

Biochar reduces PFAS mobility in contaminated soils: a global meta- analysis

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Abstract

Biochar is increasingly proposed for immobilising per- and polyfluoroalkyl substances (PFAS) in contaminated soils, yet the magnitude, chemical controls and context dependence of its effects have not been quantitatively resolved. We systematically reviewed and synthesised 20 eligible independent studies; 18 contributed quantitative evidence, and 16 contributed to the primary mobility synthesis. The compound-resolved database contained 598 exact biochar-control contrasts from 14 studies, but inference was study-balanced to avoid pseudo-replication. Across 16 independent studies, biochar reduced PFAS mobility by a median of 58.2% (95% distribution-free interval 34.7–90.5%). Effect magnitude nevertheless varied widely among studies. Molecular structure provided the clearest mechanism: long-chain PFAS ($\geq C8$ PFCAs and $\geq C6$ PFSAAs) showed a 30.8% lower treatment/control mobility ratio than short-chain PFAS (11/12 studies; $p = 0.006$), with each additional carbon atom corresponding to an 8.3% lower ratio. Soil total organic carbon (TOC) was the strongest secondary matrix signal, with negative within-study slopes in 7/7 studies ($P = 0.0156$), whereas biochar dose, pyrolysis temperature and experimental system showed no robust associations (all $P \geq 0.315$). Evidence of secondary outcomes—the amount of PFAS retained or accessible in soil and its transfer to plants—remained sparse. Biochar therefore shows consistent potential to reduce PFAS mobility, but performance depends strongly on PFAS chemistry and soil context.

Introduction

Per- and polyfluoroalkyl substances (PFAS) are highly persistent environmental contaminants whose widespread use and resistance to complete degradation have resulted in contamination of soils through sources including aqueous film-forming foams, industrial releases, contaminated irrigation water, and land-applied biosolids. Their global occurrence and extraordinary environmental persistence have been recognised for more than two decades (Giesy & Kannan, 2001). PFAS encompass a broad structural and chemical universe; under the revised OECD definition, they include fluorinated substances containing at least one fully fluorinated methyl or methylene carbon atom ($-CF_3$ or $-CF_2-$, with specified exceptions), extending beyond the earlier definition of Buck et al. (2011) (OECD, 2021; Wang et al., 2021). Once present in soil, PFAS can migrate to groundwater, remain available for plant uptake, and enter terrestrial food chains, while their diverse physicochemical properties cause substantial differences in mobility among individual compounds.

Remediation of PFAS-contaminated soil therefore remains particularly challenging because destructive or extractive technologies such as thermal treatment and soil washing can be energy- and resource-intensive and may substantially alter soil physical, chemical and biological properties. In this context, soil-preserving in situ stabilisation approaches are particularly relevant because they can reduce contaminant mobility while avoiding excavation and intensive processing of the soil matrix. Biochar has emerged as a promising material for in situ PFAS stabilisation because it can be produced from renewable or residual biomass, modified to enhance sorption properties, and potentially applied at soil-relevant amendment rates (Liang et al., 2024; Pan et al., 2026; Skjennum et al., 2025; Wang et al., 2025).

The effectiveness of biochar is unlikely to be uniform across PFAS compounds, soils, or biochar materials. PFAS sorption to carbonaceous surfaces is governed by a combination of affinity-related interactions, including hydrophobic interactions, London dispersion forces, electron donor–acceptor interactions, electrostatic interactions, surface functional groups and cation bridging, together with capacity-related factors such as accessible pore volume and pore-size distribution (Kim et al., 2024; Lu & Na, 2024). Early mechanistic work demonstrated that PFAS sorption to sediments varies systematically with molecular structure and matrix properties, including organic carbon content (Higgins & Luthy, 2006), a pattern subsequently reinforced across a broader range of soils and sediments (Li et al., 2018).

These mechanisms are strongly influenced by PFAS molecular structure. Longer-chain PFAS generally show stronger affinity for carbonaceous sorbents because their larger fluorinated tails provide stronger hydrophobic and dispersion interactions, which can offset electrostatic repulsion between anionic headgroups and negatively charged biochar surfaces (Liang et al. 2025). For short-chain PFAS, these tail-driven interactions are weaker, making retention more dependent on electrostatic interactions and specific surface chemistry (Pan et al., 2026; Wang et al., 2025). Biochar properties—including pore architecture, accessible surface area, activation, and surface chemistry—may consequently influence performance, while soil organic carbon, contamination history, and hydrological conditions can further modify sorption and transport. Recent experiments across batch systems, soil columns, lysimeters, and soil–plant systems illustrate this strong context dependence (Fu et al., 2025; Holly et al., 2024; Hubert et al., 2025; Skjennum et al., 2026; Sørmo et al., 2024).

Despite the rapidly expanding experimental literature, the evidence base remains difficult to generalise quantitatively. Recent reviews have synthesised PFAS–biochar sorption mechanisms, modification strategies, and remediation applications and have repeatedly highlighted short-chain PFAS, long-term stability, and environmentally realistic soil conditions as major unresolved issues (Liang et al., 2024; Pan et al., 2026; Skjennum et al., 2025; Wang et al., 2025). However, the primary soil literature is highly unbalanced: individual studies frequently report many PFAS compounds, biochar treatments, doses, soils, and sampling times while containing only a small number of truly independent experimental units. Treating these treatment-by-compound observations as independent evidence would therefore substantially overstate statistical precision. Therefore, the large number of extracted PFAS treatment contrasts should not be confused with the much smaller number of independent studies available for statistical inference.

To address this gap, we conducted the first global meta-analysis of experimental biochar applications to PFAS-contaminated soils. Unlike previous reviews, which have primarily synthesised PFAS–biochar sorption mechanisms, material modification strategies and remediation applications qualitatively, our study quantitatively evaluates the magnitude and consistency of biochar effects on PFAS mobility and tests whether these effects vary systematically with PFAS molecular structure, soil properties and biochar-treatment characteristics (Liang et al., 2024; Pan et al., 2026; Wang et al., 2025). Throughout the synthesis, the independent study rather than the individual PFAS treatment contrast was retained as the inferential unit. We addressed three questions: (1) How strongly and consistently does biochar reduce

PFAS mobility in contaminated soils? (2) Does PFAS molecular structure—particularly chain class, carbon number and headgroup—systematically control the magnitude of immobilisation? (3) To what extent is biochar performance associated with feedstock, amendment dose, production conditions, soil organic carbon, contamination regime, and experimental system? Secondary evidence for soil retention/accessibility and plant uptake/bioavailability was evaluated separately to determine whether reduced mobility was accompanied by consistent changes in other remediation-relevant endpoints.

Results

Evidence base and analytical coverage

The systematic review identified 20 eligible studies evaluating biochar in PFAS-contaminated soils, of which 18 contributed quantitative evidence and 16 contributed to the primary mobility synthesis. Within the 16-study mobility synthesis, 15 studies provided exact study-level point estimates, and one contributed an interval-censored estimate. Only six studies reported or allowed recovery of treatment-level variance with sufficiently defensible experimental replication for the conventional variance-weighted mobility core. Across the 14 studies with exact terminal PFCA/PFSA data, the compound-resolved chemistry dataset contained 598 biochar-control effect-size rows. These rows were never treated as independent observations; they were collapsed to Study x PFAS summaries, paired contrasts or study-specific slopes before cross-study inference. PFAS coverage spanned terminal PFCAs and PFSA, ether PFAS and several precursors, but was uneven across studies (Table 1). This reporting asymmetry motivated a prespecified evidence hierarchy in which the independent study, rather than the individual PFAS contrast, remained the inferential unit.

Table 1
Study-level PFAS coverage and chemical classes represented in the evidence base

Study	PFAS scope/compounds represented	Class/type represented	Chain representation
Kupryianchyk et al. (2016)	PFOS, PFOA, PFHxS plus site PFAS	PFCA; PFSA	Short + long
Silvani et al. (2019)	Multiple PFAS; PFOS, PFHxS, PFOA and PFHxA emphasised	PFCA; PFSA	Short + long
Askeland et al. (2020)	PFOS, PFOA, PFHxS, PFHxA	PFCA; PFSA	Short + long
Sørmo et al. (2021)	22 analysed; focal PFBS, PFHxS, PFOS, PFBA, PFHxA, PFOA	PFCA; PFSA	Short + long
Zhang & Liang (2022a)	PFBS, PFHxA, HFPO-DA, PFHpA, PFHxS, PFOA, PFNA, PFOS, PFDA, PFUnDA	PFCA; PFSA; ether PFAS	Short + long + ether
Zhang & Liang (2022b)	10 PFAS + Σ PFAS; PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFBS, PFHxS, PFOS, HFPO-DA	PFCA; PFSA; ether PFAS	Short + long + ether
Navarro et al. (2023)	Up to 28 PFAS; PFHxS, PFOS and PFOA emphasised	PFCA; PFSA; precursors/other	Short + long + precursors
Kabiri et al. (2023)	Multiple AFFF-associated PFAS	Mixed terminal PFAS	Mixed
Sørmo et al. (2024)	39 targets; 10 focal PFAS; PFOS dominant	PFCA; PFSA; precursors/other	Short + long + precursors
Holly et al. (2024)	28 measured; 15 analytes in exact flow-weighted table	PFCA; PFSA; precursors/other	Short + long + precursors
Openiyi et al. (2025)	52 monitored; 24 exact compound mass-balance contrasts	PFCA; PFSA; precursors/other	Short + long + precursors
Battisti et al. (2025)	13 PFAS targeted	Mixed terminal PFAS	Mixed
Jiang et al. (2025)	PFHxA, PFHpA, PFOA, PFNA, PFBS, PFHxS, PFOS, HFPO-DA	PFCA; PFSA; ether PFAS	Short + long + ether
Fu et al. (2025)	PFOA	PFCA	Long

Note: PFAS scope reflects explicitly reported panels and/or focal compounds used in each study. Broad-panel studies may include additional analytes not listed individually here. Full study characteristics are provided in Table S2 and compound definitions in Table S13.

Study	PFAS scope/compounds represented	Class/type represented	Chain representation
Hubert et al. (2025)	18 targets: 11 PFCAs, PFBS/PFHxS/PFOS, 4:2/6:2/8:2 FTS and FOSA	PFCA; PFSA; fluorotelomer/PFSA precursors	Short + long + precursors
Xin et al. (2025)	14 PFAS; PFOA, PFNA and PFDA emphasised in aged-soil remediation	PFCA-dominant mixed PFAS panel	Primarily long-chain focal PFAS
Kabiri et al. (2026)	28 targets; 16 detected PFAS emphasised	Mixed PFAS panel	Mixed
Zhang et al. (2026)	PFBA, PFOA	PFCA	Short + long
Hu et al. (2026)	PFOA	PFCA	Long
Skjennum et al. (2026)	Σ27 PFAS plus precursors	PFCA; PFSA; precursors	Short + long + precursors
Note: PFAS scope reflects explicitly reported panels and/or focal compounds used in each study. Broad-panel studies may include additional analytes not listed individually here. Full study characteristics are provided in Table S2 and compound definitions in Table S13.			

Biochar consistently lowers PFAS mobility

Across the 16-study all-evidence synthesis, every independent study estimate or admissible interval was benefit-aligned. The interval-aware median corresponded to a 58.2% reduction in PFAS mobility relative to unamended soil (benefit-aligned $\ln RR = 0.871$), with a conservative distribution-free 95% median interval equivalent to 34.7–90.5% lower mobility and an exact sign-test $P = 3.05 \times 10^{-5}$ (Fig. 1a). Excluding the interval-censored study yielded a similar median reduction, confirming that the primary result was not sensitive to its inclusion (Table 2). Primary and sensitivity estimates are summarised in Table 2.

Table 2
Magnitude and robustness of biochar effects on PFAS mobility in contaminated soils

Analysis	Studies included	Benefit-aligned lnRR (95% CI)	Back-transformed interpretation	Statistical support
Overall PFAS mobility – primary	16 studies (15 exact estimates + 1 bounded estimate)	0.871 (0.426–2.355)	58.2% lower mobility; median interval 34.7–90.5% lower	All 16 studies benefit-aligned; exact sign test $P = 3.05 \times 10^{-5}$
Exact-point sensitivity	15 studies with exact estimates	0.968 (0.464–2.355)	62.0% lower mobility; 37.1–90.5% lower	All 15 studies benefit-aligned; exact sign test $P = 6.10 \times 10^{-5}$
Variance-supported REML + Hartung–Knapp	6 studies with usable experimental variance	2.350 (–0.461 to 5.162)	90.5% lower point estimate; CI ranges from 58.6% higher to 99.4% lower mobility	$P = 0.084$; $\tau^2 = 7.09$; $I^2 = 99.8\%$
Multilevel REML + CR2	Same 6 variance-supported studies	2.431 (–0.337 to 5.199)	91.2% lower point estimate; CI ranges from 40.0% higher to 99.4% lower mobility	$P = 0.073$; total $\tau^2 = 11.88$
Replicated missing-variance sensitivity	8 replicated studies (variance imputed for 2)	1.847 (–0.196 to 3.891)	84.2% lower point estimate; 95% CI crosses the null	$\tau^2 = 5.89$; $I^2 = 99.8\%$
Long-chain vs short-chain PFAS	12 studies with paired short/long-chain data	0.369 (0.305–0.638)	30.8% lower mobility ratio for long-chain PFAS; 26.3–47.2%	Long-chain response stronger in 11/12 studies; exact sign test $P = 0.006$
Carbon-number gradient	12 studies with eligible carbon-number gradients	0.0863 per + 1 C (0.0183–0.2062)	8.3% lower mobility ratio per additional carbon atom; 1.8–18.6%	Positive gradient in 11/12 studies; exact sign test $P = 0.0063$
Note: Benefit-aligned lnRR > 0 denotes lower PFAS mobility under biochar. Percentage translations use $(100 \times [1 - \exp(-B)])$. Confidence intervals are distribution-free for the study-level median and conventional model-based intervals for variance-supported analyses. τ^2 and I^2 apply only to variance-supported random-effects analyses.				

The variance-supported core, restricted to the six studies with usable experimental variance, produced a larger point estimate but substantially greater uncertainty than the broader 16-study synthesis. In these six studies, REML with Hartung–Knapp inference estimated a benefit-aligned lnRR of 2.350 (95% CI –0.461 to 5.162), equivalent to a 90.5%-point reduction in mobility. Heterogeneity was, however, extreme ($\tau^2 = 7.09$; $I^2 \approx 99\%$), and the prediction interval crossed the null widely when only considering these six studies. Expanding this core to eight genuinely replicated studies through multiple imputation of missing

variance changed uncertainty but not observed point effects and gave a pooled lnRR of 1.847 (95% CI – 0.196 to 3.891; 84.2%-point reduction). The agreement in direction between the broad 16-study synthesis and these smaller variance-supported sensitivity models supports a robust mobility-reduction signal, while the wide variation in effect size shows that the magnitude of benefit differs substantially among study contexts. Compound-specific study-balanced medians also showed substantial heterogeneity (Fig. 1b). The 598 exact compound-resolved effect-size rows represented substantial analytical density, but multiple treatments within the same study did not provide additional independent replication. Accordingly, observations were first collapsed to one value per Study x PFAS combination so that studies reporting more treatments did not contribute disproportionate weight to the analysis. The resulting pattern motivated explicit within-study tests of PFAS molecular structure rather than analysing all compound-level observations together across studies, which would have treated dependent observations as if they were independent (Fig. S5).

PFAS molecular structure

PFAS chain length was the clearest and most reproducible mechanistic moderator. The continuous carbon-number analysis showed that mobility reduction strengthened progressively with increasing PFAS chain length: headgroup-adjusted slopes were positive in 11 of 12 independent studies, with a median slope of 0.086 benefit-lnRR units per additional carbon atom (exact 95% median CI, 0.018–0.21; exact sign-test $P = 0.0064$; Fig. 2b). This corresponds to an 8.3% lower treatment/control mobility ratio for each additional carbon atom. The complementary binary analysis showed the same pattern: in 12 studies containing both short- and long-chain PFAS under matched experimental contexts, long-chain compounds showed stronger mobility reduction in 11 studies, with a median treatment/control mobility ratio 30.9% lower than for short-chain PFAS (exact sign-test $P = 0.0064$; Fig. 2a).

Headgroup provided weaker evidence. Across 12 paired studies, PFSA responses exceeded PFCA responses in nine studies, with a median PFSA-minus-PFCA contrast of 0.37 benefit-lnRR units, but the exact sign test was not statistically robust ($P = 0.15$). PFAS class was therefore retained as a suggestive modifier rather than a primary mechanistic conclusion.

Soil and treatment context shape observed responses

Among the secondary continuous moderators, soil total organic carbon (TOC) showed the strongest evidence of systematic effect modification. Across 12 study-level medians, biochar benefit declined as soil TOC increased (Spearman $\rho = -0.55$, $P = 0.064$; Fig. 3c). More importantly, all seven studies that contained sufficient internal TOC variation showed negative within-study slopes (7/7; exact sign-test $P = 0.016$), indicating that the TOC pattern was not driven solely by the extremely high-TOC study. This pattern is consistent with attenuation of the incremental benefit of added biochar in carbon-rich matrices, but the cross-study association is observational and should not be interpreted as a causal

threshold or universal TOC response function. The evidence structure and numerical results for all main moderators are summarised in Table S14.

Biochar dose showed a weak positive cross-study association with mobility reduction ($k = 11$; $\rho = 0.33$, $P = 0.31$; Fig. 3b). Four studies supported within-study dose slopes, and all four were positive, although the exact sign test remained underpowered ($P = 0.12$). Pyrolysis temperature showed no consistent association ($k = 11$; $\rho = -0.11$, $P = 0.74$; Fig. 3d), and within-study directions were evenly split (2/4 positive; $P = 1.00$). The absence of an overall temperature association should be interpreted cautiously because pyrolysis temperature is intertwined with feedstock, reactor conditions and other production characteristics that were not sufficiently balanced across studies for independent evaluation. Feedstock categories were also too unevenly represented for robust independent-study comparison, so feedstock-specific temperature effects cannot be excluded. The result therefore argues only against treating nominal pyrolysis temperature alone as a reliable cross-study predictor of PFAS immobilisation (Sørmo et al., 2024).

Contextual comparisons suggested, but did not establish, differences among contamination histories and experimental systems. Introduced contamination showed a larger median benefit than native/legacy contamination ($k = 15$ exact studies; introduced-minus-native median contrast = 1.41 benefit-lnRR units; exact permutation $P = 0.096$; Fig. 3e). Column/lysimeter studies also showed a positive median contrast relative to batch/stabilization studies ($k = 12$; contrast = 0.408; $P = 0.481$; Fig. 3f), although this difference was not statistically robust (Hubert et al 2025; Sørmo et al 2024). All comparisons are naturally confounded by study design, biochar choice, PFAS composition and soil properties and are interpreted only as contextual descriptors.

Study-by-compound response architecture

Figure 4 | Study-level PFAS response architecture. The heatmap is derived from 598 exact compound-resolved biochar-control effect-size rows from 14 studies, collapsed to one median response for each independent Study x PFAS combination before plotting. Red indicates lower PFAS mobility with biochar, blue indicates higher mobility, and grey indicates no exact compound-resolved estimate. PFCA and PFSA are separated into short- and long-chain groups. The colour scale is capped at $\pm 100\%$ for display. Statistical annotations summarise independent-study tests (long vs short $P = 0.006$; carbon-number trend $P = 0.006$; PFSA vs PFCA $P = 0.146$); the heatmap itself is descriptive and does not imply cell-wise significance.

Evidence for soil retention and plant transfer remains sparse

Secondary remediation endpoints were quantitatively recoverable from too few independent studies for a stable cross-study meta-analysis. Soil retention/accessibility had two variance-supported studies, and both study-level estimates were benefit-aligned, whereas plant uptake/bioavailability had two studies

with opposite directions under a stabilisation objective. One study showed an approximately 98.6% reduction in plant transfer, while another showed an approximately 81.1% increase in plant uptake/transfer. Greater plant uptake indicates poorer contaminant immobilisation under an in-situ stabilisation objective, although it could be favourable where deliberate phytoextraction is the management goal. These endpoints were therefore kept separate from the mobility synthesis and reported as study-specific Supplementary evidence rather than pooled into a headline effect.

Discussion

A robust directional effect despite substantial variation in magnitude

Biochar showed a marked and consistent directional effect across the evidence base, but the magnitude of immobilisation was strongly context dependent. This variability is mechanistically plausible because PFAS retention by biochar reflects the combined influence of molecular structure, sorbent properties, soil matrix characteristics and experimental conditions rather than a single amendment effect. The larger effects observed in the variance-supported subset should therefore be viewed as a feature of the studies represented in that smaller evidence set, rather than as a more general estimate of biochar performance. Overall, the evidence supports biochar as a consistently beneficial immobilisation strategy while indicating that its effectiveness must be interpreted in the context of the specific PFAS–soil–biochar system.

Molecular size emerges as the dominant mechanistic control

The strongest mechanistic result was the dependence of biochar performance on PFAS carbon number. The binary long-versus-short comparison and the continuous carbon-number analysis were constructed differently, yet both showed stronger immobilisation with increasing molecular size in 11 of 12 independent studies. The continuous analysis is especially informative because it does not depend on an arbitrary chain-class boundary: after accounting for headgroup, each additional carbon atom was associated with an 8.3% lower treatment/control mobility ratio (Fig. 2b). The available evidence does not, however, support a discrete carbon-number threshold below which biochar immobilisation becomes ineffective, because effect magnitude remained strongly context-dependent across compounds and studies.

The compound-specific results provide a useful view of this pattern. Among PFAS represented by at least six independent studies, the largest study-balanced median reductions occurred for PFOS (79.3%), PFHpS (76.2%) and PFHxS (71.7%), while PFOA showed a median reduction of 62.1% (Table S8). In contrast, several shorter-chain compounds showed substantially weaker responses, including PFBA (20.4%), PFPeA (14.0%) and PFHxA (29.6%). The pattern was not perfectly ordered at the individual-compound level - PFHpA, for example, showed a relatively strong response, whereas PFNA and PFDA

exhibited more moderate effects - illustrating why simple comparisons among pooled compound medians are insufficient. The stronger evidence comes from matched within-study contrasts, where soil, biochar and experimental conditions are more comparable. This distinction strengthens the interpretation of carbon number as a molecular control rather than merely a consequence of different compounds being studied under different experimental conditions.

Most studies also investigated PFAS mixtures in which individual compounds occurred at substantially different concentrations. Competitive sorption may therefore contribute to compound-specific responses, as higher-affinity PFAS can preferentially occupy available sorption sites and reduce the retention of lower-affinity compounds (Krahn et al., 2023). Concentration differences may also influence mass transfer into biochar pores, because compounds present at higher porewater concentrations can maintain stronger concentration gradients for diffusion. These effects could not be separated from chain length, headgroup and study context in the present evidence base and therefore remain plausible contributors to the observed heterogeneity.

Mechanistically, increasing perfluoroalkyl chain length strengthens hydrophobic interactions and London dispersion forces, generally increasing PFAS affinity for organic and carbonaceous sorption domains; electron donor–acceptor interactions with π -rich carbonaceous surfaces may provide an additional sorption mechanism (Higgins & Luthy, 2006; Kim et al., 2024; Liang et al., 2024; Lu & Na, 2024; Pan et al., 2026). Biochar introduces additional microporous and carbonaceous sorption domains, while activation can increase accessible porosity within relevant pore-size ranges and alter surface charge and functionality (Skjennum et al., 2025). Short-chain PFAS have weaker tail-driven interactions and are therefore more sensitive to electrostatic repulsion, pore accessibility and competition with dissolved or soil organic matter. This provides a coherent explanation for the wider range of neutral or adverse responses among short-chain compounds in the study-by-PFAS architecture, whereas strong immobilisation was more common among longer-chain PFCAs and PFSA.

Headgroup chemistry appears to modify this molecular-size effect rather than replace it. PFSA responses were stronger than PFCA responses in nine of 12 paired studies, although the contrast was not statistically robust. PFSA generally show somewhat greater hydrophobicity and sorption affinity than PFCAs of comparable chain length, which can contribute to stronger retention on carbonaceous surfaces (Hubert et al., 2024). However, the present evidence does not support headgroup as an independent predictor comparable in strength to carbon number. The concordant long-versus-short and carbon-number results, despite adjustment for headgroup, therefore identify molecular size as the more reproducible chemical control.

The dataset also indicates why a corresponding biochar-property mechanism cannot yet be resolved. Woody biomass was represented in 11 of the 20 studies, whereas sewage-sludge/biosolids, crop-residue and nut-shell biochars were represented less frequently. Unmodified biochar occurred in 18 studies, while activated biochars were evaluated in only a small number of studies and mineral modification in only one. Descriptive within-study comparisons often placed activated or modified materials among the

stronger-performing treatments, including the activated biochars evaluated by Silvani et al. (2019) and Sørmo et al. (2021, 2024), but these comparisons simultaneously differ in pore structure, surface chemistry and sometimes dose. They therefore cannot isolate activation itself as the causal factor. The present synthesis consequently supports a molecular mechanism more strongly than a material-design rule.

This distinction also explains why nominal pyrolysis temperature performed poorly as a moderator. Pyrolysis temperature is a process condition rather than a sorption property: biochars produced at the same temperature can differ substantially in microporosity, mineral content, aromaticity and surface chemistry depending on feedstock and activation history (Skjennum et al., 2025). Conversely, materials produced at different temperatures can possess similar functional sorption domains. Future mechanistic work should therefore prioritise directly measured micropore and mesopore structure, method-specific surface area, surface charge, aromaticity and functional chemistry rather than using production temperature as their surrogate. Carbon number itself should also remain process specific: the absence of a significant chain-length effect in the recent global synthesis of PFAS trophic magnification (Ricolfi et al., 2025) emphasises that the strong gradient identified here pertains to sorption and transport in soil–biochar systems rather than to all PFAS environmental processes.

Soil organic carbon modifies the incremental benefit of biochar

Soil TOC emerged as the most coherent matrix-level moderator. Although the between-study association was only suggestive, all seven studies with sufficient within-study TOC variation showed decreasing biochar benefit as TOC increased. This consistency is important because within-study contrasts reduce confounding by study-specific methodology and amendment choice. Studies containing both low- and high-carbon soil contexts, including Silvani et al. (2019) and Sørmo et al. (2021), also show the same qualitative pattern in the compound-resolved dataset: biochar produced a substantially larger incremental reduction in mobility in the low-carbon mineral soil than in the organic-rich soil.

A plausible explanation is that soils rich in native organic carbon already provide substantial sorption capacity, leaving less additional partitioning capacity to be supplied by biochar (Higgins & Luthy, 2006; Li et al., 2018). Organic-rich matrices may also increase dissolved organic matter, resulting in competitive sorption and restricted accessibility of PFAS to biochar pores. The result therefore does not imply that biochar performs poorly in carbon-rich soils in an absolute sense. Rather, the relative gain over the untreated control may be smaller because background retention is already greater.

Dose affects capacity, but does not provide a universal design rule

The dose evidence is consistent with a capacity-dependent mechanism but remains insufficient for a general quantitative prescription. All four studies with usable within-study dose gradients showed increasing benefit with dose, whereas the between-study association was weak. The compound-resolved

data help explain this difference. Some experiments show clear separation among progressively larger biochar additions, whereas others approach near-complete immobilisation at relatively modest doses, leaving little scope for further improvement. Dose response is therefore likely to depend on the ratio between available sorption capacity and PFAS loading rather than amendment percentage alone.

This also explains why comparing nominal doses among studies is problematic. A 1% amendment of a highly microporous activated material is not functionally equivalent to 1% of a low-surface-area unmodified biochar, and the relevant sorption demand differs with PFAS concentration, chain distribution, soil carbon and competing solutes. Future dose-response experiments would be more informative if amendment rate were normalised to sorption-relevant material properties, particularly the internal surface area and pore volume available within PFAS-accessible pore-size ranges and interpreted alongside contaminant loading rather than as an isolated predictor.

Contamination history and experimental system describe context rather than causal controls

Introduced contamination showed a larger median biochar benefit than native or legacy contamination, but the contrast was not statistically conclusive. This difference is nevertheless mechanistically plausible because contamination ageing can strengthen PFAS association with the soil matrix: penetration of deeper pores gives more strongly retarded diffusion which consequently reduces the readily desorbable contaminant pool. Experimentally spiked PFAS with limited ageing may therefore remain weaker associated with soil and more available for transfer to newly added biochar than PFAS in long-contaminated soils (Zhao et al., 2026).

Similarly, batch and column/lysimeter systems did not differ robustly. This is reassuring in one sense because the directional biochar effect was not confined to static batch experiments. However, agreement in median direction should not imply environmental equivalence. Columns and lysimeters differ from batch tests in hydrological forcing and liquid-to-solid ratio: batch tests often expose soil to a relatively large aqueous volume at once, potentially mobilising a larger PFAS pool, whereas flow-through systems progressively increase the cumulative liquid-to-solid ratio while allowing more time for PFAS desorption, diffusion into biochar pores and sorption to biochar surfaces. The evidence base therefore supports the persistence of the immobilisation signal across experimental scales while remaining too small to quantify how laboratory effects translate to field performance.

Remediation success depends on the endpoint and management objective

Reduced mobility should not be equated automatically with complete remediation. Immobilisation can reduce groundwater transport while leaving PFAS mass in the amended soil, where long-term accessibility, plant uptake and redistribution remain relevant. The two available plant-transfer studies illustrate this distinction particularly clearly: biochar strongly reduced plant transfer in one soil–plant system but increased uptake in another (Fu et al., 2025; Zhang & Liang, 2022b). Under a stabilisation

objective, the latter response is adverse, whereas increased uptake could be useful if deliberate phytoextraction were the management objective.

The scarcity of these secondary outcomes is therefore itself important. Mobility is currently the best-supported endpoint, but long-term remediation claims ultimately require simultaneous evidence for leaching, soil retention, plant transfer and amendment durability. Future experiments should define their intended remediation endpoint explicitly and measure multiple PFAS compartments whenever possible.

Limitations and priorities for the next generation of PFAS–biochar studies

The principal limitation is not the volume of extracted PFAS data but the number and distribution of independent experiments. Only six studies supplied sufficiently defensible variance information for the conventional variance-supported synthesis despite hundreds of compound-level observations. This constrained precision-based meta-analysis and reduced the ability to distinguish among material characteristics.

The evidence base is also geographically and experimentally concentrated. The 20 studies originated from only six countries, with 18 conducted in Norway, the United States, Australia or China (Fig. S6). Nine studies used batch systems and six used columns, whereas only two were field studies, two were greenhouse studies and one used lysimeters. Thus, the global scope of the review reflects the literature search and synthesis rather than geographically balanced field evidence. Caution is warranted when extrapolating to tropical soils, highly weathered soils, different hydrological regimes and regions currently absent from the literature.

Material coverage is similarly uneven. Woody biomass dominated the evidence base, whereas sludge-derived, crop-residue and nut-shell biochars were represented by only a few studies. Activated and chemically or mineral-modified materials were also too sparsely and unevenly distributed for robust comparative inference. Consequently, the absence of a strong feedstock, modification or pyrolysis-temperature moderator should not be interpreted as evidence that these properties are unimportant; the current literature simply does not provide sufficiently balanced independent comparisons.

Future studies would benefit most from more consistent experimental replication and reporting, together with direct characterisation of the biochar properties most relevant to PFAS sorption, particularly pore structure, surface area and surface chemistry. Greater comparability in soil properties, PFAS composition, contamination history and amendment dose would also strengthen cross-study inference. Most importantly, long-duration field experiments that simultaneously track leaching, soil retention and plant uptake are needed to determine whether initial immobilisation persists under realistic environmental conditions.

Conclusion

Across a heterogeneous and methodologically uneven literature, biochar consistently reduced PFAS mobility in contaminated soils, with a conservative all-evidence median reduction of approximately 58%. The most reproducible mechanistic signal was molecular size: long-chain PFAS were immobilised more strongly than short-chain compounds, and mobility reduction strengthened progressively with total carbon number. Soil organic carbon emerged as the strongest secondary matrix control, whereas nominal pyrolysis temperature and broad experimental system did not provide reliable predictive rules. The evidence therefore supports biochar as a promising PFAS-stabilisation intervention while shifting the design question from whether biochar works to which PFAS–soil–biochar combinations deliver durable reductions in mobility. Progress towards that goal will require more comparable experimental designs, broader PFAS panels including precursors and emerging compounds, consistent characterisation of biochar and soil properties, and long-term field studies that track mobility, retention and biological transfer simultaneously.

Methods

Literature search and study selection

The systematic review was reported in accordance with the PRISMA 2020 statement (Page et al., 2021). Scopus, Web of Science Core Collection and Google Scholar were searched using combined terms for biochar, PFAS and soil systems (full search string in the Supplementary Information). The consolidated search set contained 144 records (cutoff 14 June 2026), all of which were screened by title and abstract. A total of 117 records were excluded at this stage, 27 reports were sought for retrieval, one report was not retrieved, 26 reports were assessed at full text, and six were excluded, leaving 20 studies in the systematic review (Fig. S1). Web of Science yielded no additional unique eligible study. As a supplementary search, the first 200 Google Scholar results were also screened, but no additional eligible studies were identified.

Review scope, eligibility and evidence corpus

This systematic review and meta-analysis evaluated experimental evidence in which biochar was applied to PFAS-contaminated soil and compared with an appropriate unamended or no-biochar control. Eligible systems included batch soil tests, soil columns or lysimeters, greenhouse/pot studies and field experiments. Water-only adsorption studies without a soil phase were excluded from the quantitative corpus. The final corpus comprised 20 primary studies; all available main articles and Supplementary Information were audited together. Eighteen studies contributed quantitative information to at least one outcome domain, while two remained qualitative/mechanistic because the available data did not support a defensible treatment-control effect for the prespecified quantitative synthesis.

Data extraction, harmonisation and experimental independence

For each study, extraction captured the experimental unit, treatment and control arms, biochar dose and basis, feedstock, pyrolysis conditions, activation/modification, specific surface area and measurement method, pore metrics, pH and surface-chemistry descriptors when reported. PFAS were harmonised to exact compound identity, headgroup/class and carbon count. Soil metadata included pH with method, total organic carbon (TOC) or soil organic matter as separately reported variables, texture/fractions, cation exchange capacity and other matrix descriptors. Experimental context included contamination regime, system type, duration/aging, hydrological forcing and endpoint definition. Replication was classified as independent experimental, analytical, nested, repeated-measures or pseudo-replicated; analytical or nested replicates were never promoted to independent treatment replication.

Multiple PFAS, biochars, doses, soils and time points within one publication were treated as dependent observations originating from the same independent study. Quantitative analyses therefore used study-balanced aggregation, paired within-study contrasts, multilevel random effects or study-clustered robust inference as appropriate. The number of row-level observations was never interpreted as the independent sample size.

Effect-size orientation and sampling variance

For directly comparable mobility or leaching endpoints, the raw response ratio was expressed as:

$$\ln RR = \ln(MT/MC)$$

where MT and MC are the biochar-treatment and control means. Mobility outcomes were then expressed on a benefit-aligned scale, $B = -\ln RR$, such that $B > 0$ denotes lower PFAS mobility after biochar amendment. Source-reported percentage reductions, cumulative fractions, partitioning metrics and other endpoint forms were converted only when a finite and unambiguous treatment/control ratio could be reconstructed; no arbitrary continuity correction was applied to zero/censored cells.

For contrasts with defensible experimental-unit standard deviations and replicate numbers, the conventional sampling variance of $\ln RR$ was calculated as:

$$v_i = SD^2T/(n_T M^2T) + SD^2C/(n_C M^2C)$$

Variance provenance was audited at the study level. Reported analytical precision, uncertainty values estimated rather than directly measured from independent experimental replicates, duplicated measurements, nested subsamples or undefined $\pm$ statistics were not treated as independent experimental variance. These rules intentionally produced a smaller variance-supported core than the broad all-evidence corpus.

Evidence hierarchy for the primary mobility outcome

Because variance reporting was incomplete and highly heterogeneous, no single inverse-variance model could represent the complete literature without fabricating uncertainty. We therefore used a four-layer evidence hierarchy: (i) a variance-resolved core containing only studies with defensible experimental variance; (ii) a replicated-study expansion that added genuinely replicated studies lacking usable variance by imputing uncertainty only; (iii) an all-evidence study-level median that allowed studies without sampling variances to contribute without inverse-variance weighting; and (iv) an interval-aware extension that retained one study reported only as a bounded interval without assigning an arbitrary midpoint. The interval-aware study-level median was the primary manuscript estimate because it maximised independent-study coverage while preserving the actual resolution of the source evidence.

Variance-supported mobility models and missing-variance sensitivity

The variance-supported core comprised six independent studies with directly observed or recoverable experimental-unit variances. Within each study, treatment contexts were weighted equally, and PFAS within a context were weighted equally. Dependence among effects within the same experimental context was accounted for in the within-study covariance structure, with sensitivity analyses examining alternative correlation assumptions. The resulting study-level estimates were pooled using random-effects REML with Hartung-Knapp small-sample inference. Heterogeneity was summarised using τ^2 , I^2 and a prediction interval. A complementary multilevel REML model retained study, context and effect nesting and used CR2 study-clustered inference with Satterthwaite degrees of freedom.

A prespecified missing-variance expansion added two independently replicated studies that lacked directly usable endpoint variance. Missing sampling variances were multiply imputed using the empirical variability observed in variance-resolved studies. Imputation affected uncertainty only; observed treatment/control means and lnRR point estimates were never altered. Full imputation procedures are provided in the Supplementary Methods.

All-evidence study-level synthesis

The exact-point all-evidence synthesis used one prespecified mobility estimate per independent study ($k = 15$), defined as the median benefit-aligned lnRR across the endpoint selected by the prespecified outcome hierarchy and its eligible treatment contexts. The cross-study summary was the sample median. Uncertainty was quantified with an exact distribution-free order-statistic confidence interval, and directionality was assessed with an exact two-sided sign test. Leave-one-study-out analyses recalculated the median after omitting each study in turn.

The interval-aware all-evidence synthesis added one study whose soil response was recoverable only as a bounded removal interval. The interval was retained throughout. The lowest and highest possible overall medians were obtained by propagating the study lower and upper bounds; the conservative exact median confidence interval used the corresponding order statistics of the bound vectors. No midpoint or sampling variance was invented. In the observed data, the overall median remained point-identified despite the interval censoring.

Compound-specific responses and PFAS chemistry

Compound-specific summaries were constructed from exact chain-resolved mobility effects. Multiple observations were first collapsed to one median benefit-InRR per Study $\times$ PFAS combination. For each PFAS, study-level values were then summarised using the median and an exact distribution-free median confidence interval. Only compounds represented by at least six independent studies were displayed in the main compound panel.

For the short- versus long-chain analysis, long-chain PFAS were defined as PFCAs with ≥ 8 total carbon atoms and PFSAAs with ≥ 6 total carbon atoms; compounds below these thresholds were classified as short-chain. Within each Study $\times$ experimental context, the median benefit-InRR was calculated separately for short- and long-chain compounds when both classes were represented. The long-minus-short contrast was then summarised to one median contrast per study and finally across studies using an exact median confidence interval and exact sign test. Headgroup-adjusted, headgroup-stratified, mean-context and leave-one-study-out analyses were used as sensitivities.

The continuous carbon-number analysis avoided imposing a single chain threshold. Within each study, context and PFAS headgroup, Theil–Sen slopes related benefit-InRR to total PFAS carbon count. The median eligible slope within each independent study formed the independent study-level statistic. Cross-study inference used the median slope, exact distribution-free confidence interval and exact sign test. PFSA–PFCA differences were analysed analogously using paired within-context class contrasts and were treated as suggestive because the prespecified primary sign test did not reject the null.

Secondary moderators and contextual comparisons

Moderator analyses were deliberately constrained by the number of independent studies rather than the number of PFAS rows. Continuous moderators were promoted to main-text analysis only when study-level coverage met the prespecified approximate threshold of ten independent studies and the underlying measurements were reasonably comparable. Biochar dose (% w/w), pyrolysis temperature and soil TOC met this criterion. For each moderator, one median response and one median moderator value were calculated per independent study; study-level Spearman rank correlation and a descriptive Theil–Sen association were reported. Where a study contained multiple values of the same moderator, within-study Theil–Sen slopes were additionally summarised by direction with an exact sign test.

Specific surface area was kept method-specific (N_2 -BET and CO_2 -DFT) and was not combined across gas/analysis methods. Neither SSA stratum met the prespecified independent-study threshold for main inference. Feedstock and activation/modification were also retained as descriptive/Supplementary variables because category support was highly unbalanced. Contamination regime and experimental system were evaluated as contextual, non-causal comparisons of independent-study medians using exact label-permutation tests.

Secondary remediation outcomes

Soil retention/accessibility and plant uptake/bioavailability were analysed separately from the primary mobility endpoint. Endpoint directions were harmonised so that positive values consistently represented benefit under a stabilisation objective. Shared-control covariance was reconstructed where source information permitted and dependent contrasts were aggregated to one study-domain estimate. Because only two independent variance-supported studies were available in each domain, no headline random-effects cross-study estimate was calculated. Study-specific estimates and covariance sensitivities are reported in the Supplementary Information.

Small-study effects and software

Formal funnel-plot asymmetry, Egger regression and rank-based publication-bias testing were not used for the primary mobility inference. The variance-supported core contained fewer than ten independent studies, while the broad study-level evidence set intentionally included studies without valid sampling variances; precision-based funnel diagnostics would therefore not have a defensible common interpretation. This decision was prespecified in the analysis plan. Analyses were performed in R version 4.6.1 using the metafor, clubSandwich, dplyr, tidyr, readr, ggplot2 and patchwork packages principally. AI tools (ChatGPT, OpenAI) were used to assist with language editing and manuscript preparation, and Grammarly was used for grammar checking.

Declarations

Competing Interests

B.G. is employed by Ibero Massa Florestal S.A., a company that produces and commercialises biochar. E.S. and G.C. declare no competing interests.

Author Contribution

B.G. conceived the study, developed the methodology, conducted the literature search and screening, performed data extraction and curation, conducted the statistical analyses and visualisation, and wrote

the original manuscript. E.S. and G.C. contributed to the interpretation of the results and critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Data Availability

The dataset underlying the analyses reported in this study is provided as Supplementary Data.

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Figures

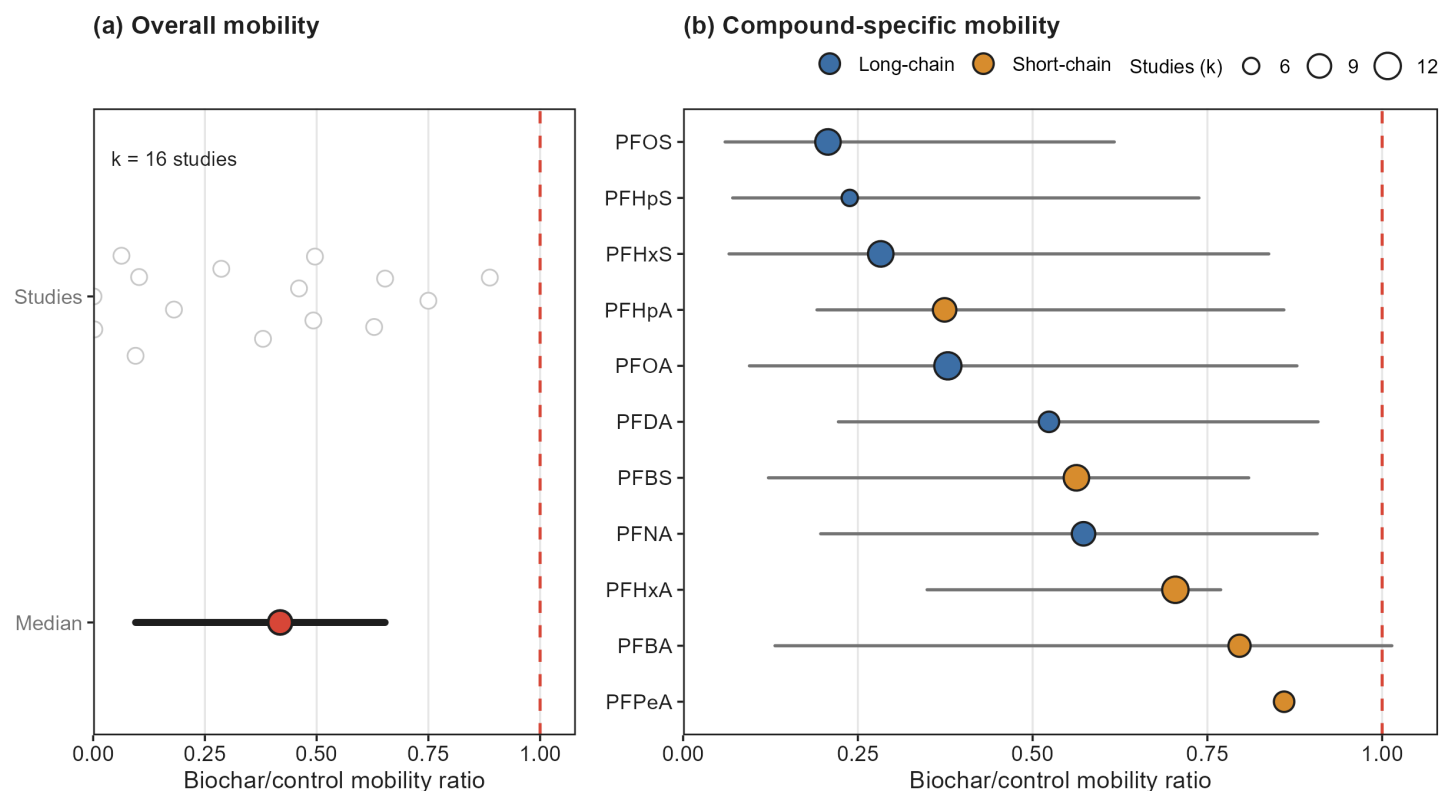


Figure 1

Overall and compound-specific effects of biochar on PFAS mobility in soil. (a) Grey circles show exact independent-study mobility medians; the red summary point is the primary interval-aware median across 16 independent studies, and the horizontal interval is the conservative distribution-free median confidence interval. One study contributes an interval-censored estimate and is not assigned a midpoint. The x-axis is the biochar/control mobility ratio, so values <1 indicate lower mobility under biochar. (b) Compound-specific estimates were first collapsed to one value per Study x PFAS and then summarised as study-balanced medians with exact distribution-free confidence intervals. The underlying chemistry dataset contained 598 exact biochar-control effect-size rows from 14 studies before this collapse. Point size indicates the number of independent studies and fill denotes short- versus long-chain class. Only compounds meeting the display threshold are shown; row-level evidence density is shown separately in Fig. S5.

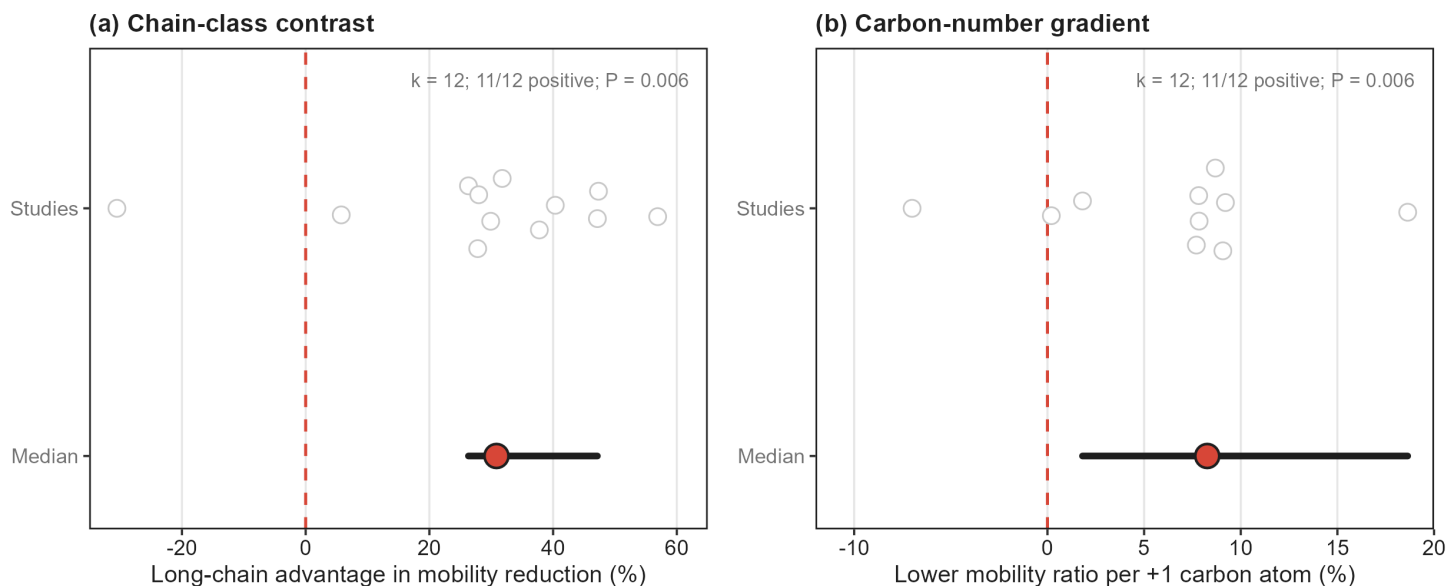


Figure 2

PFAS chain length controls the strength of biochar-associated mobility reduction. (a) Grey circles are 12 independent study-specific long-minus-short chain contrasts; the red point and black interval show the cross-study median and exact distribution-free median confidence interval. Positive values indicate greater mobility reduction for long-chain PFAS. (b) Grey circles are 12 independent study-specific, headgroup-adjusted Theil-Sen slopes relating benefit-aligned $\ln RR$ to total PFAS carbon number; the red point and interval show the cross-study median and exact confidence interval. The effect scale is translated to the percentage decrease in the treatment/control mobility ratio per added carbon atom. Both panels are derived from the compound-resolved evidence base but use the independent study as the inferential unit; paired context-level evidence is shown in Fig. S5.

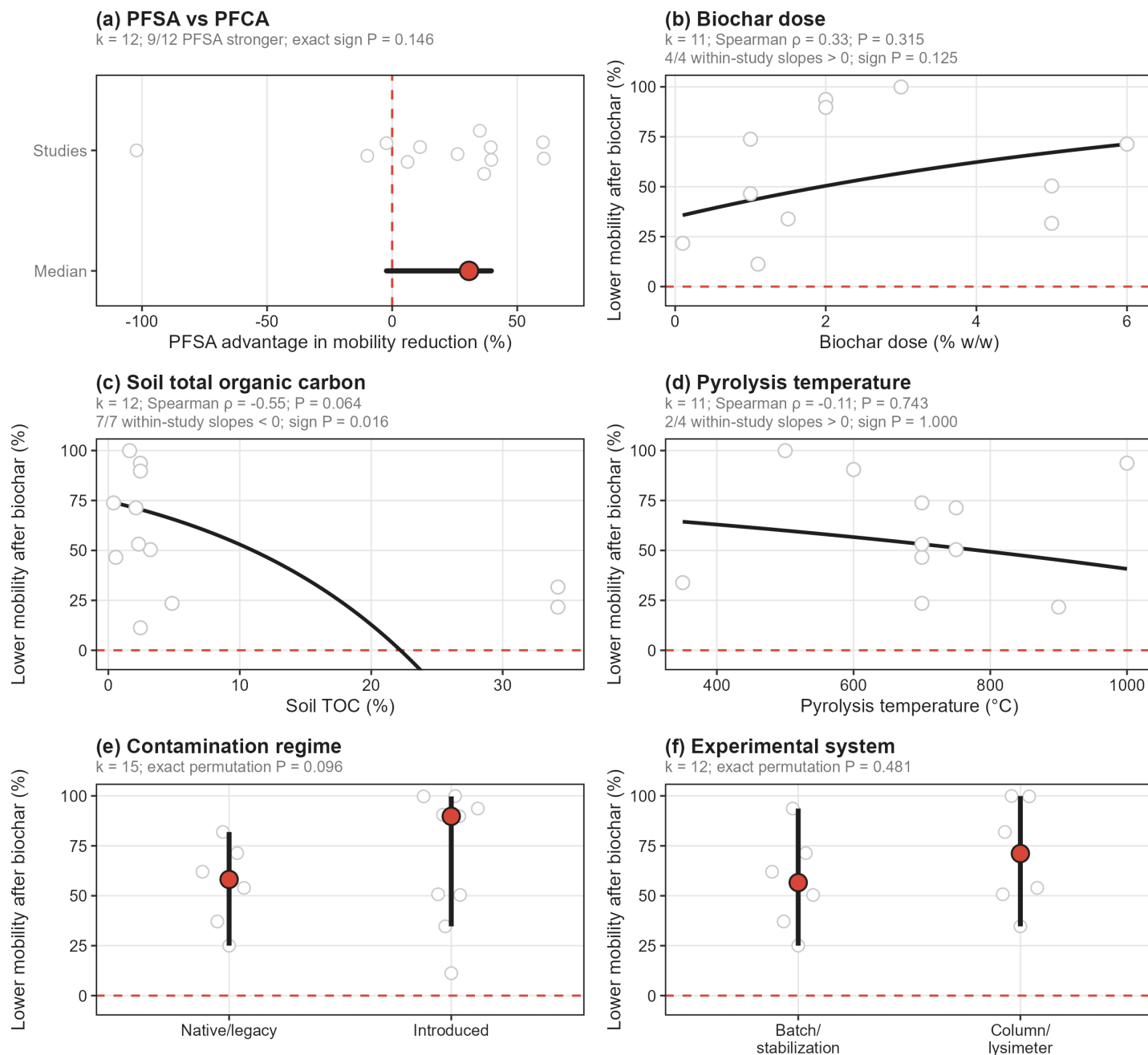


Figure 3

Moderator landscape for PFAS mobility responses to biochar. (a) Paired PFSA-versus-PFCA contrast. (b-d) Study-balanced associations with biochar dose, soil total organic carbon (TOC) and pyrolysis temperature, respectively. The corresponding compound-resolved analysis universes contained 520 exact effect-size rows for dose (11 studies), 578 for TOC (12 studies) and 393 for pyrolysis temperature (11 studies); these rows were collapsed to one study-balanced response before cross-study inference. Fitted lines are descriptive Theil-Sen associations calculated in benefit-aligned lnRR space and back-transformed for presentation; they should not be interpreted as causal dose-response functions or thresholds. (e) Contamination regime and (f) experimental system are contextual comparisons of

independent study medians. PFSA/PFCA is treated as suggestive; dose, TOC and pyrolysis as secondary observational moderators; and contamination regime/system as contextual rather than causal.

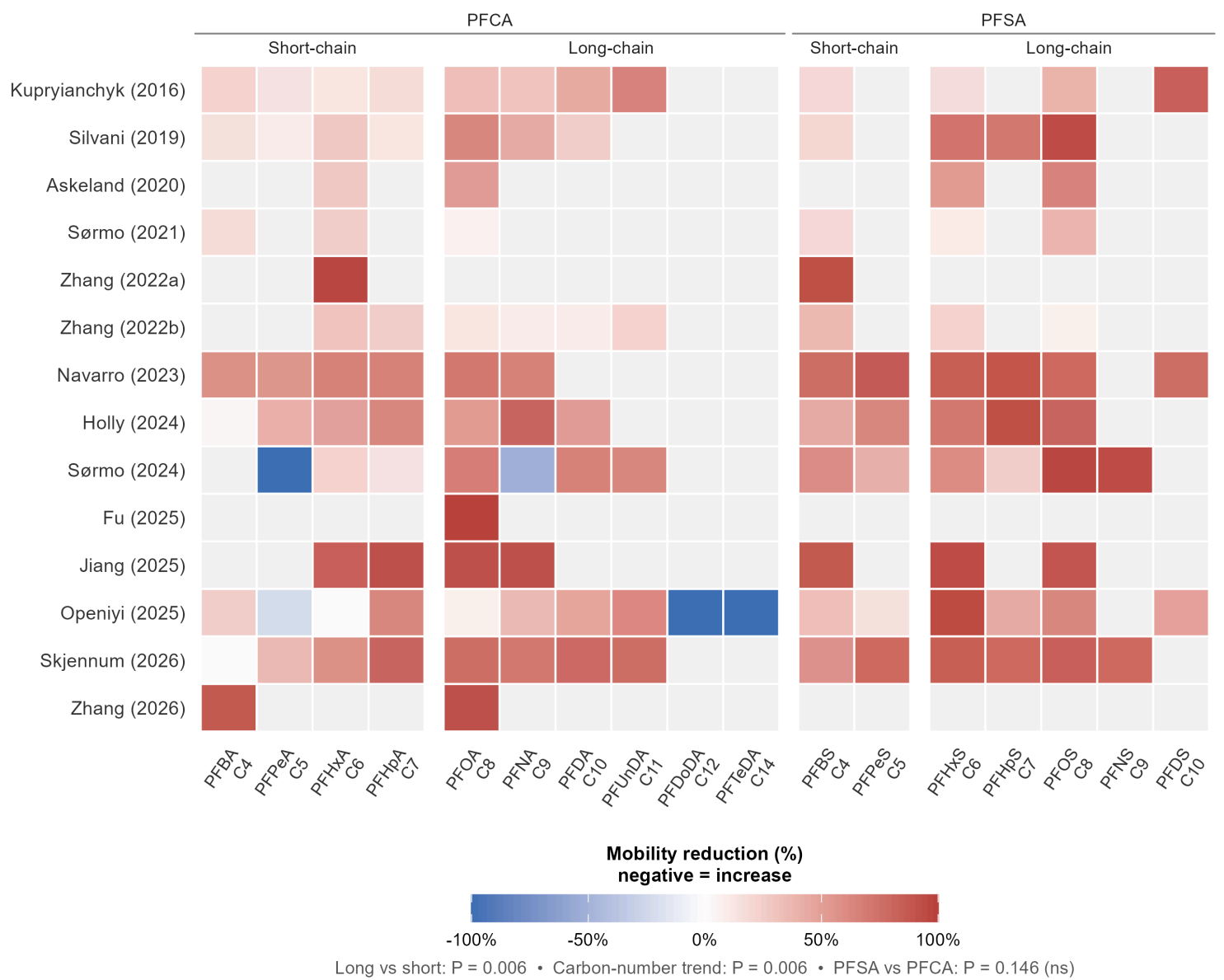


Figure 4

Study-level PFAS response architecture. The heatmap is derived from 598 exact compound-resolved biochar-control effect-size rows from 14 studies, collapsed to one median response for each independent Study x PFAS combination before plotting. Red indicates lower PFAS mobility with biochar, blue indicates higher mobility, and grey indicates no exact compound-resolved estimate. PFCA and PFSA are separated into short- and long-chain groups. The colour scale is capped at +/-100% for display. Statistical annotations summarise independent-study tests (long vs short $P = 0.006$; carbon-number trend $P = 0.006$; PFSA vs PFCA $P = 0.146$); the heatmap itself is descriptive and does not imply cell-wise significance.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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