Derived Adsorbents for Organic and Nutrient Removal

Natural minerals and waste-derived carbons are the most extensively investigated class of low-cost adsorbents for organic and nutrient removal. The dominant targets are COD and ammoniacal nitrogen (NH_3-N), which frequently exceeds 500 mg/L in stabilized leachate. The mechanisms differ: NH_3-N is captured mainly by ion exchange at negatively charged aluminosilicate surfaces, whereas organic matter is removed through hydrophobic partitioning, π–π interactions, and pore filling, which explains why single materials rarely excel at both and why mixtures and composites have attracted sustained attention. Zeolite- and clay-bearing materials were the strongest performers for NH_3-N. A feldspar–zeolite–activated carbon–cockle shell mixture optimized by D-optimal mixture design yielded predicted R^2 values of 0.9839 for NH_3-N and 0.8972 for COD [23]; a zeolite-to-moringa leaf powder ratio of 24:16 delivered 70.14% COD and 86.94% NH_3-N reduction at pH 5.9, 113 min, and 100 g/L [36]; and natural Turkish zeolite removed NH_4-N effectively across wide pH, dosage, agitation, and particle size ranges [91]. At the lower end, cockle shells and silica sand removed 48–51% of NH_3-N from stabilized leachate [38] [78].

For organic matter, the performance of waste-derived carbons depended strongly on precursor chemistry and activation. Coffee-waste carbon activated with H_3PO_4 removed 51.0% COD, 32.8% ammonia, and 97.1% copper [34]. Oat hull carbon (100% H_3PO_4 impregnation, 500 °C) removed colour completely and up to 90% of COD from real leachate [41]. KOH-impregnated sea mango biochar achieved 95.1% colour, 84.94% COD, and 95.77% NH_3-N removal, following pseudo-second-order kinetics and the Langmuir isotherm [86]. Wheat straw biochar removed 95.08% of nitrogen from ammonium chloride solution versus 93.11% for commercial activated carbon, although its capacity fell in the leachate matrix [52]. Oil palm empty fruit bunch and frond carbons showed favourable kinetics and reusability, the latter achieving 77% COD, 75% colour, and 69% Fe removal [54] [94], and rice husk

ash composites adsorbed 2.2578 mg/g of ammonia and 2.8893 mg/g of COD [49].

Industrial and biological wastes were also effective. Pressmud ash (400 °C) reduced COD, ammonia, and colour of real Pulau Burung leachate by 60.76%, 64.37%, and 35.78% [27]; waste paper sludge achieved 85.9% COD and 49.3% NH_3-N removal at a 2:2 replacement ratio with activated carbon [37]; green mussel shell removed 58% of COD and 48% of NH_3-N [39]; and fish scale–derived mesoporous carbon removed 60.1% colour and 37.3% COD while lowering the leachate inhibition ratio from 20.4% to as low as 10.9% [81]. Red mud was evaluated for COD and ammonia-nitrogen uptake [72], peat and compost for boron [84], and municipal solid waste–derived biochar for benzene [56]. Fibre sludge ash and peat adsorbed up to 115 µg/g Zn and 112 µg/g Cu and Pb in batch tests, but column tests with industrial leachate showed markedly lower uptake owing to ion competition [57].

Non-carbonaceous minerals gave instructive results for nitrogen. Nador bentonite removed 48% of ammonium, 40% of nitrate, and 85% of nitrite at 35 °C, falling to 40%, 15%, and 25% at 25 °C [31]; a bentonite–lime mixture eliminated 96% of nitrates within 20 min, whereas sodium bentonite reached only 45% after more than two hours [50]; and sol–gel fly ash calcined at 500 °C approached 100% NH_4^+-N removal at low initial concentration and achieved 80.24% at 16 mg/L [89]. Aluminosilicate sorbents produced a spent product usable as fertilizer [35]. Coupling with other processes extended performance: palm, coconut, and banana fibers with advanced oxidation removed 67.9–90.9% of COD [25], palm bark powder with ferric chloride coagulation reached 99% turbidity, 59% COD, and 90% colour removal [30], and Colocasia esculenta served as both wetland plant and activated carbon feedstock, removing iron by 77.97% in the wetland and 84.62% in optimized batch adsorption [55]. In fixed-bed columns, pumice stone and oyster shells reduced ammonia and nitrate below Irish limits of 4 and 50 mg/L, although phosphate removal declined over time [75], and multi-component agro-waste blends removed BOD, Pb, and Cr completely but gave negative COD removal, positioning them as pretreatment rather than stand-alone solutions [79]. Overall, zeolite-rich formulations excel at ammonium capture, carbonaceous residues at colour and COD abatement, and agro-waste blends offer cheap but limited organic removal (Table 2).

Table 2. Natural and Waste-Derived Adsorbents for Organic and Nutrient Removal from Landfill Leachate

Study ID	Adsorbent Modification/Preparation	Experimental Scale	Leachate Source
[32]	Activated carbon made from activated sludge and straw with pyrolysis; economic and reasonable addition of straw in the raw of activated sludge was 45%		
[34]	Activated carbon produced from coffee waste; activation with HCl, HCl + H2O2, H3PO4, H3PO4 + H2O2 at an impregnation rate of 1:1; best results with H3PO4 activation		Landfill leachate
[35]	raw and modified aluminosilicate		old landfill leachate
[36]	zeolite (ZE) and moringa oleifera leaf powder (MP) mixture at ZE:MP ratio of 24:16		stabilised leachate
[41]	Oat hulls were chemically activated with phosphoric acid (impregnation ratios 60% and 100%) and pyrolyzed under N2 atmosphere at 350 and 500 °C.	Adsorption batch tests	Synthetic leachate and real landfill leachate
[42]	Activated carbon and limestone mixture (15:25 by volume)	Batch and column studies	Old landfill in Taiping, Perak, Malaysia
[49]	new composite adsorbent derived from rice husk ash waste		synthetic leachate
[50]	mixture bentonite-lime and sodium bentonite	synthetic solutions of distilled water	technical burying centre (Boumergued/Algeria)
[52]	Biochar (BC) derived from wheat straw	Laboratory experiments	Landfill leachate (LLCH)
[54]	Physical activation, involving carbonization at 450° C and activation at 800° C under limited air conditions	Batch adsorption experiments	Municipal solid waste (MSW) leachate
[55]	activated carbon derived from C. esculenta	batch adsorption experiments	landfill leachate
[57]	The addition of 10% by weight of fibre ash to the peat	Batch and column experiments	Contaminated leachates from an industrial landfill
[65]	Modification of bentonite with cationic surfactant HTAB		landfill leachate
[70]	Natural zeolites activated by calcination at 700 °C for 2, 4, and 6 hours; optimal material calcined for 4 hours		Landfill leachate

[27]	Pressmud ash was prepared by burning at different temperatures from 100 to 700 degree Celsius; the pressmud with 400°C showed high potential		Municipal solid waste (MSW) Pulau Burung Sanitary Landfill (PBSL)
[73]	Sawdust was modified by adjusting pH to categorize into acidic, alkaline, and neutral groups; then added to bentonite samples at 10%, 20%, and 30% by mass.		Landfill leachate
[75]		Fixed-bed column trial (bed heights of 20 cm, flow rate of 5 mL min−1)	Powerstown landfill, Carlow, Ireland
[76]		Batch tests	Urban solid waste leachates
[78]			Pulau Burung landfill site (PBLS) in Penang, Malaysia
[79]	Multi-component bio-adsorbent (MCB) blends composed of banana peel, coconut fiber, corn cob, rice husk, and sawdust, formulated according to specific pollutant-removal objectives (Max Cation, Cr Guard, Heavy Pollutants, and Universal Start)	Modular column filtration system operated under continuous-flow conditions	Raw leachate from the Talumelito landfill in Gorontalo, Indonesia
[81]	Activated carbon obtained from fish scales		landfill leachate (LL)
[28]		pilot-scale	
[84]		Batch adsorption test	Huneault Landfill, located in Gloucester, Ontario
[86]	Activated bio-char derived from sea mango, impregnated with KOH (impregnation ratio 0.5–3), prepared at temperature 400–800°C with retention time 1–3 h		Landfill leachate
[89]	Modified by sol-gel method and calcined at 500 ℃ to remove residual organic matter		Landfill leachate of Huainan city
[92]	biophile mesopore active carbon produced in one-step activation with orange peel as raw material and zinc chloride as activator		
[94]	OPF-AC was prepared by mixing granular OPF with an aqueous solution composed of distilled water and zinc chloride (ZnCl2) at different ratios.	Batch experiment	Landfill leachate
[95]	Wood-derived biochar produced under pyrolytic temperature of 740 °C; used in two forms: pulverized (PWB) and crushed (CWB)		Landfill leachate

3.4 Engineered and Modified Adsorbents for Heavy Metal and Micropollutant Removal

Heavy metals and trace micropollutants occur at low concentrations but are toxic, persistent, and not removable by biodegradation. The engineered and modified adsorbents in Table 3 are distinguished by deliberate introduction of surface functional groups, metal oxide phases, or composite architectures. Three strategies recur: oxidative or alkaline treatment of carbonaceous precursors, impregnation with metal oxides or zero-valent metals, and intercalation of clays with cationic surfactants or inorganic binders. Such modifications typically raised capacities two- to five-fold relative to unmodified materials, although gains were often offset by reagent costs, extra preparation steps, and reduced stability or leaching of the modifying agent.

Among carbon-based adsorbents, nitric acid–oxidized coconut-shell carbon carried N–H and C–H groups identified by FTIR as the main drivers of metal uptake, and $KMnO_4$ treatment was superior for simultaneous removal of ammonia nitrogen, zinc, TSS, and sulphide [40]. Granular activated carbons removed 84–96% of metals with 40–60% COD reduction, and biochar matched the best carbon at 53% COD removal [62]. $ZnCl_2$-impregnated Parkia speciosa pod carbon removed 87.5% of COD from pretreated stabilized leachate at pH 2, with a Langmuir capacity of 142.86 mg COD/g [64]. Iron-modified Pinus biochar pyrolyzed at 900 °C acted as a heterogeneous Fenton-like catalyst [60], and orange-peel mesopore carbon targeted macromolecular contaminants poorly retained by granular carbons [92].

Metal oxide functionalization is the second principle. Iron oxide nanoparticles from iron ore removed COD, colour, and ammoniacal nitrogen under optimized conditions [85]. Iron oxide-coated gravel in fixed-bed columns removed 58.24% of Zn (II), 47.71% of Fe (II), and 39.45% of Ni (II); first-cycle desorption recovered 99.64% of Ni (II) and 99.54% of Fe (II) but under 7% of Zn (II) [93]. TiO_2 loaded on activated carbon removed 75.8% of NH_3-N at pH 7 and 30 °C [88], and chitosan–TiO_2 from fish scales was applied to lead removal from Batu Terang leachate [51]. Red mud removed over 99% of Cd, Ni, Zn, and As from abandoned-mine leachate, with Langmuir capacities of 12.58, 12.05, and 11.06 mg/g for Cd^{2+}, Zn^{2+}, and Ni^{2+} in synthetic solutions [26].

Clay-based and composite adsorbents completed the picture. An iron oxide–coated sludge/CTAB-modified

bentonite composite removed over 85% of Cd (II), DOC, and NH_3-N from model acetogenic leachate, with batch efficiency above 90% [24]. Chitosan-modified banana peel biochar (8:2) removed 100% of Zn, 66.2% of Fe, 45.8% of Pb, and 33.9% of Ni from real Pulau Burung leachate; the effluent met Malaysian limits for Cu, Fe, Ni, Pb, and Zn, but As and Cr remained above limits [90]. Calcium-saturated clays strongly attenuated Pb, Cd, Hg, and Zn, mainly by precipitation above pH 5.3 [46], and smectite-rich clay removed Cu and Ni better in column than in batch mode [29]. A calcined paper mill sludge–montmorillonite composite removed 96% of colour and 76% of COD, outperforming montmorillonite despite lower surface area, although the 80 g/L dosage and energy-intensive calcination constrain scale-up [77]. An activated carbon–calcite–alginate composite removed 54.6% of COD and 68.06% of Fe^{2+} [53], and NaCl modification increased the ammonium capacity of natural zeolite [68].

Several engineered studies addressed organics. Alkali pretreatment raised SBR COD removal from 32% to 47.7%, with powdered activated carbon and perlite then delivering over 81% and 72% [44]; perlite and bentonite as alum coagulation accelerators reached 92.8% and 85.0% COD removal [82]; and a composite of sea sand, alum sludge, zero-valent iron, and granular activated carbon removed 79.93 ± 1.95% of COD, 84.9% of total nitrogen, and 97.4% of total phosphorus [80]. Targeted surface modification can therefore bridge much of the gap to commercial activated carbon, but high dosage requirements, incomplete regeneration, and residual compliance gaps for arsenic and chromium remain.

Table 3. Engineered and Modified Adsorbents for Heavy Metal and Micropollutant Removal

Study ID	Adsorbent Modification Method	Modification Reagent / Agent	Adsorbent Dosage
[40]	Treating with nitric acid (HNO3), potassium permanganate (KMnO4), and heating at 600°C	Nitric acid (HNO3), potassium permanganate (KMnO4)	
[24]	Sludge coated with iron oxide (FeO) nanoparticles combined with an equal proportion of organically modified bentonite	Iron oxide (FeO) nanoparticles and Cetyltrimethylammonium bromide (CTAB)	5 g/50 mL
[46]	calcium-saturated clays	calcium	
[51]	Combination of chitosan extracted from red kurisi fish scales with TiO_2	TiO_2	
[53]	Composite adsorbent produced from the combination of activated carbon (AC) and calcite with alginate as binder	Alginate (binder), activated carbon, calcite	
[60]	Impregnating biochar with Fe at different Fe/BC ratios, followed by pyrolysis	Iron (Fe)	
[64]	ZnCl2 activation	ZnCl2	16 g/L
[68]	NaCl modification	NaCl	
[77]	Calcination; composite formation of calcined paper mill sludge with montmorillonite	Montmorillonite (Mt)	80 g L^{-1}
[88]	facile impregnation and pyrolysis synthesis method	TiO2	1.75 mg/L
[90]	Chitosan modification of banana peel biochar produced by hydrothermal carbonization	Chitosan	
[89]	sol-gel method		3 g/L

3.5 Adsorbents in Integrated and Hybrid Treatment Systems

Integration generally improved overall removal relative to stand-alone adsorption, and the adsorbent's role in the train determined which pollutant class was abated best (Table 4). Three integration logics emerged: oxidative or coagulation pretreatment followed by adsorption polishing, biological treatment augmented or polished by adsorbents, and coupled systems in which adsorption and another process share a reactor or treatment cell.

Sequential oxidation or coagulation followed by adsorption was the most frequent arrangement and gave the highest absolute removals. $KMnO_4$ oxidation followed by diatomite adsorption raised COD and ammonia nitrogen removal from 46% and 32% (oxidation alone) to 98% and 90% [33]; potassium ferrate oxidation followed by zeolite-dominated mullock lifted CODCr and ammonia nitrogen removal above 98% and 99%, satisfying Chinese standard GB 16889–2008 [48]. Alum coagulation with fly ash gave 82% overall COD removal, but adsorption contributed only 28% [43]. Other sequences included lime coagulation with walnut-shell bio-sorption [45], coagulation–flocculation with granular activated carbon and waste metal hydroxide sludge for the

seasonally variable Çorlu leachate [47], perlite and bentonite accelerators with alum [82], palm bark powder with coagulation–flocculation [30], and natural fibers with advanced oxidation [25].

Biological augmentation and simultaneous coupling provided the most novel mechanistic insights. Alkali pretreatment before SBR operation reduced heavy metal toxicity toward activated sludge, and powdered activated carbon or perlite then pushed COD removal above 81% and 72% [44]. A bentonite-enriched, sawdust-augmented SBR achieved 99.28% COD and 95.41% NH_3-N removal at 22 h and lost only about 17% of removal when contact time was cut to 2 h [73]. Zeolite-augmented SBRs outperformed carbon-augmented ones, with Fe, Mn, Ni, and Cd removals of 65.65%, 61.56%, 63.41%, and 60.44% [74], and zeolite polishing after an aerobic SBR lifted NH_3-N and COD removal from 65% and 30% to 96% and 43% [67]. Electrocoagulation coupled with clinoptilolite raised NH_3-N elimination from 50.0% to 93% with colour removal unchanged at 95% [69]; a second electrocoagulation–adsorption study using calcined natural zeolite reduced COD, TSS, and N-total by 91.70%, 65.85%, and 55% at 15 V, complying with Indonesian regulation P.59/Menlhk/Setjen/Kum.1/7/2016 [70]; and bioelectrochemical treatment followed by palygorskite polishing represents an emerging coupling [87].

In constructed wetlands and fixed-bed systems, adsorption and biological activity are spatially inseparable. Phragmites australis in crushed brick was efficient for zinc, whereas Typha latifolia in steel slag performed better for copper and lead [28]; Colocasia esculenta wetlands and activated carbon from the same biomass functioned as complementary stages [55]. A full-scale vertical-flow peat–ash biofilter preceded by a 500 m^3 equalization pond experienced peak loading five to six times its designed daily hydraulic limit [63]. Column systems with oyster shells and pumice [75], agro-waste blends [79], and iron oxide-coated gravel [93] are described in Sections 3.3 and 3.4.

Three cross-cutting observations follow. Integrated systems consistently outperformed stand-alone adsorption for ammoniacal nitrogen, with electrocoagulation–zeolite [69] and ASBR–zeolite [67] nearly doubling removal relative to the upstream stage. Oxidative pretreatment was most valuable for COD, extending downstream adsorbent service life [33] [48]. Biological augmentation with powdered adsorbents accelerated kinetics rather than only raising equilibrium capacity [73]. Nevertheless, regeneration and long-term data are scarce, most configurations remain at laboratory or bench scale, and few studies report hydraulic loading and cost information; the full-scale biofilter shows that hydraulic design may govern field success [63].

Table 4. Integrated and Hybrid Treatment Systems Incorporating Low-Cost Adsorbents

Study ID	Integrated/Hybrid System Type	Role Of Adsorbent in the System	Co-treatment Process/Agent	Adsorbent Material Form	Key Operating Parameters
[33]	Integrated KMnO4 oxidation and diatomite adsorption method	Adsorption of CODCr and ammonia nitrogen from landfill leachate after KMnO4 oxidation	KMnO4 oxidation	Diatomite	Optimum oxidation conditions for KMnO4
[40]	Hybrid technique using electrolysis process with AC adsorption	Removing heavy metals and multi-pollutants from landfill leachate through adsorption in a filtration process	Electrolysis process	Activated carbon produced from coconut shell	Contact time, bed depth of AC, pH, TSS, Ammonia-Nitrogen, heavy metals
[43]	Combined coagulation-adsorption process	Adsorption pretreatment of alum pre-treated stabilized leachate for COD removal	Coagulation using alum and ferric chloride	Fly ash	Coagulant dose (0.6 g/L and 0.7 g/L for alum and ferric chloride respectively for stabilized leachate; 0.8 g/L and 0.6 g/L for alum and ferric chloride respectively for fresh leachate), adsorbent dose (6 g/L), pH, contact time (equilibrium time of 210 min)
[44]	Sequence batch reactor (SBR) integrated with adsorption process	Porous adsorbent for COD removal and enhancement of microorganism activities in activated sludge treatment of landfill leachate	Alkali pre-treatment (caustic soda)	Perlite (low porosity) and powdered activated carbon (PAC)	COD of LFL: 10,500; BOD5/COD ratio: 0.68; optimum conditions of the biological process

[45]	Coagulation-flocculation with lime and bio-sorption	Adsorption of COD following lime coagulation	Lime	Walnut-shell	
[47]	Combined process of coagulation-flocculation and adsorption	Adsorption of residual pollutants and metals following coagulation-flocculation	Coagulation-flocculation using ferric chloride and aluminium	Granular activated carbon (GAC) and waste metal hydroxide (WMH) sludge	
[48]	Potassium Ferrate oxidation combined with mullock adsorption	Further treatment after oxidation to remove CODCr and ammonia nitrogen	Potassium Ferrate oxidation	Mullock (zeolite)	Oxidation stage: potassium ferrate dosage 12 g, reaction time 195 minutes, pH=10; adsorption stage: pH=7, zeolite dosage 100 g/L, adsorption time 7 h
[25]	Natural fibers intercropped with advanced oxidation processes	Adsorbent capacity for reduction of pollutants in leachate	Advanced oxidation processes	Natural fibers (palm, coconut and banana fiber)	Extremely oxidative conditions
[55]	Constructed wetlands combined with batch adsorption	Removal of chemical oxygen demand (COD) and iron (Fe) from landfill leachate	Constructed wetlands planted with Colocasia esculenta	Activated carbon derived from Colocasia esculenta	pH 6 and contact time of 53 min
[63]	Vertical-flow biofilter with a 500 m3 equalization pond prior to the filter system	Adsorptive and biological polishing of industrial leachate within the filter bed	Equalization pond	Mixture of peat and carbon-containing ash	Peak loading rates exceeded up to five to six times the designed daily hydraulic load limit
[67]	Combined biological-physical treatment system (ASBR combined with zeolite adsorption)	Secondary treatment step for polishing ammoniacal nitrogen and COD content in leachate	Aerobic sequencing batch reactor (ASBR)	Zeolite	Initial ammoniacal nitrogen concentration: 1800 mg/L; initial COD concentration: 3200 mg/L; ASBR treatment time: 7 days
[69]	Integrated Electrocoagulation (EC) - zeolite adsorption	Removal of NH3-N (ammonia nitrogen) from landfill leachate; increased NH3-N removal from 50.0% to 93% when integrated with EC	Electrocoagulation (EC) using aluminium (Al) cylindrical electrode	Clinoptilolite zeolites adsorbent	EC: current density 7-35 mA/mm2 (optimum 14.0 mA/mm2), initial pH 5-9 (optimum pH 5), electrolysis time 0-90 minutes (optimum 75 minutes), inter-electrode distance 5-25 mm (optimum 15 mm). Integrated EC-zeolite adsorption: adsorbent dosage 2.0 g/150 mL, contact time 100 minutes, initial pH 8
[70]	Electrocoagulation-adsorption	Adsorbent for treating landfill leachate	Electrocoagulation	Natural zeolites activated by calcination	Electrical voltage (5, 10, 15, 20, 25, 30, 35 V; optimal 15 V); adsorbent mass (0, 20, 40, 60, 80, 100, 120 g; optimal 60 g); calcination duration (2, 4, 6 hours at 700 °C; optimal 4 hours)
[73]	Sequencing batch reactor (SBR) process augmented with bentonite-enriched sawdust	Biomass adsorbent for water pollutant removal	Bentonite	Sawdust (pH-modified: acidic, alkaline, neutral) mixed with bentonite at 10%, 20%, and 30% by mass	Aeration rate: 7.5 L/min; contact period: 22 h (optimum) and 2 h (with sawdust); pH modification of sawdust
[74]	Powdered activated carbon and powdered zeolite augmented SBR technique	Heavy metals removal	Biological treatment (SBR)	Powdered activated carbon and powdered zeolite	Aeration rate (l min-1), reaction time (h), leachate-to-wastewater mixing ratio (%; v/v); optimum conditions: contact time 13.83 h, aeration rate 2.81 l min-1, leachate to domestic wastewater proportion 20.00%
[75]	Fixed-bed column adsorption system	Adsorbent for removal of ammonia, phosphate and nitrate contaminants from landfill leachate		Oyster shells, pumice stone, sand and zeolite (batch assays); oyster shells and pumice stone (fixed-bed column)	Bed height of 20 cm; flow rate of 5 mL min−1
[79]	Modular column filtration system operated under continuous-flow	Bio-adsorption for removal of heavy metals (Fe, Cu, Cr, Pb), total suspended solids (TSS), and biodegradable	Conventional biological treatment (noted as insufficient for	Multi-component bio-adsorbent (MCB) blends composed of	Continuous-flow conditions; four blend formulations (Max Cation, Cr Guard, Heavy Pollutants, Universal Start); monitored parameters: TSS,

	conditions, positioned as a pretreatment integrated into multi-stage treatment systems	fractions (BOD); not effective for refractory organics (COD)	stabilized leachates)	banana peel, coconut fiber, corn cob, rice husk, and sawdust	heavy metals (Fe, Cu, Cr, Pb), BOD, COD, pH
[80]	Composite adsorbent system	Adsorption of organic compounds (COD), total nitrogen (TN), and total phosphorus (TP) from landfill leachate	Washed sea sand (WSS), dewatered alum sludge (DAS), zero-valent iron (ZVI), and granular activated carbon (GAC)	Composite adsorbent composed of WSS (40%), DAS (40%), ZVI (10%), and GAC (10%) by weight	
[28]	Constructed wetland (CW) integrated with adsorbent materials (crushed brick and steel slag)	Removal of metals (Zn, Cu, Pb) from leachate	Phragmites australis (CW1) and Typha latifolia (CW2)	Crushed brick and steel slag	
[82]	Aerobic treatment process combined with coagulation-flocculation	Accelerator additive to enhance the chemical treatment process using Alum coagulant	Alum coagulant (90 mg/l constant dose)	Perlite and Bentonite	Alum dose: 90 mg/l; Perlite and Bentonite concentration: 40 mg/l each
[87]	Bioelectrochemical system (BES) combined with natural clay adsorption	Further treatment of the BES effluent (EBES)	Bioelectrochemical system (BES)	Natural clay (palygorskite)	Two different masses and sizes (i.e., 3 g and …)
[93]	Continuous fixed-bed column	Adsorption of Fe (II), Ni (II), and Zn (II) from synthetic leachate	Iron oxide coating	Iron oxide-coated gravel	Affinity order Zn (II) > Fe (II) > Ni (II); desorption recovery of 99.64% Ni (II) and 99.54% Fe (II) in first cycle
[29]	Batch and column adsorption integrated with sand amendment	Removal of copper and nickel from Jebel Chakir leachate	Sand addition	Smectite-rich clayey rock (raw AYD clay)	Column mode outperformed batch mode; sand improved depollution over a limited volume
[30]	Coagulation-flocculation coupled with adsorption	Adsorption of residual turbidity, COD and colour after coagulation	Coagulation-flocculation	Palm bark powder (PBP)	Turbidity 99%, COD 59%, colour 90%

IV. DISCUSSION

The 75 studies establish the technical feasibility of low-cost adsorbents for leachate treatment while leaving long-term performance, scalability, and economics largely unresolved. The clearest pattern is a pollutant-specific division of labour. Zeolite-bearing materials gave the highest NH_3-N removals, from about 48% for raw cockle shells and silica sand to above 96% for zeolite with biological or electrocoagulation pretreatment [38] [67] [69] [78]. Carbonaceous materials dominated colour and COD abatement, with the best activated carbons and biochars achieving 84–98% under optimized conditions [41] [77] [86]. Engineered surfaces dominated metal removal, raising capacities two- to five-fold over unmodified counterparts [24] [26] [90]. Ammonium capture by ion exchange is relatively insensitive to dissolved organic matter and so transfers more reliably from synthetic to real leachate, whereas the more heterogeneous mechanisms of carbons explain their wider performance variation across precursors.

The leachate matrix is a second decisive factor. Where synthetic and real leachate were compared, real leachate almost invariably depressed removal: fibre sludge ash and peat captured markedly less zinc in column tests with industrial leachate owing to ion competition [57], wheat straw biochar removed 95.08% of nitrogen from ammonium chloride solution but substantially less from leachate [52], and agro-waste blends removed BOD, Pb, and Cr completely yet showed negative COD removal, indicating desorption or competitive displacement of recalcitrant organics [79]. The reliance on synthetic or diluted leachate noted in the Introduction [19] is thus a systematic source of overoptimism, and laboratory capacities should be treated as upper bounds, not design values.

The evidence also contains instructive contradictions. A calcined paper mill sludge–montmorillonite composite outperformed pure montmorillonite despite the latter's larger specific surface area, indicating that surface chemistry and site accessibility matter more than porosity [77]. A zeolite-augmented SBR

outperformed a carbon-augmented one for heavy metals, contrary to the expectation that carbons dominate metal uptake [74]. Regeneration diverged by pollutant, with iron oxide-coated gravel recovering over 99% of nickel and iron but under 7% of zinc [93]. These findings argue for material- and pollutant-specific evaluation rather than broad categorical claims.

Capacity alone poorly predicts practical utility. Materials with moderate capacity but favourable kinetics, renderability, and matrix tolerance, such as sodium-modified zeolites and iron-functionalized biochars, appear more promising than high-capacity materials that foul irreversibly or lose performance to competing ions [60] [68]. We therefore propose a multidimensional performance framework that weights capacity alongside regeneration potential, matrix robustness, and cost per unit pollutant removed, rather than ranking materials on Langmuir maxima. The best treatment trains achieved their gains by sequencing processes so that each addressed the pollutant class it handles best [33] [48] [73]. For landfill operators, particularly of small-to-medium facilities in resource-constrained settings, the evidence supports a staged pathway: begin with local zeolites and clays for ammonium and metal polishing, and add modified adsorbents only where compliance gaps persist. Oxidative pretreatment with permanganate or ferrate lifted COD removal above 98%, suggesting that a modest oxidation stage may extend adsorbent service life [33] [48]. For policymakers, Indonesian and Malaysian compliance outcomes show that discharge targets can be met with low-cost adsorbents in suitably configured trains [70] [90]. The conversion of sugar mill pressmud, paper mill sludge, fish scales, and seafood shells into adsorbents also illustrate waste-to-resource thinking [27] [77] [81] [39].

This review has limitations. The search covered six databases and English-language publications, likely excluding relevant work in Chinese, Spanish, Portuguese, and Arabic; the 124 unretrievable reports add a selection bias of uncertain direction; publication bias probably inflates apparent performance, since few reports describe adsorbents that failed; the quality assessment involved subjective judgments; and heterogeneity across the 75 studies precluded formal meta-analysis, so the synthesis is narrative. Cost data were absent from most studies, so conclusions about cost-effectiveness rest on the materials' origins, not verified techno-economic analysis.

These limitations define priorities for future research: standardized protocols specifying minimum reporting of adsorbent characterization, leachate composition, and conditions; multi-cycle regeneration studies and continuous-flow column trials lasting weeks to months, since the evidence base is dominated by single-cycle batch experiments; study of the fate and leaching of modifying agents such as surfactants, metal oxides, and zero-valent iron; techno-economic and life cycle assessments that include preparation energy, reagents, regeneration, and disposal; and pilot-scale validation, which remains scarce (the one full-scale biofilter in our corpus was hydraulically overloaded five to six times its design limit, suggesting that engineering design may govern field success [63]). Integration of low-cost adsorption with advanced oxidation and membrane processes should be tuned to leachate maturation stage, and modification strategies should target arsenic and chromium, the metals that most often remained above discharge limits [90].

V. CONCLUSION

This systematic review asked whether low-cost adsorbents can serve as technically feasible and economically attractive alternatives to commercial activated carbon for landfill leachate treatment, and the 75 synthesized studies give an affirmative but qualified answer. Zeolite-bearing materials excel at ammoniacal nitrogen capture through ion exchange, carbonaceous residues dominate colour and COD abatement, and engineered or modified surfaces deliver the highest heavy metal capacities. Integrated trains that couple oxidative or biological pretreatment with adsorption polishing consistently outperformed stand-alone adsorption, with several configurations exceeding 98% COD and 99% ammonia removal. Matrix tolerance, regenerability, and kinetics proved more predictive of practical utility than maximum uptake, challenging the field's reliance on Langmuir capacity as the main figure of merit.

Operators in resource-limited settings can adopt a staged pathway beginning with local zeolites and clays, and policymakers can set discharge standards that are attainable with locally sourced media in well-configured trains, as shown in Malaysia and Indonesia.

The field nevertheless remains constrained by fragmented protocols, scarce regeneration and cost data, and a near-total absence of pilot-scale validation. Standardized reporting, multi-cycle and continuous-flow testing, techno-economic and life cycle assessment, and targeted modification for arsenic and chromium will determine whether low-cost adsorbents remain a laboratory promise or become a cornerstone of sustainable leachate management.

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