Uptake of Per- and Polyfluoroalkyl Substances (PFAS) in plants: A systematic review and meta-analysis research protocol

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Abstract

Per- and polyfluoroalkyl substances (PFAS) transfer from contaminated environments into plants, contributing to food chain accumulation and an exposure pathway central to human health risk assessment. Regulatory risk assessments commonly use plant bioconcentration factors (BCFs) to estimate dietary exposure and support the derivation of health-based guideline values, yet they have not been derived from a formal quantitative synthesis of the evidence. Following PRISMA-P guidance, this protocol describes a systematic review and multilevel meta-analysis that will map the evidence base on PFAS plant BCFs, derive pooled BCFs for the plant species and categories, and quantify the principal biological, environmental, and methodological drivers of variability in PFAS uptake across plant species. Peer-reviewed studies will be identified through systematic searches of Scopus and PubMed, supplemented by BASE and ProQuest for grey literature; eligible studies must be primary empirical investigations of PFAS uptake in plants grown for human consumption or livestock feed, reporting plant-to-matrix concentration ratios or data sufficient to calculate them. Risk of bias will be assessed using a tool adapted from SYRCLE's framework. The primary effect size, the natural logarithm of the bioconcentration factor [ln(BCF)], will

be synthesised using multilevel random-effects meta-analysis and meta-regression, with sensitivity and publication-bias analyses assessing robustness.

Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large and structurally diverse group of synthetic chemicals, valued industrially and commercially for their thermal stability and surfactant properties (Glüge et al., 2020). These same properties make PFAS persistent in the environment and prone to bioaccumulation, resulting in widespread contamination of soil, water, wildlife, and humans. Epidemiological and toxicological evidence links PFAS exposure to a range of adverse health outcomes (Fenton et al., 2021), and growing scientific and public concern has made PFAS a major focus of regulatory action worldwide (Bock & Laird, 2022). Central to this regulatory response is the challenge of estimating human exposure from contaminated environmental media, which requires robust and quantitative methods for characterising how PFAS move through the environment and into the food supply.

Plant uptake is one of the most important pathways bringing PFAS into food webs. Direct consumption of contaminated crops is a major human exposure route (Xu et al., 2022), while PFAS can also reach humans indirectly by moving from contaminated soils into pasture, forage, and feed crops, and then into livestock and animal-derived foods such as meat, milk, and eggs (Kowalczyk et al., 2013; Xing et al., 2023). Because of this dual role, plant uptake sits at the centre of most regulatory exposure models. These models typically rely on bioconcentration factors (BCFs), also termed *soil-to-plant transfer factors* or *uptake factors*, defined as the ratio of PFAS concentration in plant tissue to that in the growing medium (Alexander, 1999). Regulators generally apply BCFs at the level of broad plant and compound categories, such as green and root vegetables (Australian Government, 2024; HEPA, 2025), implicitly assuming that a single factor is representative across the diversity of PFAS chemistries and plant physiologies it is meant to describe.

However, this assumption is not well supported by the primary literature. PFAS uptake is known to vary according to compound properties, with carbon-chain length and functional groups influencing mobility, bioavailability, and accumulation within plant tissue, as well as with plant physiology, soil characteristics, and study design (Costello & Lee, 2020; Wang et al., 2020). Current understanding of these sources of variation, however, rests largely on narrative reviews (Fawad et al., 2026; Keith et al., 2026; Lesmeister et al., 2021). While informative, narrative reviews cannot quantitatively estimate BCFs, formally test proposed drivers of variation, or evaluate the extent of heterogeneity among studies (Hedges et al., 2009). As a result, the generic BCFs embedded in current regulatory guidance have not themselves been derived from a formal quantitative synthesis of the available evidence (Australian Government, 2024; Environment and Climate Change Canada & Health Canada, 2025).

This protocol describes a systematic review and meta-analysis structured around three related aims. The first is to map the extent and distribution of the existing evidence base on PFAS plant BCFs, identifying which combinations of PFAS compound, plant species, tissue type, and cultivation system are underrepresented relative to the information needs of human health risk assessment. The second is to derive pooled BCF estimates for the plant categories used in regulatory risk assessment, providing an empirically grounded, evidence-based resource for exposure modelling. The third is to quantify and rank the biological, environmental, and methodological factors that drive variability in PFAS plant BCFs across studies, using meta-regression to test a set of candidate moderators (Table 1). Several of these moderators have an established biological or methodological rationale in the primary literature but have not previously been evaluated in combination or at scale. These three aims are intended to move PFAS plant bioconcentration factors from a set of narratively derived, largely untested defaults toward a quantitative, evidence-based resource that directly supports regulatory risk assessment.

Table 1. Candidate moderators included in meta-regression analyses, together with their biological or methodological rationale and a priori predictions regarding their effects on PFAS bioconcentration factors. *Each of the hypothesised moderators is presented alongside a reference source.*

Hypothesised moderator	Rationale	Predicted effect on ln(BCF)	Reference
Cultivation system	Hydroponic vs soil-based systems argued to be non-comparable	Hydroponic systems hypothesised to show higher BCFs than soil-based systems	(Fawad et al., 2026; Scearce et al., 2025)
Perfluoroalkyl chain length	Consistent decline in BCF with increasing chain length across the combined literature	Negative (approx. −0.25 log units per additional perfluorinated carbon for PFCAs; −0.24 for PFSAs)	(Adu et al., 2023; Blaine et al., 2013, 2014; Felizeter et al., 2021; Ghisi et al., 2019; Han et al., 2025; Krippner et al., 2014; Lesmeister et al., 2021; Scearce et al., 2025; Xu et al., 2022; Zhao et al., 2012)
Functional group	Systematic differences in transfer between PFAS with different functional group of comparable chain length	PFCAs generally higher than PFSAs of equivalent chain length. No prediction for other groups	(Blaine et al., 2014; Ghisi et al., 2019; Scearce et al., 2025)
Plant tissue	PFAS accumulation differs among roots, shoots, leaves and whole-plant measurements because translocation from roots is compound-dependent	Root concentrations generally higher than shoot concentrations, particularly for long-chain PFAS	(Fawad et al., 2026; Felizeter et al., 2021; Lesmeister et al., 2021; Xu et al., 2022)
Plant category	Different plant groups vary in root architecture, transpiration rates, growth patterns, lipid content, and edible tissues, all of which may influence PFAS uptake and accumulation	BCF expected to differ between categories	(Blaine et al., 2013; Felizeter et al., 2021; Han et al., 2025; Xu et al., 2022)
Soil organic carbon	Higher soil organic carbon associated with greater PFAS sorption to	Negative relationship	(Adu et al., 2023; Blaine et al., 2013; Lee et al., 2021)

	soil, reducing bioavailability		
Biosolids	Biosolids can alter PFAS bioavailability and plant uptake by increasing PFAS inputs and changing soil properties	Biosolid-amended soils are expected to have higher ln(BCF) values than unamended soils	(Blaine et al., 2013; Kharel et al., 2025)
pH of growing medium	pH affects PFAS sorption and plant-available fraction	Higher growing-medium pH tends to increase PFAS uptake factors in plants for many anionic PFAS species	(Felizeter et al., 2021; Krippner et al., 2014)
Exposure duration / time to harvest	Uptake from soil may not be at steady state at the time of sampling in shorter experiments	Positive (longer exposure, closer to steady state, higher measured BCF), expected to plateau with time	(Zhang et al., 2019)

Methods

Reporting standards and Best Practices

This systematic review was prospectively preregistered on the Open Science Framework (OSF; https://doi.org/10.17605/OSF.IO/AY38Z). The review protocol follows the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P; Supplementary Table 1) (PRISMA-P Group et al., 2015). The review will be conducted and reported in accordance with the PRISMA-EcoEvo reporting guideline (O'Dea et al., 2021) and meet the reporting standards evaluated by the Meta-analysis Appraisal Tool for Environmental Sciences (MATES) (Morrison et al., 2026). These measures are intended to address persistent methodological and reporting shortcomings that have been documented in environmental meta-analyses, including those that have informed policy and management decisions (Morrison et al., 2025). Any deviations from the research protocol will be explicitly documented, justified, and reported. To enhance the robustness and feasibility of the review methodology, all stages of the workflow were refined through pilot testing, including preliminary literature searches, trial data extraction, and exploratory analyses. To enhance the discoverability, accessibility, and reproducibility of the review and its outputs, we will follow established best-practice recommendations for evidence synthesis communication and dissemination (Pottier et al., 2024). Contributions throughout the research lifecycle will be recorded using the Dragon Kill Points framework (Martinig et al., 2026) and MeRIT principles for transparent and equitable recognition of scholarly contributions (Nakagawa, Ivimey-Cook, et al., 2023).

Eligibility criteria

Eligibility criteria were defined *a priori* using a modified PECO framework (Population, Exposure, Comparator, Outcome) (Morgan et al., 2018).

Population. Eligible studies investigated plant species used for human consumption or livestock feed production.

Exposure. Eligible studies investigated one or more PFAS meeting the Organisation for Economic Co-operation and Development (OECD) definition of PFAS (OECD, 2021). The contaminated growing media will be the only pathway of exposure investigated in this review.

Comparator. No comparator will be required. The review aims to quantify PFAS bioconcentration factors rather than compare treatment and control groups, and thus the Comparator component of the PECO framework is not applicable.

Outcome. Studies will be required to report either (i) a plant-to-medium concentration ratio or (ii) sufficient concentration data in both plant tissue and the corresponding environmental medium to permit calculation of such a ratio. Throughout this protocol, the term bioconcentration factor (BCF) is used in accordance with literature showing crop-compartment specific transfer factors of PFAS (Mei et al., 2021; Xu et al., 2022), and refers to the ratio between PFAS concentration in plant tissue and PFAS concentration in the corresponding environmental growing medium. Because terminology varies across the literature, all eligible plant-to-medium concentration ratios will be harmonised into a common metric for quantitative synthesis.

Study design. All empirical primary study designs will be eligible, including field investigations, greenhouse and pot experiments, and hydroponic or nutrient-solution studies. No restrictions will be applied according to contamination scenario. However, studies undertaken primarily for phytoremediation purposes will be excluded because they typically investigate species and exposure scenarios selected for contaminant removal and rarely pertain to species relevant to human or livestock consumption.

Language and publication type. Studies published in English will be eligible. Evidence will be obtained from two sources: (i) peer-reviewed journal articles identified through systematic searches of two bibliographic databases and (ii) grey-literature records identified through systematic searches of two grey-literature databases. Both peer-reviewed and grey-literature records will undergo the same eligibility assessment, data extraction, and risk-of-bias procedures.

Date range. No restrictions will be applied to publication date.

Exclusion criteria. Studies will be excluded if they: (i) did not investigate PFAS; (ii) did not investigate plant species used for human or livestock consumption; (iii) neither reported a plant bioconcentration factor nor provided sufficient concentration data in both plant tissue and the corresponding environmental medium to calculate one; (iv) reported only ratios indirectly derived from previously reported factors rather than from concentrations measured within the study; (v) were secondary literature (e.g., reviews, meta-analyses, or scoping reviews); (vi) relied exclusively on modelling or simulation approaches; (vii) were phytoremediation studies; or (viii) lacked an accessible full text written in English.

Search strategy

A systematic literature search will be conducted to identify studies reporting PFAS bioconcentration factors in plants. The search strategy was developed *a priori* and structured around three core concepts: (i) PFAS terminology, (ii) plant terminology, and (iii) bioconcentration factor terminology. Searches will be performed across bibliographic databases and grey-literature sources to maximise retrieval of both peer-reviewed and non-peer-reviewed evidence. The search strategy was designed to favour sensitivity over precision. Database names and website links, full search strings, date of search, and number of hits are provided in Supplementary Table 2.

Information sources

Peer-reviewed literature will be identified through systematic searches of Scopus and PubMed, selected for their broad coverage of environmental science, toxicology, environmental health, agricultural sciences, and risk-assessment literature.

Grey literature will be identified through systematic searches of ProQuest Dissertations & Theses Global and BASE (Bielefeld Academic Search Engine). These sources were selected to capture PhD and Master's theses and other forms of non-peer-reviewed research that may not be indexed in conventional bibliographic databases.

Study selection

Screening process

All records retrieved from bibliographic and grey-literature searches will be imported into Rayyan (Ouzzani et al., 2016), a reference management database, and screened against the predefined eligibility criteria. Prior to screening, duplicate records will be identified and removed using a combination of automated and manual procedures. The deduplication procedures will be fully documented and reported. While AI-assisted screening platforms may improve efficiency in evidence synthesis, evidence indicates that AI tools continue to require human verification and oversight to ensure accuracy and reproducibility (Center for AI Safety et al., 2026; Lagisz et al., 2026). Accordingly, study selection in this review will be undertaken by human reviewers. Study selection will proceed in two sequential stages. The first stage will involve title and abstract screening to identify potentially relevant studies. Records considered potentially eligible will proceed to full-text assessment. The second stage will involve evaluation of the complete article or report against the predefined eligibility criteria.

Stage 1: title and abstract screening

Titles and abstracts will be screened to determine whether studies investigate PFAS in plant species used for human consumption or livestock feed production and report, or are likely to report, at least one BCF value or PFAS concentrations in both plant tissues and a corresponding environmental medium. Records that are clearly ineligible based on the predefined criteria will be excluded at this stage. Records for which eligibility cannot be determined from the title and abstract alone will be retained for full-text assessment. Title/abstract screening and full-text screening will be conducted independently by two reviewers. Disagreements will be resolved through discussion and, where necessary, consultation with a third, senior reviewer. The title and abstract screening will follow a predefined decision tree (Figure 1).

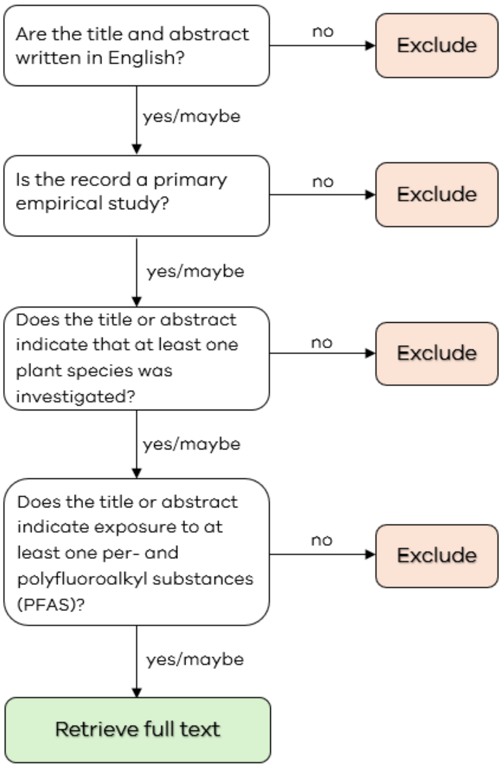

Figure 1. Title and abstract screening decision tree. *Sequential decision process used during title and abstract screening to assess records against the eligibility criteria.*

Stage 2: full-text screening

Full-text articles and reports will be evaluated against all eligibility criteria. Studies will be retained if they report a plant-to-medium concentration ratio or provide sufficient concentration data to calculate one. Studies will be excluded if they fail to meet any eligibility criterion, including the absence of eligible PFAS, plant species, outcomes, or study designs. Where multiple publications report overlapping datasets, the most complete source will be retained, and duplicate records will be excluded. The full-text screening will follow a second predefined decision (Figure 2). We will report a list of records excluded at the full-text screening stage, alongside the reasons for exclusion.

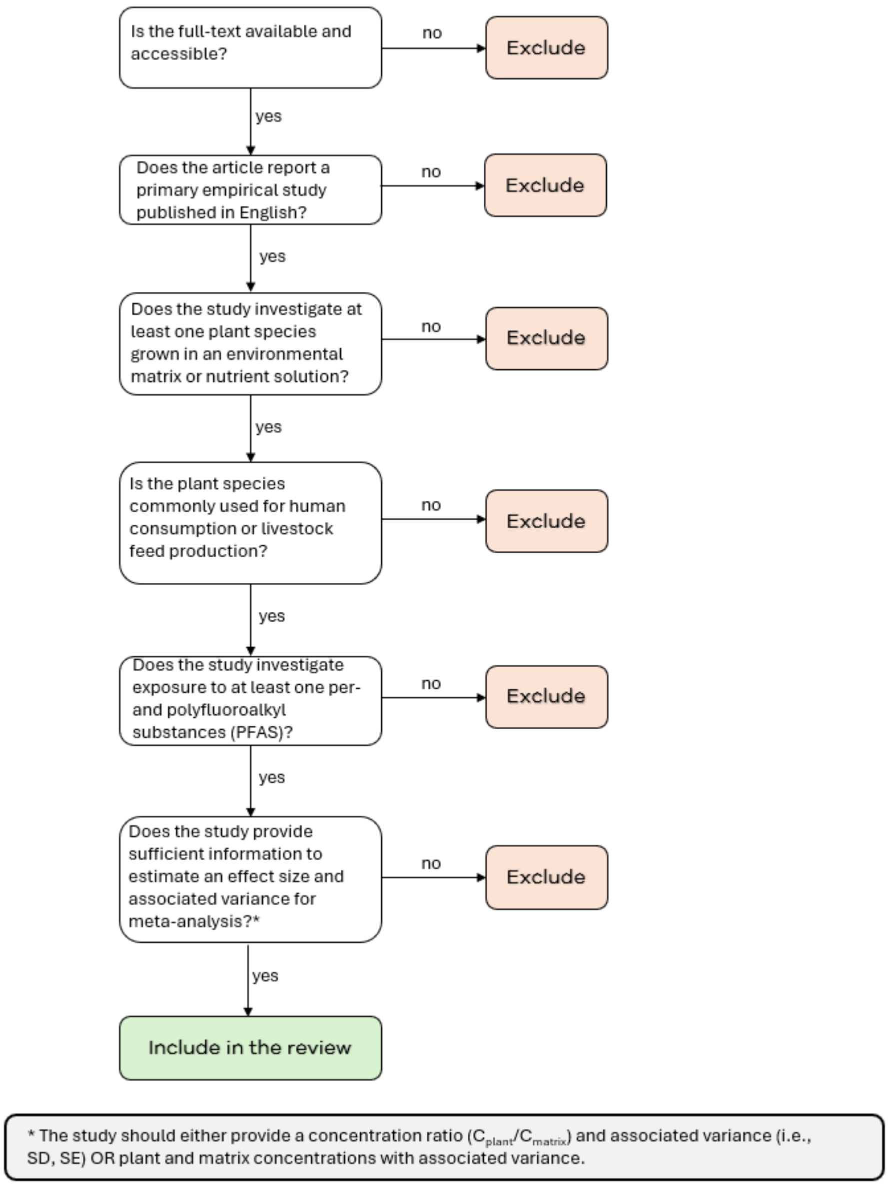

Figure 2. Full-text screening decision tree. *Sequential decision process used during full-text screening to assess studies against the review eligibility criteria.*

Data management

Data coding strategy

Data will be extracted into a relational database comprising five interconnected data tables representing studies, plant taxa, PFAS, bioconcentration factor observations, and risk-of-bias assessment (Supplementary Figure 1). The database structure is designed to accommodate the hierarchical nature of the evidence base, in which multiple PFAS, plant species, tissues, and bioconcentration factor estimates may be reported within a single study.

A “study” table will store bibliographic information and general study characteristics (e.g., publication year, country/countries of first author’s affiliation/affiliations, DOI; Figure 3). A “plant” table will contain taxonomic and information for each plant species. A “PFAS” table will contain chemical-specific information, including compound identity, chemical class, and carbon-chain length. A “bioconcentration factor” table will contain the effect-size data used in quantitative synthesis, including reported bioconcentration factors or the concentration data required for their calculation. Finally, a “risk-of-bias” table will store the results of the risk-of-bias assessment.

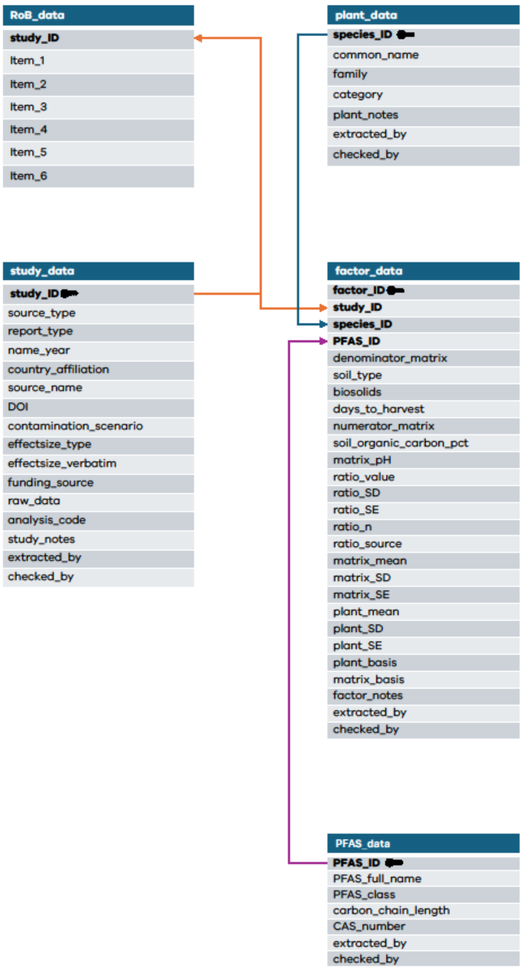

Figure 3. Overview of structure and connections among five data tables for storing data extracted from included studies. *‘study_data’ includes the information about the studies. ‘plant_data’ contains the list of plant species investigated in the included studies. ‘PFAS_data’ holds information about the individual chemicals measured by the studies. ‘factor_data’ includes the necessary data for effect size calculation. ‘RoB_data’ provides the information of the risk of bias assessment. The five data extraction tables will be provided as .csv files. Refer to Supplementary Table 3 for a detailed code book.*

These tables will be linked through unique identifiers, allowing multiple PFAS and plant taxa to be associated with a single study and multiple bioconcentration factor observations to be associated with each species–compound combination. This structure facilitates evidence mapping, moderator analyses, and multilevel meta-analysis while avoiding duplication of metadata across records. A complete description of all extracted variables, coding rules, permissible values, and examples is provided in Supplementary Table 3.

Effect size calculation

The effect size used throughout the quantitative synthesis will be the natural logarithm of the bioconcentration factor, ln(BCF) (Equation 1), where BCF is defined as the ratio between PFAS concentration in plant tissue and PFAS concentration in the corresponding growing medium (Alexander, 1999; Scearce et al., 2025). This effect size is mathematically equivalent to the logarithm of the response ratio (lnRR), widely used in ecological meta-analyses (Hedges et al., 1999). Similar approaches have been successfully applied previously in PFAS meta-analyses investigating contaminant transfer between biological compartments (Ricolfi et al., 2024). Log transformation is expected to improve normality and stabilise variance, while allowing pooled estimates to be readily back-transformed to the original scale for interpretation.

$$\ln(BCF) = \ln(\frac{C_{plant}}{C_{matrix}}) \qquad (1)$$

Where studies report bioconcentration factors directly, ln(BCF) and its sampling variance will be calculated from the reported ratio and associated dispersion metrics (e.g., standard deviation or standard error). Where studies report PFAS concentrations separately for plant tissues and environmental matrices, bioconcentration factors and corresponding effect-size variances will be calculated from the reported concentration data using standard log-response-ratio methods (Hedges et al., 1999; Lajeunesse, 2011; Senior et al., 2020). When measures of dispersion are unavailable, missing coefficients of variation will be imputed using the all-cases method (Nakagawa et al., 2022). The robustness of this approach will be evaluated through sensitivity analyses comparing models fitted to the complete dataset and to the subset of effect sizes with directly reported measures of dispersion. Detailed equations, assumptions, variance calculations, and imputation procedures are provided in Supplementary Method 1.

Risk of bias assessment

Risk of bias will be assessed using a review-specific tool adapted from SYRCLE's risk-of-bias framework for animal studies (Hooijmans et al., 2014). The tool comprises six items grouped into four domains (Table 2). Each item will be rated as low risk or high risk of bias according to predefined decision criteria.

Table 2. Risk-of-bias assessment tool used to evaluate studies included in the systematic review and meta-analysis. *The tool is adapted from the SYRCLE Risk of Bias framework for animal studies and comprises four domains and six items. Each item includes an assessment question with response options indicating either a low or high risk of bias.*

Domain	Item	Question	Answer options

Exposure characterisation	Item 1. Medium concentration measured directly	Was the denominator concentration (soil, nutrient solution, water) measured analytically during the study rather than assumed from nominal/spiked concentrations?	- Low risk (Measured concentration reported) - High risk (Only nominal/spiked concentration used)
Exposure characterisation	Item 2. Plant and medium concentrations originate from the same experimental unit	Were plant and medium concentrations measured from spatially and temporally matched samples originating from the same plot, pot, vessel, site, or sampling unit?	- Low risk (Explicitly paired) - High risk (Plant and medium concentrations originate from different units or different datasets)
Outcome measurement	Item 3. Quality-control procedures reported	Were analytical QA/QC procedures reported (e.g., recovery checks, blanks, certified reference materials, surrogate standards)?	- Low risk (At least one QA/QC procedure reported) - High risk (No QA/QC procedure reported)
Outcome measurement	Item 4. Concentration basis compatible	Were plant and medium concentrations reported on a compatible basis (e.g., dry wt / dry wt OR wet wt / wet wt) allowing a valid BCF calculation?	- Low risk (Plant and medium reported on compatible bases) - High risk (Plant and medium reported on known incompatible bases OR Concentration basis not reported for one or both matrices)
Missing data / selective reporting	Item 5. Complete outcome reporting	For compounds and species described in Methods, were results reported for all measured combinations?	- Low risk (Complete reporting) - High risk (Evidence of omitted compounds/species/treatments OR methods insufficiently detailed)
Precision and reproducibility	Item 6. Replication reported	Was a sample size (n) reported for the concentrations contributing to the BCF estimate?	- Low risk (n reported) - High risk (n not reported)

Risk-of-bias assessments will primarily be used to characterise the methodological quality of the evidence base and identify common sources of bias across studies. In addition, risk-of-bias ratings will inform sensitivity analyses, whereby the primary meta-analytic model will be re-fitted after excluding studies containing at least one high-risk rating. Risk-of-bias assessments will be conducted independently by two reviewers, with disagreements resolved through discussion and, where necessary, consultation with a third, senior reviewer.

Statistical analyses

Quantitative synthesis

The quantitative synthesis will pursue two complementary objectives: (i) estimation of pooled PFAS bioconcentration factors across the available evidence base and (ii) derivation of bioconcentration factors suitable for regulatory application. Overall pooled bioconcentration factors will be estimated using multilevel random-effects meta-analysis implemented through the *rma.mv* function in the *metafor* package (Viechtbauer, 2009). To account for the hierarchical structure of the dataset and the non-independence of effect sizes, random effects will be specified for study, plant species, PFAS compound, and effect size. Cluster-robust variance estimation will be taken into consideration using the *clubSandwich* package (J. Pustejovsky, 2016), with studies treated as the clustering unit, to obtain robust standard errors and valid statistical inference in the presence of dependent effect sizes (Yang et al., 2024). In presenting meta-analytic results, emphasis will be placed not only on the direction of effects but also on their magnitude, uncertainty, heterogeneity, and potential limitations of the underlying evidence base, following recent recommendations for the interpretation and use of ecological meta-analyses (Yang et al., 2023; Pollo et al., 2025).

Category-specific pooled bioconcentration factors

To address the second research aim, pooled bioconcentration factors will be estimated for plant categories (Table 3) using subgroup meta-regression models (J. E. Pustejovsky & Tipton, 2022) with plant category included as a moderator. Subgroup meta-regression modelling is often implemented in meta-analyses to compare effect sizes across different study groups (Ricolfi et al., 2025). Predicted marginal means and 95% confidence intervals will be calculated for each category while accounting for the dependencies among effect sizes.

Table 3. Example of plant categories used in human health risk assessments and regulatory applications. *Table adapted from Supporting Document 4 of the PFAS National Environmental Management Plan (NEMP) 3.0 (HEPA, 2025).*

Plant category	Included in NEMP 3.0?	Representative examples (plant common names)
Green vegetables	Yes	Lettuce, spinach, kale
Root vegetables	Yes	Carrot, radish, beetroot
Tuber vegetables	Yes	Potato, sweet potato, yam
Fruit vegetable	Yes	Tomato, cucumber, capsicum
Forage and pasture species	No	Ryegrass, fescue, alfalfa/lucerne
Cereals and grains	No	Wheat, rice, maize
Legumes	No	Soybean, pea, lentil

Additional summaries stratified by both plant category and PFAS compound will be generated for compounds of particular regulatory interest (e.g., PFOS, PFOA, and PFHxS), taking into consideration the statistical power of the model. To avoid unstable estimates, category-specific bioconcentration factors will only be discussed where the number of independent studies and effect sizes are sufficient for a stable model prediction.

Moderator analyses

To address the third research aim, potential sources of variability in bioconcentration factors will be evaluated using meta-regression. Each moderator will first be examined individually using univariable models. Moderators will subsequently be screened for collinearity and missingness prior to inclusion in multivariable models. Variables with more than 50% missing observations will be excluded from multivariable analyses but retained in univariable analyses.

Model selection will follow an information-theoretic approach based on Akaike's Information Criterion corrected for small sample size (AICc). Candidate models will be compared using the *MuMIn* package, and the relative importance of moderators will be quantified by summing Akaike weights across the candidate model set. Candidate moderators were selected *a priori* based on relationships previously identified in the PFAS plant-uptake literature and include plant, chemical, environmental, and methodological characteristics (Table 2).

Sensitivity analysis

Several sensitivity analyses will be conducted to evaluate the robustness of the quantitative synthesis. First, the primary model will be re-fitted after excluding studies with at least one high-risk-of-bias rating to assess the influence of study quality on pooled bioconcentration factor estimates. Second, a study-level leave-one-out analysis will be performed to identify any disproportionately influential studies. Third, analyses will be repeated using only effect sizes with directly reported measures of dispersion to evaluate the impact of imputed variance estimates.

Potential publication bias will be assessed visually using funnel plots of effect size [ln(BCF)] against standard error. Funnel-plot asymmetry will be interpreted cautiously because ecological meta-analyses commonly exhibit substantial biological and methodological heterogeneity, which can generate asymmetry in the absence of publication bias. Consequently, funnel plots will be used as an exploratory diagnostic rather than a definitive test of publication bias. Where feasible, publication-bias-adjusted estimates will be compared with primary pooled estimates and any resulting changes in effect magnitude, precision, or statistical inference will be reported.

Data synthesis and presentation

Review findings will be synthesised using a combination of descriptive evidence mapping, quantitative meta-analysis, and risk-of-bias assessment. Results will be presented using tables, graphical visualisations, and narrative summaries to address the review objectives and support interpretation of the evidence base.

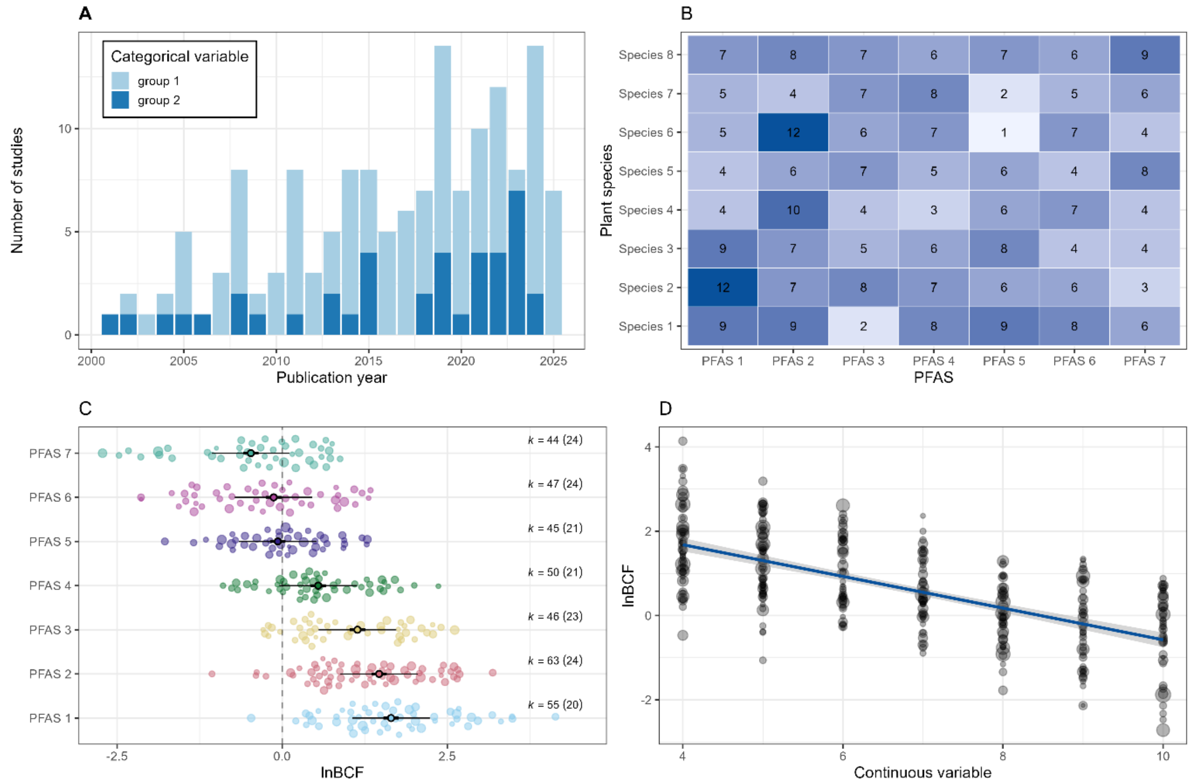

***Figure 4**. **Illustrative examples of planned data synthesis and presentation outputs.** Panel **A** shows the annual distribution of studies included in the evidence base, stratified by a categorical variable composed of two groups. Panel **B** presents an evidence map summarising the distribution of bioconcentration factors across plant species and compounds. Panel **C** shows an example orchard plot illustrating how pooled bioconcentration factor estimates and their associated uncertainty will be presented for different compounds. Panel **D** shows an example meta-regression examining the relationship between bioconcentration factors and a continuous moderator variable. All panels were generated using simulated data and are provided solely to illustrate the planned presentation of results; the values and patterns shown do not represent findings from the systematic review or meta-analysis.*

Evidence synthesis outputs will be presented in the order of the review objectives:

1. Evidence mapping (Figure 4A-B). The distribution of evidence across PFAS, plant species, plant tissues, cultivation systems, contamination scenarios, and study designs will be summarised using descriptive statistics, tables, evidence maps, and heatmaps. These analyses will address the first research aim by identifying areas of extensive study as well as potential knowledge gaps relevant to human health risk assessment.
2. Quantitative synthesis (Figure 4C). Overall and category-specific pooled estimates will be presented using orchard plots (Nakagawa, Lagisz, et al., 2023) and associated summary statistics, including measures of uncertainty and between-study variability. These analyses will address the second research aim by quantifying PFAS bioconcentration factors across plant categories and environmental conditions.
3. Drivers of variability (Figure 4D). Sources of heterogeneity will be investigated using subgroup analyses and meta-regression. Results will be presented using graphical visualisations, such as bubble plots, and predicted relationships for

selected moderator variables. These analyses will address the third research question by identifying factors associated with variation in PFAS transfer.

In addition to graphical outputs, quantitative synthesis results will be summarised in tabular form (Table 4). Tables will present pooled transfer factors for combinations of plant categories and PFAS, together with measures of uncertainty (e.g., 95% CI and PI) and the amount of supporting evidence (e.g., *k* and *n*). Tables are intended to provide a readily usable summary of the evidence base that may support future revisions of PFAS bioconcentration factors used in human health risk assessments. The tabulated estimates may also assist researchers and regulators undertaking PFAS exposure assessments or developing site-specific risk assessment models.

Table 4. Illustrative example of the planned presentation of pooled PFAS bioconcentration factors by plant category and individual PFAS. *For each combination of plant category and chemical, the table reports the pooled bioconcentration factor, associated 95% confidence interval (CI), 95% prediction interval (PI), and the number of contributing studies and observations. This format is intended to provide a transparent and readily implementable summary of the evidence base for use in human health risk assessments. Values shown are simulated and provided for illustrative purposes only and do not represent the findings of the review.*

Plant category	PFAS	BCF	95% CI	95% PI	Studies (*n*)	Observations (*k*)
Category 1	PFAS 1	0.42	0.31-0.56	0.08-2.10	8	56
Category 1	PFAS 2	0.19	0.12-0.29	0.03-0.91	5	33
Category 1	PFAS 3	0.61	0.45-0.83	0.11-3.42	11	67
Category 2	PFAS 1	1.25	0.94-1.67	0.24-6.75	12	71
Category 2	PFAS 2	0.73	0.53-1.01	0.12-4.33	9	58
Category 2	PFAS 3	1.84	1.31-2.58	0.32-10.51	4	75
Category 3	PFAS 1	0.94	0.69-1.28	0.18-5.42	6	48
Category 3	PFAS 2	0.56	0.39-0.81	0.09-3.18	4	19
Category 3	PFAS 3	1.16	0.86-1.56	0.21-5.98	7	52
Category 3	PFAS 4	0.28	0.19-0.40	0.05-1.62	2	11

Risk-of-bias assessment results will be summarised using tables and graphical summaries, including domain-level summaries and study-level traffic-light plots (Figure 5A-B). These assessments will be used to characterise the methodological quality of the evidence base and to inform the sensitivity analyses described above.

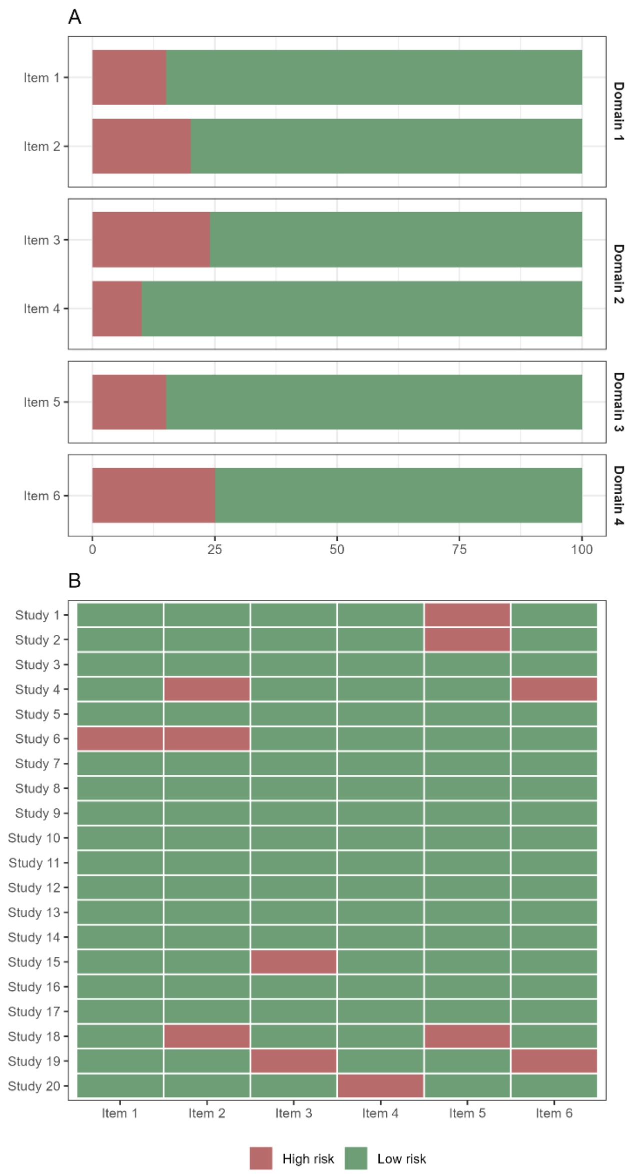

Figure 5. Illustrative examples of planned risk of bias (RoB) assessment outputs. *Panel* ***A*** *shows a summary of RoB judgments across all included studies, presenting the percentage of studies classified as high risk or low risk for each RoB item. Items are grouped according to the four domains of the assessment tool. Panel* ***B*** *shows an example study-level RoB assessment, where each cell represents the judgment assigned to a specific study for a given RoB item. This visualization illustrates how patterns of bias will be assessed across studies and how studies containing one or more high-risk judgments may be identified for sensitivity analyses. All panels were generated using simulated data and are presented solely to demonstrate the planned format of results presentation; the values and patterns shown do not represent actual study assessments.*

Development and piloting

The review methodology was pilot tested prior to implementation. Pilot exercises included testing of the search strategy, title-and-abstract screening procedures, and data-extraction framework. The search strategy was benchmarked against studies cited in the PFAS National Environmental Management Plan (NEMP) 3.0 Supplementary Document 4 (HEPA, 2025) to verify retrieval of key reference studies, and a subset of records were screened to assess the feasibility and consistency of the eligibility criteria. Results of the pilot exercises informed minor refinements to the search strategy, screening procedures, and data-coding framework. Detailed results of the pilot search, benchmark testing, and screening exercises are provided in Supplementary Method 2.

CRediT authorship contribution statement

Lorenzo Ricolfi: Conceptualization, Methodology, Software, Formal Analysis plan, Data Curation plan, Project administration, Resources, Visualisation, Writing – Original Draft, Writing – review & editing. **Kara Fry**: Conceptualization, Writing – review & editing. **Antti Mikkonen**: Conceptualization, Writing – review & editing.

Data availability

Code for the analyses planned for this systematic review and meta-analysis was archived and is available via the OSF project repository (https://doi.org/10.17605/OSF.IO/PTU8X).

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Uptake of Per- and Polyfluoroalkyl Substances (PFAS) in plants: A systematic review and meta-analysis research protocol

SUPPLEMENTARY MATERIAL

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Supplementary Tables

Supplementary Table 1

***Table S1. Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P)**. The protocol was developed and reported in accordance with the PRISMA-P guideline. The table summarises protocol compliance with the PRISMA-P reporting items.*

Section & Topic	Item No.	Checklist Item	Check
ADMINISTRATIVE INFO			
Title			
Identification	1a	Identify the report as a protocol of a systematic review	**X**
Update	1b	If the protocol is for an update of a previous systematic review, identify as such	**N/A**
Registration			
Registration	2	If registered, provide the name of the registry (such as PROSPERO) and registration number	**X**
Authors			
Contact	3a	Provide name, institutional affiliation, e-mail address of all protocol authors; provide physical mailing address of corresponding author	**X**
Contributions	3b	Describe contributions of protocol authors and identify the guarantor of the review	**X**
Amendments			
Amendments	4	If the protocol represents an amendment of a previously completed or published protocol, identify as such and list changes; otherwise, state plan for documenting important protocol amendments	**N/A**

Support			
Sources	5a	Indicate sources of financial or other support for the review	X
Sponsor	5b	Provide name for the review funder and/or sponsor	X
Role of Sponsor or Funder	5c	Describe roles of funder(s), sponsor(s), and/or institution(s), if any, in developing the protocol	X
INTRODUCTION			
Rationale			
Rationale	6	Describe the rationale for the review in the context of what is already known	X
Objectives			
Objectives	7	Provide an explicit statement of the question(s) the review will address with reference to participants, interventions, comparators, and outcomes (PICO)	X
METHODS			
Eligibility Criteria			
Eligibility criteria	8	Specify the study characteristics (such as PICO, study design, setting, time frame) and report characteristics (such as years considered, language, publication status) to be used as criteria for eligibility for the review	X
Information Sources			
Information sources	9	Describe all intended information sources (such as electronic databases, contact with study authors, trial registers or other grey literature sources) with planned dates of coverage	X
Search Strategy			
Search strategy	10	Present draft of search strategy to be used for at least one electronic database, including planned limits, such that it could be repeated	X
Study Records			
Data management	11a	Describe the mechanism(s) that will be used to manage records and data throughout the review	X
Selection process	11b	State the process that will be used for selecting studies (such as two independent reviewers) through each phase of the review (that is, screening, eligibility and inclusion in meta-analysis)	X
Data collection process	11c	Describe planned method of extracting data from reports (such as piloting forms, done independently, in duplicate), any processes for obtaining and confirming data from investigators	X
Data Items			
Data items	12	List and define all variables for which data will be sought (such as PICO items, funding sources), any pre-planned data assumptions and simplifications	X
Outcomes and Prioritization			
Outcomes and prioritization	13	List and define all outcomes for which data will be sought, including prioritization of main and additional outcomes, with rationale	X
Risk of Bias			
Risk of bias in individual studies	14	Describe anticipated methods for assessing risk of bias of individual studies, including whether this will be done at the outcome or study level, or both; state how this information will be used in data synthesis	X
Data Synthesis			
Data synthesis	15a	Describe criteria under which study data will be quantitatively synthesised	X

	15b	If data are appropriate for quantitative synthesis, describe planned summary measures, methods of handling data and methods of combining data from studies, including any planned exploration of consistency (such as I^2, Kendall's τ)	**X**
	15c	Describe any proposed additional analyses (such as sensitivity or subgroup analyses, meta-regression)	**X**
	15d	If quantitative synthesis is not appropriate, describe the type of summary planned	**X**
Meta-bias(es)			
Meta-bias(es)	16	Specify any planned assessment of meta-bias(es) (such as publication bias across studies, selective reporting within studies)	**X**
Confidence in Evidence			
Confidence in cumulative evidence	17	Describe how the strength of the body of evidence will be assessed (such as GRADE)	**X**

Supplementary Table 2

Table S2. Literature search strategy and search results. *Databases searched, website addresses, search strings, search dates, and the number of records retrieved for the systematic review. The searches were conducted to identify studies relevant to the review objectives.*

Database	**Terms**	**Search date**	**Number of hits**
Scopus (https://www.scopus.com)	TITLE-ABS-KEY (("forever chemical*" OR *fluoroalkyl OR perfluorin* OR perfluo* OR polyfluo* OR pfas* OR pfaa* OR pfca* OR pfgsa* OR pfba OR pfpea OR pfhxa OR pfhpa OR pfoa OR pfna OR pfda OR pfdea OR pfdca OR pfunda OR pfuna OR pfua OR pfuda OR pfdoa OR pfdoda OR pftrda OR pftrida OR pftra OR pfta OR pfteda OR pfo4da OR pfo5doda OR pfbs OR pfbus OR pfpes OR pfhxs OR pfhps OR pfos OR pfns OR pfds OR fts OR ftsa OR pfechs OR fosa OR pfosa OR netfosaa OR "Et-PFOSA-AcOH" OR nmefosaa OR "Me-PFOSA-AcOH" OR adona OR "Cl-PFAES" OR "F-53B" OR genx OR "HFPO-TA" OR "HFPO-DA" OR "Hydro-Eve" OR "Nafion BP2" OR teflon OR tfa OR "FTOHs" OR "diPAPs" OR fluorotelomer*) AND (plant* OR crop* OR grass* OR cereal* OR wheat OR triticum OR maize OR corn OR "zea mays" OR rice OR oryza OR barley OR soybean OR rye* OR secale OR oat* OR hordeum OR avena OR sorghum* OR millet* OR vegetable* OR lettuce OR lactuca OR spinach OR spinacia OR kale OR cabbage* OR broccoli* OR celery OR chard OR watercress OR tomato* OR	07/08/2026	1643

	carrot* OR daucus OR potato* OR “solanum tuberosum“ OR radish* OR raphanus OR beet* OR “beta vulgaris” OR onion* OR “allium cepa” OR garlic OR “allium sativum” OR cucumber* OR cucumis OR pepper* OR capsicum OR eggplant OR aubergine* OR zucchini* OR pumpkin* OR squash* OR strawberr* OR bean* OR pea* OR lentil* OR chickpea* OR alfalfa* OR lucerne OR trifolium OR clover* OR fescue* OR pasture* OR forage* OR sunflower* OR helianthus OR canola OR poplar* OR willow* OR root* OR shoot* OR leaf OR leaves OR macrophyte* OR duckweed* OR lemna* OR Phragmites OR Arabidopsis OR Lolium OR Festuca OR “pak choy” OR vegetation OR fruit* OR herb*) AND (uptake OR "concentration factor*" OR bioaccumulation OR bioconcentration OR "transfer factor*" OR "enrichment factor*" OR "concentration ratio*" OR enrichment OR "translocation factor*" OR residue* OR partition* OR carryover OR "soil-to-plant" OR "soil to plant" OR "soil-plant" OR "soil-to-root" OR "soil to root" OR "growth solution W/2 plant" OR "nutrient solution W/2 plant" OR bcf OR baf OR bsaf OR rcf OR scf OR ptf OR stf) AND NOT (review OR "meta-analysis"))		
PubMed (https://pubmed.ncbi.nlm.nih.gov/)	(("forever chemical*"[tiab] OR fluoroalkyl*[tiab] OR perfluorin*[tiab] OR perfluo*[tiab] OR polyfluo*[tiab] OR PFAS*[tiab] OR PFAA*[tiab] OR PFCA*[tiab] OR PFGSA*[tiab] OR PFBA[tiab] OR PFPeA[tiab] OR PFHxA[tiab] OR PFHpA[tiab] OR PFOA[tiab] OR PFNA[tiab] OR PFDA[tiab] OR PFDEA[tiab] OR PFDCA[tiab] OR PFUnDA[tiab] OR PFUnA[tiab] OR PFUA[tiab] OR PFUdA[tiab] OR PFDoA[tiab] OR PFDoDA[tiab] OR PFTrDA[tiab] OR PFTriDA[tiab] OR PFTrA[tiab] OR PFTA[tiab] OR PFTeDA[tiab] OR PFO4DA[tiab] OR PFO5DoDA[tiab] OR PFBS[tiab] OR PFBuS[tiab] OR PFPeS[tiab] OR PFHxS[tiab] OR PFHpS[tiab] OR PFOS[tiab] OR PFNS[tiab] OR PFDS[tiab] OR FTS[tiab] OR FTSA[tiab] OR PFECHS[tiab] OR FOSA[tiab] OR PFOSA[tiab] OR NEtFOSAA[tiab] OR "Et-PFOSA-AcOH"[tiab] OR NMeFOSAA[tiab] OR "Me-PFOSA-	07/08/2026	694

	AcOH"[tiab] OR ADONA[tiab] OR "Cl-PFAES"[tiab] OR "F-53B"[tiab] OR GenX[tiab] OR "HFPO-TA"[tiab] OR "HFPO-DA"[tiab] OR "Hydro-Eve"[tiab] OR "Nafion BP2"[tiab] OR Teflon[tiab] OR TFA[tiab] OR FTOH*[tiab] OR diPAP*[tiab] OR fluorotelomer*[tiab] OR "Perfluorinated Alkyl Substances"[Supplementary Concept] OR "Perfluorooctanoic Acid"[Mesh]) AND (plant*[tiab] OR crop*[tiab] OR grass*[tiab] OR cereal*[tiab] OR wheat[tiab] OR triticum[tiab] OR maize[tiab] OR corn[tiab] OR "zea mays"[tiab] OR rice[tiab] OR oryza[tiab] OR barley[tiab] OR soybean[tiab] OR rye[tiab] OR ryes[tiab] OR secale[tiab] OR oat[tiab] OR oats[tiab] OR hordeum[tiab] OR avena[tiab] OR sorghum*[tiab] OR millet*[tiab] OR vegetable*[tiab] OR lettuce[tiab] OR lactuca[tiab] OR spinach[tiab] OR spinacia[tiab] OR kale[tiab] OR cabbage*[tiab] OR broccoli*[tiab] OR celery[tiab] OR chard[tiab] OR watercress[tiab] OR tomato*[tiab] OR carrot*[tiab] OR daucus[tiab] OR potato*[tiab] OR "solanum tuberosum"[tiab] OR radish*[tiab] OR raphanus[tiab] OR beet*[tiab] OR "beta vulgaris"[tiab] OR onion*[tiab] OR "allium cepa"[tiab] OR garlic[tiab] OR "allium sativum"[tiab] OR cucumber*[tiab] OR cucumis[tiab] OR pepper*[tiab] OR capsicum[tiab] OR eggplant[tiab] OR aubergine*[tiab] OR zucchini*[tiab] OR pumpkin*[tiab] OR squash*[tiab] OR strawberr*[tiab] OR bean*[tiab] OR pea[tiab] OR peas[tiab] OR lentil*[tiab] OR chickpea*[tiab] OR alfalfa*[tiab] OR lucerne[tiab] OR trifolium[tiab] OR clover*[tiab] OR fescue*[tiab] OR pasture*[tiab] OR forage*[tiab] OR sunflower*[tiab] OR helianthus[tiab] OR canola[tiab] OR poplar*[tiab] OR willow*[tiab] OR root*[tiab] OR shoot*[tiab] OR leaf[tiab] OR leaves[tiab] OR macrophyte*[tiab] OR duckweed*[tiab] OR lemna*[tiab] OR phragmites[tiab] OR arabidopsis[tiab] OR lolium[tiab] OR festuca[tiab] OR "pak choy"[tiab] OR vegetation[tiab] OR fruit*[tiab] OR herb*[tiab] OR "Plants"[Mesh]) AND (uptake[tiab] OR bioaccumulation[tiab] OR		

	bioconcentration[tiab] OR translocation[tiab] OR enrichment[tiab] OR residue*[tiab] OR partition*[tiab] OR carryover[tiab] OR "concentration factor"[tiab] OR "concentration factors"[tiab] OR "transfer factor"[tiab] OR "transfer factors"[tiab] OR "enrichment factor"[tiab] OR "enrichment factors"[tiab] OR "concentration ratio"[tiab] OR "concentration ratios"[tiab] OR "translocation factor"[tiab] OR "translocation factors"[tiab] OR "soil-to-plant"[tiab] OR "soil to plant"[tiab] OR "soil-plant"[tiab] OR "soil-to-root"[tiab] OR "soil to root"[tiab] OR BCF[tiab] OR BAF[tiab] OR BSAF[tiab] OR RCF[tiab] OR SCF[tiab] OR PTF[tiab] OR STF[tiab] OR "Bioaccumulation"[Mesh])) NOT (review[pt] OR systematic review[pt] OR meta-analysis[pt])		
ProQuest (https://www.proquest.com)	TI,AB((PFAS* OR PFOA OR PFOS OR perfluoro* OR polyfluoro* OR fluorotelomer*) AND (plant* OR crop* OR vegetation*) AND ("transfer factor*" OR "concentration ratio*" OR "concentration factor*" OR "uptake factor*" OR BCF OR BAF OR STF OR PTF)) NOT TI,AB(review OR "meta-analysis")	07/08/2026	74
BASE (Bielefeld Academic Search Engine) (https://api.base-search.net/) Collections included: Theses (undergraduate, postgraduate and postdoctoral) and reports doctype:(14 18*)	uptake* factor* perfluor* doctype:(14 18*)	07/08/2026	36

Supplementary Table 3

Table S3. Data extraction codebook for the relational database used in the systematic review and meta-analysis. *The codebook provides detailed descriptions of all variables included in the five data tables (study_data, plant_data, PFAS_data, factor_data, and RoB_data), including variable names, definitions, available options, and example entries.*

Data table name	Meta-data	Explanation	Options	Example
study_data	study_ID	Unique identifier for each included study	NA	s001
	source_type	Whether the study is a peer reviewed scientific article or grey literature. Choose one of the options.	peer-reviewed / grey literature	NA
	report_type	For grey literature only. Choose one of the options.	site investigation / human health	NA

			risk assessment / ecological risk assessment / monitoring report / other	
	name_year	Surname of the first author and year of publication	NA	Smith_2020
	country_affiliation	Country/countries of first author's affiliation/affiliations. Comma separated.	NA	Australia, Italy
	source_name	Journal name (peer-reviewed) or issuing/commissioning agency (grey literature)	NA	Environment International
	DOI	Digital Object Identifier	NA	10.1039/D0EM00291G
	contamination_scenario	The type of contamination. Choose one of the options.	field-contaminated site / laboratory-spiked / background concentrations / mixed / not reported	NA
	effectsize_type	Whether the effect size (bioconcentration factor) is a reported ratio by the study or if it was calculated from concentration pairs (concentration in plant / concentration in the medium). Choose one of the options.	reported ratio / concentration pair	NA
	effectsize_verbatim	If effectsize_type is a reported ratio, what was it called in the study? Choose one of the options.	uptake factor / bioaccumulation factor / bioconcentration factor/ bioconcentration factor / other	NA
	funding_source	Study's funding source (usually found at the end of an article). Universities and government are an example of non profit organisations. A private company is an example of a for profit organisation. Choose one of the options.	for profit organisation / non profit organisation	NA
	raw_data	Whether the study provides the raw data (usually disclosed at the end of an article). Raw data can be provided in supplementary material or in external repositories (e.g., GitHub).	available / not available	NA

		Tables providing statistical results (mean, sd, sample size) are not considered raw data. Choose one of the options.		
	analysis_code	Whether the study provides the analysis code (usually disclosed at the end of an article). Choose one of the options.	available / not available	NA
	study_notes	Free-text field for any notes relevant to extracting this study.	NA	I've contacted the corresponding author (A.I. García-Valcárcel). Unfortunately, the email address is not active anymore. The study is too old. Ratios do not have dispersion values and we don't know if the error bars in fig 1 are SD or SE, so we are left with only one option: impute SD values of ratios.
	extracted_by	Initials of the person who extracted the data	NA	LR
	checked_by	Initials of the person who checked the extracted data	NA	AM
plant_data	species_ID	Species scientific name. Use Plants of the World Online as a refence (https://powo.science.kew.org/).	NA	Medicago sativa
	common_name	Species common name. Use Plants of the World Online as a refence (https://powo.science.kew.org/).	NA	Alfalfa
	family	Plant family (standardised). Use Plants of the World Online as a refence (https://powo.science.kew.org/).	NA	Fabaceae
	category	Plant category. When possible, use Plants of the World Online as a refence (https://powo.science.kew.org/). Choose one of the options.	green vegetables / root vegetables / tuber vegetables / fruit vegetable / forage and pasture species / cereals and	NA

			grains / legumes / other	
	plant_notes	Free-text field for any notes relevant to extracting this plant species.	NA	Woody shrubs; not typically used as food crops
	extracted_by	Initials of the person who extracted the data	NA	LR
	checked_by	Initials of the person who checked the extracted data	NA	AM
PFAS_data	PFAS_ID	Unique identifier for each investigated chemical. The identifier is the chemical acronym. Multiple studies will share the same PFAS_ID.	NA	PFOS
	PFAS_full_name	Full name of the chemical. Use PubChem as a refence (https://pubchem.ncbi.nlm.nih.gov/).	NA	perfluorooctane sulfonic acid
	PFAS_class	PFAS class. Use PubChem as a refence (https://pubchem.ncbi.nlm.nih.gov/). Choose one of the options.	perfluoroalkyl carboxylic acid (PFCA) / perfluoroalkyl sulfonic acid (PFSA) / fluorotelomer carboxylic acid (FTCA) / fluorotelomer sulfonic acid (FTSA) / perfluorophosphinic acid (PFPiA) / sulfonamide-based / other	PFSA
	carbon_chain_length	Length of the carbon chain. Integer. Use PubChem as a refence (https://pubchem.ncbi.nlm.nih.gov/).	NA	8
	CAS_number	CAS Registry Number is a unique identifier assigned by the Chemical Abstracts Service. Use PubChem as a refence (https://pubchem.ncbi.nlm.nih.gov/).	NA	1763-23-1
	extracted_by	Initials of the person who extracted the data	NA	LR
	checked_by	Initials of the person who checked the extracted data	NA	AM
factor_data	factor_ID	Unique identifier for each factor. A study could have multiple factor_ID, for example for different chemicals.	NA	f_001
	study_ID	Foreign key linking to study_data table. Report	NA	s_001

		here the respective study_ID.		
	species_ID	Foreign key linking to plant_data table. Report here the respective species_ID.	NA	p_001
	PFAS_ID	Foreign key linking to PFAS_data table. Report here the respective pfas_ID.	NA	PFOS
	denominator_medium	The medium used as the denominator of the reported ratio, i.e. the environmental or biological medium against which the plant concentration was compared. Hydroponic studies use nutrient soultions. Choose one of the options.	soil / nutrient solution / sediment	NA
	soil_type	Type of soil in which the plant was grown, or the soil medium from which the sample was taken, as described in the study (e.g., texture or soil classification).	NA	sandy loam
	biosolids	Whether biosolids (treated sewage sludge) were applied to, or present in, the growing medium or contamination source. Choose one of the options.	yes / no / not reported	NA
	days_to_harvest	Number of days between the start of plant exposure (e.g., spiking, planting, or onset of field contamination) and harvest/sampling of the plant.	NA	60
	numerator_plant	The plant component used as the numerator of the reported ratio, i.e. the plant part or tissue for which the PFAS concentration was measured. Choose one of the options.	shoot / root / leaf /stem / fruit / flowers / whole plant	NA
	soil_organic_carbon_pct	Percentage of soil organic carbon as reported by the study.	NA	0.20%
	medium_pH	pH value of the medium (e.g., soil) as reported by the study.	NA	7
	ratio_value	The numeric value of the bioconcentration factor (mean value) as directly reported by the study, on whatever basis the study used.	NA	0.85

	ratio_SD	The standard deviation of the factor value, as reported by the study.	NA	0.2
	ratio_SE	The standard error of the factor value, as reported by the study.	NA	0.1
	ratio_n	The sample size of the factor value, as reported by the study.	NA	10
	ratio_source	Source of the ratio_value (e.g., tables, figures, text, supplementary material)	NA	Table 2
	medium_mean	Mean concentration in the medium. Extract only if ratio_value is not provided by the study.	NA	416.8
	medium_SD	Standard deviations of the medium_mean. Extract only if ratio_value is not provided by the study.	NA	29.5
	medium_SE	Standard error of the medium_mean. Extract only if ratio_value is not provided by the study.	NA	20.1
	medium_unit	The unit of measurement used for medium_mean	NA	mg/kg
	plant_mean	Mean concentration in the plant/plant tissue. Extract only if ratio_value is not provided by the study.	NA	4310.3
	plant_SD	Standard deviations of the plant_mean. Extract only if ratio_value is not provided by the study.	NA	303
	plant_SE	Standard error of the plant_mean. Extract only if ratio_value is not provided by the study.	NA	106.7
	plant_unit	The unit of measurement used for plant_mean	NA	mg/kg
	plant_basis	The mass or weight basis on which the numerator (plant) concentration is expressed. Choose one of the options.	dry weight / wet weight / fresh weight / not reported	NA
	medium_basis	The mass, weight, or volume basis on which the denominator (e.g., soil) concentration is expressed. Choose one of the options.	dry weight / wet weight / fresh weight / not reported	NA
	factor_notes	Free-text field for any notes relevant to extracting this factor, such as assumptions made	NA	NA
	extracted_by	Initials of the person who extracted the data	NA	LR
	checked_by	Initials of the person who checked the extracted data	NA	AM

Supplementary Figures

Supplementary Figure 1

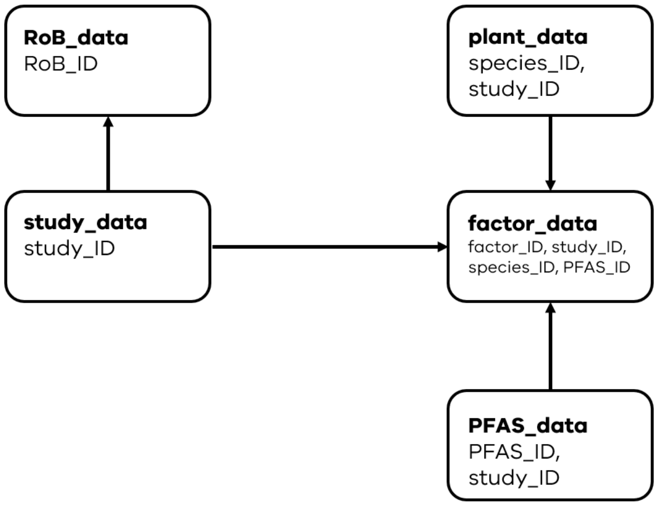

Figure S6. *Structure of the relational database used for systematic review and meta-analysis of PFAS bioconcentration factors.*

Supplementary Methods

Supplementary Method 1

The effect size used throughout the quantitative synthesis will be the natural logarithm of the bioconcentration factor, ln(BCF), where BCF is defined as the ratio between PFAS concentration in plant tissue and PFAS concentration in the corresponding environmental medium (HEPA, 2025a). The ln(BCF) is mathematically equivalent to the log response ratio (lnRR) used in response-ratio meta-analyses (Hedges et al., 1999; Lajeunesse, 2011; Senior et al., 2020):

$$\ln(BCF) = \ln(\frac{C_{plant}}{C_{matrix}})$$

Reported-ratio studies: Where a study directly reports a calculated ratio together with a measure of dispersion (SD, SE, or CV) and a sample size, ln(BCF) and its sampling variance are calculated directly from the reported ratio and its dispersion, using the standard delta-method conversion between SD/SE and CV.

Concentration-pair studies: Where a study reports separate mean concentrations (with SD and sample size, where available) for plant tissue and the environmental medium, without a calculated ratio, ln(BCF) and its sampling variance are calculated as for a log response ratio:

$$\ln(BCF) = \ln\left(\frac{\bar{X}_{plant}}{\bar{\bar{X}}_{matrix}}\right) + \frac{1}{2}\left[\frac{SD^2{}_{plant}}{\left(n_{plant}\bar{X}^2_{plant}\right)} - \frac{SD^2_{matrix}}{\left(n_{matrix}\bar{X}^2_{matrix}\right)}\right]$$

$$v(\ln BCF) = \frac{SD^2_{plant}}{n_{plant}\bar{X}^2_{plant}} + \frac{SD^2_{matrix}}{n_{matrix}\bar{X}^2_{matrix}} - 2r(covariance\ term)$$

Treatment of the correlation term, "r": Plant tissue and environmental medium concentrations are conceptually paired (they are measured within the same pot, plot, or field site) but are very rarely paired at the level of individual sampling units: plant replicates and medium (soil/water) samples are typically collected, composited, and analysed independently, and in different numbers, within the same experimental unit. For this reason, the correlation coefficient r will be set to 0 throughout. This is the conservative choice since setting r = 0 tends to inflate rather than deflate the sampling variance, and avoids making an unsubstantiated assumption about the within-study dependency structure between plant and medium measurements.

Missing dispersion (SD/SE) values: For effect sizes missing a reported measure of dispersion for either the plant or medium concentration, the "all-cases" coefficient-of-variation imputation method (Nakagawa et al., 2022) will be applied: the missing CV is imputed from the average CV computed across other complete-case effect sizes in the dataset. This method has been validated as performing well across a broad range of simulated meta-analytic conditions. The robustness of pooled estimates to this imputation will be tested via sensitivity analysis, comparing the full imputed dataset against a model restricted to effect sizes with directly reported dispersion measures only.

Supplementary Method 2

We conducted a pilot search, a pilot screening, and a pilot data extraction to test our search and mapping strategy. We used the Scopus search string reported in the Search strategy (Table S2).

Search results: 1,621 records on 23/07/2026.

Benchmark studies test from the PFAS National Environmental Management Plan (NEMP) 3.0 Supplementary Document 4 (HEPA, 2025b):

1. 10.1016/j.chemosphere.2020.127608 (RETRIEVED)
2. 10.1002/etc.4571 (RETRIEVED)
3. 10.1021/jf201355y (RETRIEVED)
4. 10.1016/j.envres.2020.109751 (RETRIEVED)
5. 10.1021/es504150h (RETRIEVED)
6. 10.1016/j.scitotenv.2016.07.010 (RETRIEVED)
7. 10.1016/j.scitotenv.2020.137333 (RETRIEVED)
8. 10.1016/j.envpol.2016.06.032 (RETRIEVED)
9. 10.1007/s00244-008-9272-9 (RETRIEVED)

10. 10.1016/j.envpol.2013.09.032 (RETRIEVED)

The search strategy retrieved all ten benchmark studies, proving its comprehensiveness.

We randomly selected and screened a sample of 100 records against the eligibility criteria. The pilot title and abstract screening took 30 minutes in total (18 seconds per study, on average). The full-text screening took of 5 minutes per study, on average.

References

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, *80*(4), 1150–1156. https://doi.org/10.1890/0012-9658(1999)080%5B1150:TMAORR%5D2.0.CO;2

HEPA. (2025a). *PFAS NEMP 3.0 Supporting Document 2 – Derivation of ecological guidelines for wildlife diet and indirect soil exposure to perfluorooctanoic acid (PFOA) perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS)*. Heads of EPA Australia and New Zealand 2025. dcceew.gov.au/publications

HEPA. (2025b). *PFAS NEMP 3.0 Supporting Document 4 – Human health soil guideline values for PFOS+PFHxS and PFOA: Derivation of the human health investigation levels for soil for 'residential with garden/ accessible soil' (HIL A) and a review of relevant soil to plant transfer factors*. Heads of EPA Australia and New Zealand 2025. dcceew.gov.au/publications

Lajeunesse, M. J. (2011). On the meta-analysis of response ratios for studies with correlated and multi-group designs. *Ecology*, *92*(11), 2049–2055. https://doi.org/10.1890/11-0423.1

Nakagawa, S., Noble, D., Lagisz, M., Spake, R., Viechtbauer, W., & Senior, A. (2022). *A robust and readily implementable method for the meta-analysis of response ratios with and without missing standard deviations* [Preprint]. Life Sciences. https://doi.org/10.32942/OSF.IO/7THX9

Senior, A. M., Viechtbauer, W., & Nakagawa, S. (2020). Revisiting and expanding the meta-analysis of variation: The log coefficient of variation ratio. *Research Synthesis Methods*, *11*(4), 553–567. https://doi.org/10.1002/jrsm.1423