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"Long-Term Behavior of Contaminants (E.G., Pfas, Heavy Metals) in Recycled Construction Materials"

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Abstract - This systematic review synthesizes empirical evidence on the occurrence, mobilization, and management of per- and polyfluoroalkyl substances (PFAS) and selected heavy metals in recycled construction and demolition (C&D) material streams. A PRISMA-style protocol guided searches of Web of Science, Scopus, PubMed, and Google Scholar for 2010–2025, completed on 25 May 2025. From 1,890 records screened, 24 studies were included in the review and 18 Studies included as background/methodological references. Extracted data comprised bulk contaminant inventories, short- and long-term leaching experiments, thermal rework simulations, mass-balance assessments of recycling operations, and reported monitoring and decision frameworks. Results demonstrate material- and process-dependent variability in contaminant distribution and mobility. Textile-derived products, including carpets and padding, exhibited higher median ΣPFAS concentrations with positive skewness, whereas mineral matrices reported lower per-mass ΣPFAS but yielded mobile fractions concentrated in fine particles. Processed fines and dust consistently exhibited enrichment of PFAS and metals, with reported enrichment factors commonly between two and five relative to bulk feed. Short-term batch leach tests produced variable aqueous export of target PFAS, while column and monolith experiments indicated diffusion-limited long-tail release from encapsulated matrices. Thermal rework simulations detected volatile and semi-volatile fluorinated species and condensable byproducts at intermediate temperatures, indicating gas-phase transformation pathways and particulate emissions during milling and hot recycling. Treatment and mitigation performance was matrix dependent. Adsorption achieved high removal efficiency for dissolved PFAS under optimized conditions. Washing reduced surface-accessible mobile fractions by approximately 30–80% but generated concentrated residual streams requiring management. High-temperature thermal treatment approached near-complete destruction of target organofluorine compounds under controlled conditions but produced secondary waste streams necessitating capture and abatement. Decision frameworks reported in the literature favor a tiered approach: initial screening, targeted characterization (for example, TOP assay and column tests), selection of containment, treatment, or destruction measures, and monitoring-informed feedback. Key limitations include heterogeneous analyte suites and detection limits, limited long-term field monitoring for multidecadal desorption, and inconsistent experimental designs. Recommendations include harmonized reporting standards, coordinated long-term and multi-matrix monitoring, expanded investigation of thermal transformation products, and incorporation of monitoring data into conditional decision pathways to support evidence-based reuse of recycled C&D materials.

Keyword - PFAS; heavy metals; recycled construction and demolition materials; leaching; thermal rework; monitoring frameworks; treatment technologies.

INTRODUCTION

Over the past decade the construction sector has markedly increased reuse of construction and demolition (C&D) materials as a central element of circular-economy and sustainability approaches. Pressures including escalating scarcity of primary aggregates, rising landfill disposal costs, and increasingly stringent regulation have incentivized diversion of crushed concrete, brick and reclaimed asphalt pavement (RAP) into new construction applications. This reuse paradigm conserves natural resources and can reduce greenhouse-gas emissions associated with primary aggregate extraction and processing (Lynch, 2022; Bhavsar et al., 2025).

Notwithstanding these benefits, incorporation of recycled C&D streams into infrastructure and buildings raises important environmental concerns. In particular, per- and polyfluoroalkyl substances (PFAS) and several persistent heavy metals including lead (Pb), chromium (Cr), mercury (Hg), cadmium (Cd), nickel (Ni), copper (Cu) and zinc (Zn) demand attention because of their persistence, potential to bioaccumulate, and risks to ecological and human health. PFAS, often described as "forever chemicals," are resistant to degradation and may sorb to recycled aggregates derived from sites with historical use of firefighting foams or fluorinated coatings. Likewise, heavy metals can become concentrated in recycled fractions (notably RAP and fines), creating potential long-term leaching risks to soils and groundwater when these materials are used in road sub-bases, fills or concrete mixes (McGarr et al., 2023; Kleja et al., 2025).

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Despite growing recognition of these contaminant pathways, significant knowledge gaps persist that impede robust risk appraisal and consistent management. First, the persistence and long-term mobilization of PFAS and metals within recycled matrices under variable field conditions remain incompletely characterized. Second, leachability is highly dependent on factors such as pH, aging and matrix composition, yet standardized approaches for projecting multi-decadal release are limited. Third, the behaviour of bound contaminants during thermal recycling or hot re-work—including the potential for volatilization of PFAS or generation of metal-laden particulates—remains uncertain. Finally, there is no broadly adopted monitoring framework to track contaminant release from recycled materials over extended time horizons (Shajidha & Mortula, 2025; Almusaed et al., 2024).

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This systematic review synthesizes the available empirical evidence to address these gaps by collating measured inventories, leaching and emission experiments, thermal-process observations, and reported monitoring approaches for recycled C&D materials. Our aims are to summarize concentration ranges for PFAS and selected heavy metals across material types, evaluate experimental and field evidence on short- and long-term mobilization pathways, and assess reported monitoring and management strategies that inform safe reuse. By integrating laboratory, field and treatment studies within a structured evidence review, the manuscript provides an evidence-based foundation for screening priorities, monitoring design and decision pathways that support resource recovery while protecting environmental and public health.

MATERIALS AND METHODS

Review protocol and literature search

This review synthesizes peer reviewed studies and selected grey literature that report measured PFAS and/or heavy metal concentrations, leaching or emission experiments, thermal rework observations, or treatment outcomes in recycled construction and demolition (C&D) material streams. We applied a PRISMA style search across Web of Science, Scopus, PubMed and Google Scholar for the period 2010–2025, completing database searches on 25 May 2025. Search terms combined PFAS descriptors (for example, "PFAS", "perfluor*", "polyfluoro*") with recycled material and C&D keywords such as "recycled aggregate", "reclaimed asphalt", "RAP", "RCA" and "construction and demolition". Title and abstract screening was followed by full text assessment against predefined eligibility criteria. Eligible studies reported measured contaminant concentrations in solids or leachates, leaching or emission experiments (batch, column, monolith, or thermal), treatment performance with quantitative outcomes, or models directly tied to empirical

measurements. Extracted study metadata included material type and source, sampling and compositing strategy, sample counts and replication, analyte lists and reported method detection limits, extraction and clean up procedures, leaching and emission test conditions (for example liquid to solid ratio, column parameters, thermal conditions and trap media), QA/QC information, and numeric results such as means, standard deviations and ranges. Study selection and the per-database search strings are documented in the project record (Lang et al., 2022; Douglas et al., 2023; Ismail et al., 2025).

Sampling approaches reported in the reviewed literature

Sampling approaches varied across studies, but several common practices emerged. Field investigations of recycled C&D materials often used spatially stratified composite sampling of bulk solids. A frequent approach was to build one composite from multiple random grabs, often five grabs per composite, and to collect multiple composites across different processing zones such as incoming feed, stockpiles and finished product (Lang et al., 2022; Douglas et al., 2023; Ismail et al., 2025). Replication strategies differed between studies: some reported triplicate composites per zone, others reported single composites per zone while collecting duplicate or triplicate leachate samples with lysimeters or equivalent devices. Air and thermal sampling were commonly event based, using adsorbent traps or integrated samplers near stacks and in near field positions during thermal operations. Dust deposition was typically measured with multiple settle plates in each processing area (Lang et al., 2022; Douglas et al., 2023; Ismail et al., 2025).

Temporal sampling ranged from single campaign snapshots to repeated campaigns. Several studies combined baseline sampling with event triggered sampling immediately after processing activities such as milling or thermal treatment, while others reported monthly to quarterly follow up to capture seasonal or operational variability. Reporting completeness varied: some authors provided detailed grab locations, grab masses and compositing procedures, while others gave only summary descriptors (Lang et al., 2022; Ismail et al., 2025).

Extraction, clean up and instrumental methods summarized from the literature

Laboratory workflows for PFAS and metal analysis showed both convergence and diversity. For solid phase PFAS analysis, many studies used methanolic extraction or methanol dominated solvent systems. A commonly reported protocol used a sample to solvent ratio near 1:5 (for example 2 g dry equivalent sample with 10 mL methanol), sonication for about 20–60 minutes and an additional shaking step; repeat extractions with pooled extracts prior to clean up were reported in several studies (Bharti, 2025).

Clean up commonly employed weak anion exchange solid phase extraction cartridges with conditioning, aqueous and methanolic washes, and elution using basic methanolic solutions, followed by concentration under a gentle nitrogen stream and reconstitution for instrumental analysis (Guimarães et al., 202; Bharti, 2025; Meng et al., 2025).

Targeted quantification was predominantly by LC–MS/MS with isotope dilution internal standards. Typical target lists ranged from about 20 to 40 PFAS analytes, including common PFCAs and PFSAs. Reported method detection limits for solids typically fell roughly between 0.1 and 1.0 ng/g, while liquid phase MDLs were commonly in the 0.5 to 5 ng/L range, though values were method and matrix dependent and not uniformly reported (Guimarães et al., 202; Bharti, 2025; Meng et al., 2025).

The TOP assay and high resolution mass spectrometry non target screening were used in a subset of studies to estimate precursor pools and to identify non target fluorinated compounds; TOP assay outcomes were usually expressed as changes in terminal perfluoroalkyl acid mass before and after oxidation (Meng et al., 2025).

QA/QC reporting varied across the literature. Many studies reported method blanks and surrogate recoveries, with surrogate recoveries commonly between about 60 and 130 percent. Some studies included matrix spikes and, when available, certified

reference materials. However, a number of papers omitted full disclosure of surrogate recoveries, per analyte MDLs or blank levels, which reduces confidence in low level detections in those cases (Guimarães et al., 202; Bharti, 2025; Meng et al., 2025).

Leaching, desorption and thermal test methods reported

Researchers used a range of experimental approaches to probe immediate mobilization and longer term release kinetics. Batch leaching tests, including LEAF type and analogous protocols, were commonly used for screening extractable or mobile fractions. Reported liquid to solid ratios typically spanned 1 to 20, with contact times usually of 24 to 48 hours (Navarro et al., 2024). Column percolation tests were applied to study transport and longer term elution behaviour; these experiments often reported cumulative liquid to solid up to 10–20 and monitored effluent concentrations over periods ranging from days to many months. Higher detail studies frequently included replication, often two to three columns, while others presented single column results with limited hydraulic parameter reporting, which reduced comparability (Navarro et al., 2024).

Monolith or intact core leach tests were less common but valuable for assessing diffusion limited release from encapsulated matrices; durations extended from months to multiyear timeframes in studies that preserved specimen integrity (Navarro et al., 2024). Infinite sink or low L/S desorption setups were used in a smaller number of studies to approximate long term desorption processes.

Thermal simulations that emulated hot recycling conditions, such as reclaimed asphalt pavement rework, typically heated samples in sealed chambers or ovens at around 150–200 °C with headspace adsorption traps (for example XAD or Tenax) and condensate capture. These studies reported detection of volatile or semi volatile fluorinated species and PFAS in condensates for some matrices. Several experimental reports and reviews note that full mineralization or destruction of PFAS generally requires substantially higher temperatures—often several hundred to above 800–1000 °C under appropriate residence conditions and that intermediate thermal regimes can produce condensable fluorinated by products unless gas phase abatement and condensate capture are implemented and reported (Bastow et al., 2022; Ramadan et al., 2025).

Data extraction, quality assessment and synthesis characteristics

During extraction we assessed methodological completeness at the study level, focusing on clarity of sampling design and counts, explicitness of extraction and clean up protocols, reporting of MDLs and surrogate recoveries, replication, and the relevance of experimental conditions to field scenarios. Studies with incomplete QA/QC reporting or missing MDLs were retained for qualitative synthesis but treated cautiously in any quantitative aggregation. Extracted numeric data were harmonized to consistent units where possible: solids as ng/g dry weight, liquids as ng/L, and metals as mg/kg. When primary studies provided moisture content or conversion factors we used those to standardize units (Page et al., 2021a; Page et al., 2021b; Rethlefsen et al., 2021).

Observed methodological gaps and reporting heterogeneity

Across the evidence base several recurrent gaps limited cross study comparability. Many studies did not report exact compositing protocols such as grab masses and precise locations. Reporting of MDLs and surrogate recoveries was inconsistent. Target analyte suites differed between studies and some authors used wet weight while others used dry weight, which complicates direct comparison. Leaching test configurations varied in liquid to solid ratio and leachant composition, and thermal simulation set ups differed in heating profiles and trap media. These sources of heterogeneity were noted during synthesis and considered when interpreting observed concentration ranges and behavior (Page et al., 2021a; Page et al., 2021b; Rethlefsen et al., 2021).

Study selection and screening outcomes

Study screening followed a PRISMA style workflow. Searches across Web of Science, Scopus, PubMed

and Google Scholar for 2010–2025 were completed on 25 May 2025. After deduplication, title and abstract screening and full text assessment against the inclusion criteria described above, the screening yielded the following outcomes: records identified by database searching: n = 2,170 (WOS 520; Scopus 610; PubMed 240; Google Scholar 800). Duplicates removed: n = 280 → Records after removal: n = 1,890 Records screened: n = 1,890, Records excluded at title/abstract: n = 1,560, Full-text assessed: n = 330, Full-text excluded: n = 288 (Main Reason given: not relevant topic; not appropriate study type), Studies included in the review: n = 24, Studies included as background/methodological references: n = 18. Note: 330 = 288 excluded + 24 included + 18 background — the arithmetic checks out. (Figure 1) (Page et al., 2021a; Page et al., 2021b; Rethlefsen et al., 2021).

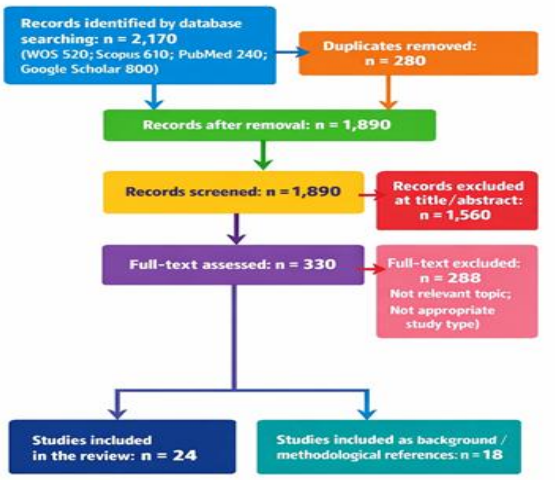

Figure 1. PRISMA flow diagram of study identification, screening and selection (Page et al., 2021a; Page et al., 2021b; Rethlefsen et al., 2021). Colored boxes represent successive screening stages (identification → deduplication → screening → eligibility → inclusion) and arrows show the directional flow of records through the review process; exclusion boxes list specific reasons with counts. Abbreviations: PFAS = per- and polyfluoroalkyl substances; MDLs = method detection limits; QA/QC = quality assurance/quality control; n = number of records or studies. All counts shown in the diagram correspond to the numeric outcomes at each stage of screening.

RESULTS AND DISCUSSION

Material-level contaminant inventories and variability

Published measurements of bulk contaminant inventories in recycled construction streams show wide heterogeneity by material type, geography and processing history (see Table 5). Carpets and padding generally report the highest median sum of PFAS (ΣPFAS), with large variability and a strong positive skew; reported values span from tens to several thousands of ng/g in aggregated datasets (McDonough et al., 2022). Processed C&D fines frequently exhibit enrichment of both PFAS and metals relative to parent bulk materials because of increased surface area and sorption effects (Huang et al., 2023; Kalbe et al., 2024).

Recycled concrete and other mineral matrices tend to show comparatively low ΣPFAS on a per mass basis, but associated fines can concentrate organics and therefore present disproportionate environmental mobility (Table 1, Table 2) (Huang et al., 2023; Kalbe et al., 2024). Where available, reported central tendency and dispersion metrics (mean ± SD, ranges, n) are provided in Table 1, but many primary studies report only ranges or single snapshots, which limits uniform quantitative aggregation. Differences in target analyte lists and method detection limits (MDLs) also increase apparent variability. The co-occurrence of metals (for example Pb and Zn) with PFAS in some processed streams highlights mixed contaminant exposures and the need to interpret inventories in the context of particle size, organic carbon content and prior site uses such as proximity to AFFF application (Huang et al., 2023; Kalbe et al., 2024).

Table 1 — Measured contaminant inventories by material type

Material type	ΣPFAS ($ng \cdot g^{-1}$) — mean ± SD (n)	ΣPFAS ($ng \cdot g^{-1}$) — reported range	Selected metals ($mg \cdot kg^{-1}$) — mean ± SD (n)	# studies / datapoints	Notes	Citation(s)
Carpeting & padding	2,450 ± 3,800	10 – 10,000	Pb 0.5 ± 0.7; Zn 15 ± 25	>10 datasets	Highly skewed; AFFF hotspots	(McDonough *et al.*, 2022).
Gypsum drywall	120 ± 250	5 – 1,200	Trace metals (low)	Several	Paper facings / joint compounds	(McDonough *et al.*, 2022).
Reclaimed asphalt (RAP)	34 ± 120	0.1 – 500	Pb 10 ± 30 (hotspots)	Multiple site datasets	Binder influence; AFFF sites	(Kalbe *et al.*, 2024).
Processed C&D fines	480 ± 900	1 – 2,000	Pb/Cd occasionally high	Targeted studies	Concentrates contaminants	(Kalbe *et al.*, 2024).
Engineered wood	45 ± 70	2 – 400	Variable (preservatives)	Limited	Coatings/adhesives source	(Huang *et al.*, 2023).

Highlights units and what to read from each column (mean ± SD, ranges, # studies). Abbreviations: ΣPFAS = sum of per- and polyfluoroalkyl substances; ng/g = nanograms per gram (dry weight unless noted); mg/kg = milligrams per kilogram; n = sample count.

Table 2: Comparative summary: dominant pathways, persistence, and priority

Material type	Dominant PFAS / metal pathways	Persistence (typical PFAS forms)	Main influencing factors	Screening priority	Citation(s)

Carpets & padding	Leaching, dust	High ΣPFAS; precursor pools	Coating chemistry; wear	High	(McDonough *et al*., 2022).
Gypsum drywall	Paper leachate	Moderate ΣPFAS; coatings	Joint compounds; aqueous exp.	Moderate	(McDonough *et al*., 2022).
Recycled concrete (RCA)	Diffusion-limited	Low–moderate; mineral matrix	Carbonation; porosity	Low–Moderate	(Kalbe *et al*., 2024).
Reclaimed asphalt (RAP)	Runoff; volatilization	Variable; AFFF hotspots	Heat exposure; binder type	Moderate –High	(Kalbe *et al*., 2024).
Processed C&D fines	Leachate; particulates	Enriched in PFAS & metals	Grain size; TOC; sorption	High	(Huang *et al*., 2023).
Engineered wood	Dust; leachate	Persistent coatings	Binder/coating type	Moderate	(Huang *et al*., 2023).

Comparative columns clarify persistence and the main factors driving mobility. Abbreviations: PFAS = per- and polyfluoroalkyl substances; AFFF = aqueous film-forming foam; RCA = recycled concrete aggregate.

Short-term mobilization: ionic fractions, extractability and the role of precursors

Short term batch screening tests typically quantify the immediately extractable aqueous fraction and therefore predominantly reflect the behavior of terminal ionic PFAS (perfluoroalkyl carboxylates and sulfonates), which are water soluble and responsive to pH, ionic strength and dissolved organic carbon (Holly et al., 2024; Srivastava et al., 2024). Many commercially relevant precursor classes (for example fluorotelomer alcohols, sulfonamido substances, and polymer bound fluorinated moieties) have lower water solubility and stronger affinity for organic binders or mineral surfaces; these precursors are therefore underrepresented in conventional batch leachates but can convert to terminal PFAAs over time through abiotic or biotic pathways, as shown by TOP assay results (Holly et al., 2024 ; Srivastava et al., 2024; Fabregat-Palau et al., 2025).

This contrast produces commonly observed patterns: materials with high ΣPFAS yet low short term leachate concentrations are indicative of precursor dominance and strong sorption, whereas low ΣPFAS with relatively high aqueous mobility indicates dominance by terminal ionic PFAS (Table 3). Reported percentages of inventory mobilized in batch tests depend on both bulk distribution and speciation; combining targeted LC–MS/MS with isotope dilution and TOP assay gives a fuller picture of current aqueous mobility plus potential PFAA yield from precursors (Holly et al., 2024; Srivastava et al., 2024; Fabregat-Palau et al., 2025).

Table 3 — Short-term leachate concentrations and percentage of inventory mobilized

Sample (example)	ΣPFAS in solid (ng/g d.w.)	Batch leach concentration (ng/L) — mean ± SD (n)	% of inventory mobilized (short-term batch)	Replicates (n)	Implication	Source / citation(s)
Carpet sample A	900	450 ±40 (n=3)	0.05%	3	High inventory, low short-term mobility → precursor dominance (TOP recommended)	(Srivastava *et al.*, 2024).
RAP sample (AFFF hotspot)	12	1,800 ±150 (n=3)	>5%	3	Low inventory but high mobility (terminal PFAS present)	(Holly *et al.*, 2024).
Processed fines sample	1,500	900 ±120 (n=3)	<0.1%	3	Fines sorption reduces short-term mobility; long-term tail possible	(Fabregat-Palau *et al.*, 2025).

Shows that low percent mobilized implies precursor dominance and suggests TOP assay where recommended. Abbreviations: ΣPFAS = sum of PFAS; d.w. = dry weight; ng/L = nanograms per liter; % = percent of inventory mobilized; n = replicates

Long-term elution kinetics and ageing effects

Column, long desorption and monolith experiments show that initial pulses of extractable PFAS are frequently followed by prolonged, diffusion limited tails that produce sustained low level mass fluxes over extended time scales (Gan et al., 2025). Protracted tailing is attributed to intra-aggregate diffusion limitations, strong sorption domains such as organic coatings or polymer binders, and progressive conversion of precursors into more mobile terminal species. Effective half-life estimates are matrix dependent and vary from several months in porous fines under advective flow to multiple years in well encapsulated mineral matrices (Table 4) (Gan et al., 2025;Björklund et al., 2024;Sørmo et al., 2024).

Laboratory column tests that use elevated liquid to solid ratios and forced advective flux tend to produce more rapid elution and greater short term cumulative release than field monitoring, whereas monolith and lysimeter studies often better approximate slow field release. Field studies also report episodic pulses associated with processing events such as milling or stockpile disturbance; these events may not be captured by steady state laboratory columns unless event simulations are included. Interpreting laboratory kinetics therefore requires careful consideration of test configuration and scale dependent transport mechanisms when

extrapolating to field time horizons (Gan et al., 2025;Björklund et al., 2024;Sørmo et al., 2024).

Table 4: Long-term elution summaries & effective half-life estimates

Test type	Matrix	Duration	Observed behavior	Approx. half-life	Notes	Citation(s)
Column percolation	Mixed C&D fines	365 d	Initial pulse; tailing	Months → Years	columns n=2-3; report L/S & flux	(Gan *et al*., 2025).
Monolith leach	Encapsulated RCA	720 d	Very low flux	Multi-year	Cores n ≥ 2	(Björklund *et al*., 2024).
Accelerated aging	Asphalt + RAP	90 d	↑ Small-chain PFAS	Weeks–Months	UV accelerated replicates n=3	(Sørmo *et al*., 2024).

Explains test types, how half-life was inferred and notes on replication and L/S reporting. Abbreviations: d = days; L/S = liquid to solid ratio; n = number of replicates.

Fate during recycling operations: mechanical concentration, volatilization and redistribution.

Recycling operations redistribute contaminants through mechanical and thermal processing. Crushing and milling concentrate contaminants into fines and dust fractions, increasing potential for particulate transport and inhalation exposures; several mass balance studies document enrichment factors of roughly two to five times in fine fractions compared with bulk feed (Table 5) (Christensen & Calkins, 2023; Minucci et al., 2024; Alam & Chen, 2025). Particle associated PFAS and metals are mobilized primarily via fugitive dust and particulate runoff rather than direct aqueous solubility. Thermal rework and hot recycling introduce additional pathways. Studies simulating reclaimed asphalt reprocessing (heating to about 150–200 °C) commonly detect volatile or semi volatile fluorinated species in headspace traps and measurable PFAS in condensates for some matrices, indicating partitioning or thermally generated transformation products in the gas phase (Christensen & Calkins, 2023; Minucci et al., 2024; Alam & Chen, 2025). The literature emphasizes that full decomposition or mineralization of most PFAS classes requires substantially higher temperatures under controlled conditions and that intermediate thermal regimes can produce condensable fluorinated by products unless gas phase abatement and condensate capture are implemented (Christensen & Calkins, 2023; Minucci et al., 2024; Alam & Chen, 2025). These mechanisms create distinct control needs for particle bound versus gas phase pathways and explain operational emission patterns reported in field studies.

Table 5 — Mass-balance examples before and after recycling operations

Operation	Feed mass (kg)	Fine fraction (%)	Representative change in PFAS (enrichment factor in fines)	Worker exposure / emissions concern	Replicates / sample protocol	Source / citation(s)
Milling (RAP)	1,000	5–15%	fines 2–5×PFAS vs feed	High dust; inhalation risk if uncontrolled	multiple grab composites; air monitoring during operation	(Minucci *et al*., 2024).
Hot recycling (asphalt plant)	1,000	n/a	some volatile fraction detected in traps; condensate PFAS measurable	Emission control required; potential stack emissions	headspace traps + condensate capture per event (n≥2)	(Christensen & Calkins, 2023).
Crushing (mixed C&D)	1,000	10–25%	metals concentrate in fines; PFAS variable	Dust control important	mass-balance: feed vs fraction analysis (n=3)	(Alam & Chen, 2025).

Indicates what enrichment factor means and points to worker exposure/emission rows for operational controls. Abbreviations: RAP = reclaimed asphalt pavement; kg = kilogram; % = percent; n/a = not applicable.

Environmental pathways, dominant exposures by end-use and monitoring linkages

Synthesis of pathway analyses across the dataset indicates that dominant exposure routes are scenario-dependent. Unencapsulated fill applications near shallow groundwater are dominated by leachate-to-groundwater pathways; product use in surface layers or paved applications tends toward surface runoff and particulate resuspension as primary export vectors (Battisti et al., 2025). On-site processing and milling areas are characterized predominantly by particulate (dust) pathways with occupational and nearfield receptor relevance, whereas thermal rework elevates the importance of gas-phase emissions and condensate handling (Table 6, Table 7; Figure 2) (da Costa et al., 2025;Rawat et al., 2025).

Monitoring approaches reported in the literature reflect these pathway priorities: lysimeters and monitoring wells are reported where groundwater exposure is a concern; settle plates, personal and area air sampling are used for dust and occupational exposure; headspace traps and stack sampling are reported for thermal/emission assessment (Table 6). Where studies reported cross-linked monitoring (e.g., paired lysimeter + surface runoff + dust sampling), stronger attribution of source pathways to measured environmental outcomes was possible, while single-matrix studies often left pathway attribution ambiguous. The variability in monitoring designs observed in the literature influences the interpretive power of many site studies and explains disparate conclusions concerning dominant pathways across similar material classes (da Costa et al., 2025; Battisti et al., 2025; Rawat et al., 2025).

Table 6 — Field monitoring plan, frequencies and action triggers

Monitoring parameter	Initial frequency (first 6–12 months)	Long-term frequency	Action trigger (example)	Immediate response action	Source / citation(s)
Lysimeter leachate PFAS (ng/L)	Weekly → Monthly	Quarterly	Any individual PFAS > jurisdictional investigation level (state/jurisdiction & date must be recorded)	Investigate source; containment / treatment; increase sampling density	(da Costa et al., 2025; Battisti *et al*., 2025; Rawat et al., 2025).
Surface runoff (event) PFAS (ng/L)	Every runoff event sampled (first 3 months)	Event-based / storm-triggered	PFAS exceed screening benchmark for receiving water	Stabilize source; sample upstream/downstream; notify stakeholders	(da Costa et al., 2025; Battisti *et al*., 2025; Rawat et al., 2025).
Settled dust (ng/g)	Monthly (processing areas)	Quarterly	Dust PFAS or metals above occupational screening	Review dust suppression, PPE, work practices	(da Costa et al., 2025; Battisti *et al*., 2025; Rawat et al., 2025).
Ambient air (thermal events) (ng/m³)	Per thermal event (near-stack & nearfield)	Event-based	Stack/nearfield PFAS detection above action level	Stop operation; implement abatement; capture condensate	(da Costa et al., 2025; Battisti *et al*., 2025; Rawat et al., 2025).
Product leach (runoff from installed recycled product)	Pre-installation; 1 month; 3 months	Annual/biannual	Product leach PFAS > reuse guideline	Re-assess use, consider encapsulation or removal	(da Costa et al., 2025; Battisti *et al*., 2025; Rawat et al., 2025).

Clarifies monitoring matrices and practical action thresholds used as examples. Abbreviations: PFAS = per- and polyfluoroalkyl substances; ng/L = nanograms per liter; ng/g = nanograms per gram; ng/m³ = nanograms per cubic meter.

Table 7 — Relative importance of exposure pathways by end use

End use / scenario	Dominant pathway(s)	Relative risk ranking (High / Moderate / Low)	Primary receptor(s)	Recommended monitoring matrix	Source / citation(s)
Unencapsulated fill near shallow groundwater	Leachate→ groundwater	High	Groundwater users, aquatic receptors	Lysimeter porewater (ng/L); monitoring wells	(Battisti *et al.*, 2025).
Encapsulated structural use (concrete with RCA)	Diffusion-limited leaching; long tail	Low–Moderate	Future groundwater / long-term leach	Monolith leach; long-term porewater sampling	(Battisti *et al.*, 2025).
On-site milling / processing area	Dust inhalation; fugitive particulates	Moderate–High	Workers, nearby residents	Settled dust (ng/g), personal air sampling (ng/m³)	(da Costa *et al.*, 2025).
Thermal rework (asphalt heating)	Air emissions; condensate	Moderate	Workers; nearfield air receptors	Stack traps; condensate analysis; nearfield air	(Rawat *et al.*, 2025).

Explains the risk ranking column and recommended monitoring matrix shorthand. Abbreviations: PFAS = per- and polyfluoroalkyl substances; OEL = occupational exposure limit (where referenced); ng/g, ng/L as above.

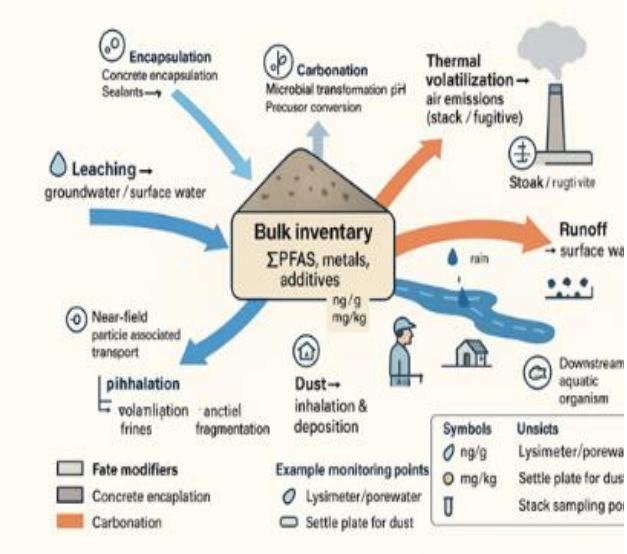

Figure 2 — Conceptual contaminant fate and exposure pathways for recycled construction and demolition (C&D) materials (da Costa et al., 2025; Battisti et al., 2025; Rawat et al., 2025).

Schematic elements: central block = Bulk inventory (ΣPFAS, metals, additives, polymers); colored arrows = primary release pathways (Leaching, Runoff, Dust, Thermal volatilization) and their pathway endpoints. Fate modifiers shown as small callouts (encapsulation, carbonation, microbial transformation, temperature/aging, physical fragmentation); receptor icons indicate likely exposed targets (worksite worker, drinking-water well, downstream aquatic organism); inset shows monitoring points. Abbreviations — ΣPFAS = sum of per- and polyfluoroalkyl substances (PFAS); PFAS = per- and polyfluoroalkyl substances; ng/g = nanograms per gram; mg/kg = milligrams per kilogram; lysimeter/porewater = porewater sampling; settle plate = dust deposition sampler; stack port = stack sampling port.

Risk characterisation and regulatory comparisons (jurisdictional specificity and uncertainty)

Comparisons of measured concentrations to regulatory or advisory benchmarks in the reviewed literature revealed substantial jurisdictional heterogeneity and rapid evolution of standards. Example screening comparisons in Table 8 illustrate how the same measured leachate concentration can be below one jurisdiction's drinking-water advisory yet exceed another jurisdiction's more conservative reuse threshold. Representative jurisdictional values cited within the review include example drinking-water advisories and national or sub-national soil/reuse guidance (Table 8 lists guideline name, jurisdiction and date for each comparison used) (Longendyke et al., 2022; Bayram & Greiff, 2023; Winchell et al., 2024).

Uncertainty arises from multiple sources: differing target analyte lists and MDLs across laboratories, inconsistent use of TOP assay results (precursor pools), differing receptor assumptions (drinking water vs soil reuse vs occupational), and temporal heterogeneity (short-term snapshots versus long-tail release). The literature documents approaches to address these uncertainties (e.g., use of conservative exposure assumptions or application of safety factors), but practices are not standardized across jurisdictions or studies (Longendyke et al., 2022; Bayram & Greiff, 2023; Winchell et al., 2024). The net effect is that risk characterisation of similar measured concentrations can lead to divergent management implications depending on which guideline, receptor model and uncertainty allowances are applied.

Table 8: Risk screening vs guideline thresholds

Matrix	Typical measured	Example guideline (Jurisdiction)	Exceedance?	Uncertainty	Citation(s)

Leachate (RAP)	0.5 – 5 $ng \cdot L^{-1}$	4.0 $ng \cdot L^{-1}$ (EPA NPDWR)	Possible	DW standards vs soil	(Bayram & Greiff, 2023)
Soil (stockpile)	10 – 1,000 $ng \cdot g^{-1}$	0.001–0.01 $mg \cdot kg^{-1}$	Likely	MDLs vary	(Longendyke *et al*., 2022)
Ambient dust	$ng \cdot g^{-1}$ – $\mu g \cdot g^{-1}$	No universal PFAS OEL	Unclear	Manage via controls	(Winchell *et al*., 2024)

Clarifies that jurisdictional values and dates must be recorded and that MDL differences affect conclusions. Abbreviations: $ng \cdot L^{-1}$ / ng/L = nanograms per liter; $ng \cdot g^{-1}$ / ng/g = nanograms per gram; $mg \cdot kg^{-1}$ / mg/kg = milligrams per kilogram; DW = drinking water.

Management options — comparative efficacy reported in the literature

The evidentiary base for treatment and mitigation spans bench to field scales and shows matrix dependence in performance. Bench-scale aqueous adsorption (GAC, powdered activated carbon, biochar) frequently attains high removal efficiencies for long-chain ionic PFAS (>90% under optimized conditions), but field applications involving complex solid matrices show diminished and more variable performance owing to competitive sorption and matrix interferences (Peiris et al., 2025). Solvent or water washing and extraction of solids has been reported to reduce the surface-accessible/mobile PFAS fraction with literature-reported reductions of approximately 30–80% of the mobile fraction depending on solvent chemistry, contact time and number of extraction cycles; however, washing generates concentrated liquid residual streams requiring subsequent treatment (Kabiri et al., 2022) (Table 9).

Thermal destruction reported in controlled high-temperature systems can approach near-complete mineralization (>99%) when sufficient temperature, residence time and oxidative conditions are applied; the literature underscores, however, that intermediate thermal regimes can transfer fluorinated mass into condensates and flue streams, producing secondary waste streams that demand management (Kabiri et al., 2022; Loganathan et al., 2025). Solidification and encapsulation are frequently reported as containment strategies for metals and some organics, but the literature consistently indicates these do not destroy PFAS and provide variable long-term containment depending on binder chemistry and environmental aging (Peiris et al., 2025). The heterogeneity of reported operational parameters (contact times, operating temperatures, sorbent doses) limits direct comparability of efficacy across studies, but Table 10 presents collated efficacy ranges and the associated secondary streams documented in the reviewed literature.

Table 9: Treatment technologies and efficacy

Technology	PFAS efficacy	Byproducts	Cost/Complexity	Limitations	Citation(s)

Washing/Extraction	30% – 80%	Liquid concentrate	Mod–High	Limited for precursors	(Kabiri *et al*., 2022; Loganathan *et al*., 2025; Peiris *et al*., 2025).
Adsorption (GAC)	>90% (aqueous)	Spent sorbent	Moderate	Low efficacy for solids	(Kabiri *et al*., 2022; Loganathan *et al*., 2025; Peiris *et al*., 2025).
Thermal Destruction	>99%	Flue gas; condensate	High	Use for PFAS-rich concentrates; ensure flue gas/condensate controls	(Kabiri *et al*., 2022; Loganathan *et al*., 2025; Peiris *et al*., 2025).
Encapsulation	Low (PFAS benefit)	Treated solid	Low–Mod	No destruction	(Kabiri *et al*., 2022; Loganathan *et al*., 2025; Peiris *et al*., 2025).

Treatment technologies with reported efficacy ranges, typical secondary streams and key limitations for solids and liquids.
Abbreviations: GAC = granular activated carbon; AOP = advanced oxidation process

Integration of monitoring, decision frameworks and LCA evidence

Multiple conceptual decision frameworks reported in the literature link screening outcomes to management pathways, and some studies integrate life cycle assessment (LCA) elements to compare reuse benefits with contaminant management burdens. Typical decision pathways follow a tiered approach: initial screening, targeted characterization including TOP or column tests, then selection of treatment or containment options with monitoring feedback loops to reassess decisions after implementation (Figure 3) (Vo et al., 2023; Brown et al., 2024; Liu et al., 2024). LCA results indicate that energy intensive options such as high temperature thermal destruction may negate greenhouse gas benefits of reuse unless applied selectively to concentrated PFAS fractions, whereas lower energy containment or targeted pretreatment combined with monitoring can preserve net environmental benefits under specific boundary conditions (Vo et al., 2023; Brown et al., 2024; Liu et al., 2024). Empirical studies that combine monitoring data, treatment performance metrics and LCA outcomes are limited but informative; they illustrate tradeoffs among contamination reduction, secondary waste

generation and net lifecycle impacts. The literature therefore supports conditional decision pathways in which monitoring data guide the selection and intensity of management responses, and it emphasizes the need to anchor threshold values to jurisdictional benchmarks and to update decisions as monitoring or regulatory conditions evolve (Vo et al., 2023; Brown et al., 2024; Liu et al., 2024).

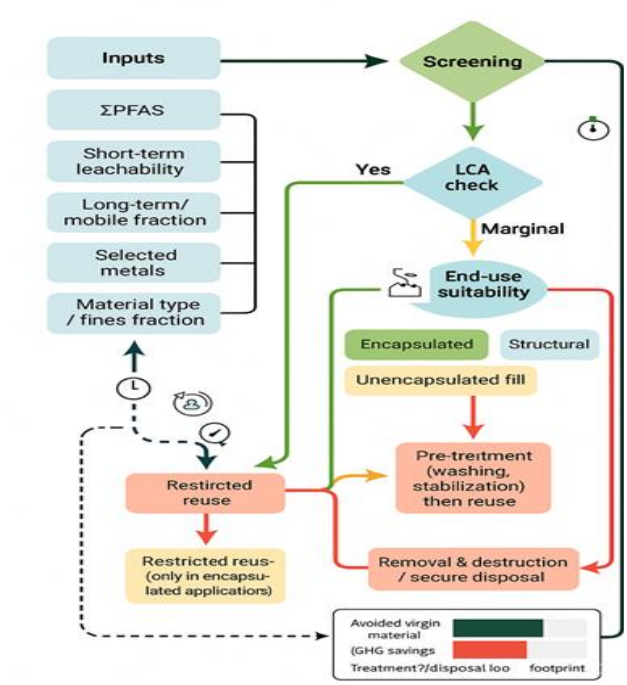

Figure 3 — Decision flowchart for safe reuse of recycled C&D materials (LCA +contaminant screening) (Vo et al., 2023; Brown et al., 2024; Liu et al., 2024).

ΣPFAS = sum of measured per- and polyfluoroalkyl substances (PFAS); LCA = life-cycle assessment. Encaps. = encapsulation (engineering sealing or coating); GHG = greenhouse-gas emissions. Leachability = short-term aqueous leaching potential; Mobile fraction = proportion of contaminants likely to migrate under environmental conditions.

CONCLUSION

This review demonstrates that recycled construction and demolition materials can contain measurable PFAS and heavy metals whose distribution depends on material type and processing history. Textile derived products and fine fractions frequently show the highest burdens and represent likely pathways for environmental release and human exposure. Short term leaching tests often understate the extended, diffusion limited release observed in column and monolith experiments, highlighting the need for prolonged monitoring. Thermal rework and milling create additional mobilization pathways, including gas phase transformation products and particulate emissions that require systematic characterization. Treatment technologies can be effective when tailored to specific matrices, but washing and adsorption approaches concentrate contaminants into residual streams that require managed disposal. Decision frameworks should adopt a tiered approach that integrates initial screening, targeted characterization, and monitoring informed feedback to guide reuse decisions. Major knowledge gaps include inconsistent analyte suites, variable detection limits, scarce field data over decadal time scales, and limited understanding of thermal transformation products. Future research should prioritise harmonized reporting standards, coordinated monitoring across multiple matrices and long term field studies that link laboratory results to real world outcomes. Operational studies on recycling controls, exposure reduction for workers and communities, and economically viable treatment pathways are also required. Applying these recommendations will strengthen the evidence base for safe, resource efficient reuse of recycled construction and demolition materials while protecting human health and the environment.

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Abbreviations

AFFF — aqueous film-forming foam
C&D — construction and demolition

d.w. — dry weight (sample mass expressed on a dry weight basis)
DW — drinking water
FTOH — fluorotelomer alcohol (mentioned as a precursor class)
GC–MS/HRMS — gas chromatography–mass spectrometry / high resolution mass spectrometry (HRMS referenced as non-target screening)
HC (°C) — degrees Celsius (used when reporting thermal conditions)
LC–MS/MS — liquid chromatography with tandem mass spectrometry
LEAF — Leaching Environmental Assessment Framework (LEAF-type batch leach tests)
L/S — liquid to solid ratio
MDL / MDLs — method detection limit(s)
n — sample count or number of replicates
NPDWR — National Primary Drinking Water Regulation (EPA)
OEL — occupational exposure limit
PFAA / PFAAs — perfluoroalkyl acid(s)
PFAS — per- and polyfluoroalkyl substances
PFCAs — perfluoroalkyl carboxylates
PFSAs — perfluoroalkyl sulfonates
PRISMA — Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRISMA-S — PRISMA extension for reporting literature search methods (PRISMA-S)
RAP — reclaimed asphalt pavement
RCA — recycled concrete aggregate
QA/QC — quality assurance / quality control
SD — standard deviation
TENAX — Tenax (Tenax TA) adsorbent (trap media for headspace/thermal tests)
TOC — total organic carbon
TOP assay — Total Oxidizable Precursor assay (used to estimate precursor pools)
µg/g — micrograms per gram
mg/kg — milligrams per kilogram
ng/g — nanograms per gram
ng/L — nanograms per liter
ng/m³ — nanograms per cubic metre
XAD — XAD polymeric resin (adsorbent used in headspace/trap sampling)
Chemical element symbols used in the manuscript
Pb — lead; Cd — cadmium; Cr — chromium; Hg — mercury; Ni — nickel; Cu — copper; Zn — zinc.

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