

Plant-Based Biomonitoring of Airborne Microplastics: A Systematic Review

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Abstract

Background

Airborne microplastics (AMPs) are recognized as atmospheric pollutants. Traditional monitoring methods provide limited spatial and temporal resolution. Plants may offer an alternative for evaluating atmospheric microplastic deposition. Despite this potential, a review synthesizing field-based evidence supporting the approach has not been conducted.

Objective

This systematic review evaluated vascular plants, mosses, and lichens as biomonitors of airborne microplastic deposition, emphasizing biomonitor selection, sampling and analytical methods, particle characteristics, methodological quality, and current research gaps.

Methods

PubMed, Web of Science, Scopus, Embase, ScienceDirect, and Google Scholar were searched from database inception through June 2026. Additional records were identified through backward and forward citation tracking, author searches, and manual reference screening. Eligible studies generated original field-based data on airborne microplastics associated with naturally occurring, transplanted, or experimentally deployed vegetation. Two reviewers independently performed study selection, data extraction, and methodological-quality assessment. Findings were synthesised narratively in accordance with PRISMA 2020. An exploratory bibliometric analysis was conducted using bibliometrix in R, with network visualisation in Python.

Results

Twenty peer-reviewed studies published between 2021 and 2026 met the inclusion criteria. The studies were conducted in nine countries and examined plant foliage, pine needles, mosses, lichens, and combined moss–lichen systems across urban, industrial, rural, forested, and protected environments. Fibres were the most frequently reported particle morphology, while polymer profiles varied considerably among studies and analytical approaches. Several investigations reported greater plant-associated particle burdens in settings with stronger anthropogenic influence, although differences in biomonitor morphology, exposure conditions, extraction procedures, detection thresholds, and reporting units prevented quantitative pooling. Ten studies were classified as high quality and 10 as moderate quality; none were rated low quality. Bibliometric analysis identified three keyword communities and 13 disconnected co-authorship groups, indicating an emerging but fragmented research field.

Conclusions

Plant-based biomonitoring offers time-integrated data on airborne microplastic deposition and spatial variability. However, plant particle burdens should not be interpreted as indicators of ambient concentration, internal uptake, or human exposure. Wider application requires standardized sampling and reporting protocols, validated matrix-specific extraction methods, stringent quality assurance and control measures, and calibration against conventional atmospheric samplers.

1. Introduction

The growing acknowledgment of airborne microplastics (AMPs) as a novel element of atmospheric pollution necessitates the development of monitoring methods that can effectively capture spatial variations and cumulative deposition over time. Plant-based biomonitoring has garnered increasing interest due to the stationary nature, widespread distribution, and continuous exposure of vegetation to atmospheric particles. Various biomonitoring matrices, including vascular-plant leaves and needles, mosses, and lichens, have been examined, although their effectiveness varies based on factors such as surface morphology, wax composition, trichome density, thallus structure, canopy position, and exposure conditions. In the majority of field-based studies, AMPs are evaluated as particles deposited on or retained by external plant surfaces through processes such as interception, adhesion, entrapment, and association with epicuticular waxes or other surface structures. Consequently, the observed particle burdens should

be interpreted primarily as indicators of atmospheric deposition and surface retention, rather than as evidence of internal absorption or translocation into plant tissues.(Jafarova et al., 2022; Capozzi et al., 2023a, 2023b; Leonard et al., 2023; Perera et al., 2024; Sunaga et al., 2024).

A variety of plant matrices have been employed to explore various aspects of AMP deposition. Mosses and lichens are utilized in passive sampling, transplantation, and comparative biomonitoring studies due to their high surface-area-to-volume ratios and structurally intricate external surfaces (Bertrim and Aherne, 2023; Capozzi et al., 2023a, 2023b; Jafarova et al., 2023a). Vascular plants, such as *Ficus virens*, *Robinia pseudoacacia*, *Quercus serrata*, pine needles, and edible leaves like *Lactuca sativa*, have been investigated for canopy interception, spatial and seasonal variation, long-term retention, and potential contamination of food-crop surfaces (Liu et al., 2022; Canha et al., 2023; Huang et al., 2023; Jafarova et al., 2023b; Sunaga et al., 2024). Additionally, leaf biosampling has been applied to other airborne contaminants, establishing a broader methodological framework for vegetation-based environmental surveillance. However, these studies should not be misconstrued as direct evidence of AMP biomonitoring (Barroso et al., 2019).

The methodological complexity inherent in interpreting plant-associated microplastics remains significant. Variations in biomonitor species, sampling height, exposure duration, canopy position, meteorological conditions, extraction procedures, and particle-size thresholds can markedly affect the reported abundance. When microplastics are embedded within epicuticular waxes or are strongly retained by complex surfaces, particle recovery may be incomplete. Additionally, differences in washing, ultrasonication, digestion, and filtration procedures can further complicate comparability among studies (Leonard et al., 2023; Sunaga et al., 2024). Reliable identification necessitates chemical confirmation through techniques such as Fourier-transform infrared spectroscopy, μ -FTIR, Raman spectroscopy, or related spectroscopic methods, as visual examination alone is inadequate for definitive polymer identification (Löder et al., 2015; Ivleva, 2021). Despite advancements in analytical capabilities, inconsistencies in contamination control, recovery validation, spectral-matching criteria, detection thresholds, and reporting practices continue to hinder cross-study synthesis and quantitative comparison (Pérez-Guevara et al., 2022; Shruti and Kutralam-Muniasamy, 2023).

Jahedi et al. (2025) recently reviewed plant biomonitoring of microplastics across multiple environmental compartments, including atmospheric, terrestrial, and aquatic settings. Their work provided an important broad overview of plant-based microplastic biomonitoring. However, the evidence specific to field-based monitoring of airborne deposition requires more detailed evaluation because it involves distinct questions concerning particle interception, surface retention, biomonitor selection, extraction from plant surfaces, and comparability with conventional atmospheric sampling. To our knowledge, the present review provides a focused synthesis of field-based plant biomonitoring of airborne microplastic deposition, while also evaluating methodological quality and examining the emerging conceptual and collaborative structure of this research area through exploratory bibliometric analysis.

This systematic review examines four key questions: (i) which plant species and biomonitor matrices have been employed to evaluate airborne microplastic deposition; (ii) which sampling, extraction, and analytical methods have been utilized; (iii) what evidence exists concerning the occurrence, distribution, morphology, and polymer composition of plant-associated airborne microplastics (AMPs); and (iv) what methodological limitations, knowledge gaps, and research priorities are identified from the current evidence base. By addressing these questions, the review seeks to elucidate the current capabilities and limitations of plant-based AMP biomonitoring and to facilitate the development of more harmonized, reproducible, and interpretable monitoring approaches.

2. Methods

2.1. Protocol and Registration

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review protocol was prospectively developed and approved by the National Institute for Medical Research Development (NIMAD) and the Ethics Committee of Ahvaz Jundishapur University of Medical Sciences prior to the commencement of the study. Because of the substantial time elapsed between the original submission and resubmission of the manuscript, the literature search was updated through June 2026 to incorporate newly published evidence and ensure a comprehensive synthesis of the available literature. All previously included studies were subsequently re-screened alongside newly identified records using the predefined eligibility criteria to ensure methodological consistency throughout the review process.

2.2. Eligibility Criteria

To ensure the relevance and scientific rigor of the evidence base, this review included original peer-reviewed studies that investigated the use of plants as biomonitors, passive samplers, or indicators of airborne microplastics (AMPs) under relevant environmental conditions. Eligible studies employed naturally occurring, transplanted, or experimentally deployed vegetation to assess atmospheric microplastic contamination in field conditions. Studies involving mosses, lichens, tree leaves, needles, crop plants, or other vegetation were included if they directly quantified airborne or atmospheric microplastics associated with plant matrices.

Exclusion Criteria: Studies were excluded if they (i) did not explicitly investigate airborne or atmospheric microplastics; (ii) did not employ plants or vegetation as biomonitoring matrices; (iii) focused exclusively on laboratory ecotoxicological exposures unrelated to atmospheric biomonitoring; (iv) investigated non-plant environmental matrices (e.g., street dust, soil, sediments, or water) without a plant-based component; (v) were review articles, editorials, conference abstracts, preprints, or other non-original publications; or (vi) were published in languages other than English.

Methodological studies were retained if they generated original field-based data on airborne microplastics associated with vegetation and evaluated the suitability of plant matrices for atmospheric microplastic biomonitoring.

2.3. Sources

A systematic literature search was conducted using the electronic databases PubMed, Web of Science, Scopus, Embase, ScienceDirect, and Google Scholar, encompassing studies published from the inception of each database until June 2026. Owing to the significant time lapse between the original submission and the resubmission of the manuscript, the literature search was updated prior to the revision to include newly published evidence. All previously included studies were re-screened alongside newly identified records using the predefined eligibility criteria. To ensure comprehensive evidence retrieval, the reference lists of all the included articles were manually screened, and backward and forward citation chasing was performed using the CitationChaser R package (Haddaway et al., 2021). Additional author-based searches and manual verification of publication records were conducted to identify potentially relevant studies that were not captured through database searches and to prevent the duplicate inclusion of the same study. Grey literature sources, including conference proceedings and preprint repositories, were also screened to assess the completeness of the evidence retrieval; however, only peer-reviewed studies were included in the primary qualitative synthesis. Preprints identified during the search process were checked for subsequent peer-reviewed publications, and only the final peer-reviewed versions were retained in the analysis.

2.4. Search Strategy

The search strategy was developed in consultation with a research librarian and combined controlled vocabulary terms (e.g., Medical Subject Headings [MeSH], where applicable) with free-text keywords using the Boolean operators. The search terms included combinations of "airborne microplastics," "atmospheric microplastics," "plant biomonitoring," "biomonitor*", "passive sampler," "moss," "lichen," "tree leaves," "pine needles," "vegetation," "environmental monitoring," and "microplastic pollution."

Search strategies were adapted to the indexing systems and functionalities of each database. The complete database-specific search strings are provided in Supplementary File S1.

2.5. Study Selection

All retrieved records were imported into reference management software, and duplicate records were removed before screening. Two reviewers independently screened the titles and abstracts based on predefined eligibility criteria. Full-text articles were subsequently retrieved for studies deemed potentially eligible or when eligibility could not be determined from the abstract alone. Disagreements between reviewers during both screening stages were resolved through discussion and consensus. If consensus could not be reached, a third reviewer adjudicated the final decision. Following the updated literature search, newly identified records and all previously included studies were independently re-screened by the two reviewers using the predefined eligibility criteria to ensure methodological consistency throughout the review process. The study selection process was documented using a PRISMA 2020-compliant flow diagram generated with the PRISMA2020 R package and Shiny application (Haddaway et al., 2022), which was subsequently refined graphically using Inkscape for publication purposes.

2.6. Data Extraction and Quality Assessment

Two reviewers independently conducted data extraction utilizing a standardized form specifically created for this review. The variables extracted encompassed the year of publication, the location of the study, the biomonitor species or plant matrix involved, the design of the study, the sampling strategy employed, the conditions of exposure, the procedures for sample preparation, the analytical methods

used, the abundance of microplastics, the morphology of particles, the composition of polymers, and the main findings. Any disagreements were addressed through discussion and mutual agreement; if consensus was not achieved, a third reviewer made the final decision.

2.7. Risk of Bias Assessment

The quality of the methodologies in the studies included was evaluated separately by two reviewers, employing an eight-domain framework that was predefined and adapted from existing guidelines for microplastic research and the Newcastle–Ottawa Scale (Hermesen et al., 2018; Stang, 2010). This framework was specifically adjusted for plant-based environmental biomonitoring and assessed factors such as seasonal and spatial coverage, comparative study design, extraction and isolation techniques, geographical diversity, repeatability, consideration of environmental confounders, analytical identification methods, and the thoroughness of quantitative reporting. Any disagreements were settled by reaching a consensus or, if needed, by consulting a third reviewer. Supplementary File S2 contains the detailed scoring criteria and the thresholds for quality classification.

2.8. Data Synthesis and Analysis

The extracted data were synthesized using a narrative approach owing to the considerable heterogeneity in the study designs, plant matrices, sampling strategies, analytical methodologies, and outcome measures, which rendered a quantitative meta-analysis unfeasible. The findings were categorized thematically into plant species used, methodological approaches, characteristics of airborne microplastics, methodological quality, and risk-of-bias outcomes. Geospatial mapping techniques were used to visualize the geographical distribution of the included studies, identify research hotspots, and highlight regions with limited evidence of research. Subsequently, trends, knowledge gaps, and priorities for future research were identified and discussed in this paper.

2.9. Exploratory Bibliometric Analysis

In addition to the systematic review, an exploratory bibliometric analysis was undertaken to delineate the conceptual framework, collaboration dynamics, and emerging research themes in the domain of plant-based biomonitoring of airborne microplastics. Bibliographic metadata from the 20 selected studies were compiled in BibTeX format and analyzed using R version 4.6.0 and Bibliometrix version 5.4.1 (Aria & Cuccurullo, 2017). Prior to analysis, the bibliographic records were screened for completeness, standardization, and deduplication. A customized term-normalization thesaurus was employed to consolidate synonymous expressions, standardize singular and plural forms, and spelling variants, as well as to eliminate generic or non-informative terms. A keyword co-occurrence analysis was conducted to identify principal research themes and inter-concept relationships. Co-authorship analysis examined collaboration patterns among authors, while country-level collaboration analysis assessed international research partnerships. Bibliographic coupling was evaluated to identify similarities among publications based on shared cited references. The resulting network datasets and bibliometric indicators were exported from R and visualized using Python version 3.13.9 with pandas, NumPy, NetworkX, Matplotlib, and adjustText. In the keyword network, node size indicated keyword occurrence frequency, and edge thickness indicated co-occurrence strength. In the co-authorship network, node size represented the number of publications contributed by each author, and edge thickness represented the number of co-authored publications. Independent research teams were identified as connected components. Deterministic force-directed layouts were utilized solely for graphical positioning. Due to the limited number of included studies and incomplete bibliographic information in some records, the findings were considered exploratory and interpreted with caution. The bibliometric analysis aimed to provide complementary insights into the conceptual and collaborative structure of this emerging field rather than to serve as a comprehensive scientometric assessment.

3. Results

3.1. Study Selection

The initial literature search, conducted in 2024, identified studies published until that year. After screening and assessing eligibility, 16 studies met the predefined inclusion criteria and were included in the initial version of this review. Owing to the extended revision period and rapidly expanding literature on plant-based biomonitoring of airborne microplastics, the search strategy was updated during successive revision rounds and again immediately prior to resubmission on June 24, 2026, to ensure the inclusion of the most recent evidence.

The updated search yielded 86 records in total. After removing 32 duplicates, 54 unique records remained for the title and abstract screening. At this stage, 32 records were excluded for not meeting the predefined eligibility criteria, primarily due to irrelevance to

plant-based biomonitoring, absence of airborne microplastic assessment, or insufficient methodological information.

Subsequently, 22 full-text articles were retrieved and assessed for eligibility. Two studies were excluded after full-text evaluation because they did not meet the predefined inclusion criteria, including laboratory-only exposure designs and investigations that did not specifically address the issue of airborne microplastics.

Following the updated search and re-screening process, 20 peer-reviewed studies published between 2021 and 2026 met the eligibility criteria and were included in the final qualitative synthesis of this review. Additionally, one conference-based record identified through grey literature searches met the topical eligibility criteria; however, it was not included in the primary evidence synthesis because it had not undergone peer review.

The study selection process is summarized in Fig. 1, which illustrates the stages of identification, screening, eligibility assessment, and final inclusion, along with the reasons for exclusion at the full-text stage. This transparent and iterative approach ensured that the review incorporated the most current and methodologically robust evidence available on plant-based biomonitoring of airborne microplastics.

3.2. Study characteristics

The review encompassed 20 peer-reviewed field studies published between 2021 and 2026 (Table 1). These studies were conducted in nine countries, with a notable concentration in Europe and Asia (Fig. 2). Italy contributed the highest number of studies ($n = 7$), followed by China ($n = 5$) and Türkiye ($n = 2$). Additionally, one study was conducted in Australia, Canada, Iran, Japan, Portugal, and the United States. No eligible studies were identified in Africa or South America, highlighting the geographical imbalance in the available evidence, which does not yet provide global coverage. The investigations spanned a diverse range of environmental settings, including areas adjacent to landfills, industrial zones, urban and peri-urban environments, urban gardens, rural and semi-natural areas, forested landscapes and protected areas. Several studies have evaluated spatial variation along gradients of urbanization or pollution, while others have compared regions with varying degrees of anthropogenic influence (Capozzi et al., 2023a; Işık & Yıldız, 2026; Jafarova et al., 2022; Kocakaya et al., 2025; Loppi et al., 2021; Taurozzi et al., 2024). Most studies employed observational passive biomonitoring designs based on naturally exposed vegetation. Other methodologies include lichen transplantation (Jafarova et al., 2022), moss-bag deployment (Bertrim & Aherne, 2023) combined with moss and lichen transplantation (Capozzi et al., 2023b), comparative assessment of mosses and lichens (Jafarova et al., 2023a), controlled plant exposure experiments (Perera et al., 2024), and methodological validation of leaf-based biomonitoring (Leonard et al., 2023). These designs collectively assess atmospheric deposition, particle interception and retention, spatial and seasonal variability, and the suitability of different plant matrices for monitoring airborne microplastics. The included studies were categorized into five distinct biomonitoring categories: plant foliage was the most frequently represented category, accounting for eight studies (40% of studies). Lichens were utilized in five studies (25%), three studies (15%) jointly evaluated lichens and mosses, mosses alone were used in two studies (10%), and pine needles were examined in two studies (10%). Studies assessing both lichens and mosses were assigned to a single combined category and counted once in the geographical and biomonitoring group series, as presented in Fig. 2.

Table 1

Characteristics of peer-reviewed studies included in the qualitative synthesis on plant-based biomonitoring of airborne microplastics (2021–2026)

Ref.	Year	Location	Plant Species / Biomonitor	Study Design and Methodologies Employed	Key Findings	Other Specific Details
Loppi et al.	2021	Italy	<i>Flavoparmelia caperata</i> (lichen)	Passive biomonitoring study; field sampling of epiphytic lichens around a landfill, wet peroxide digestion, stereomicroscopy, μ -FTIR	Airborne MPs accumulated significantly in lichens collected near the landfill; fibers predominated and PET was the dominant polymer.	First field study demonstrating lichen biomonitoring of airborne MPs near a landfill.
Jafarova et al.	2022	Milan, Italy	<i>Evernia prunastri</i> (lichen transplant)	Transplant biomonitoring study; lichen transplantation along an urban gradient, digestion, filtration, microscopy, and spectroscopic identification	MP accumulation increased with urbanization intensity; fibers predominated.	Demonstrated the applicability of transplanted lichens as active biomonitors of atmospheric MPs.
Liu et al.	2022	Shihezi, China	Pine needles	Passive biomonitoring study; pine needle sampling, density separation, microscopy, and Raman spectroscopy	Pine needles effectively accumulated atmospheric MPs; urban sites exhibited higher concentrations; fibers and PE predominated.	First study employing pine needles as passive samplers of AMPs.
Bertrim & Aherne	2023	Canada	Moss bags	Transplant biomonitoring study; moss-bag exposure, digestion, microscopy, and FTIR analysis	Moss bags successfully monitored atmospheric MP deposition in urban environments; fibers were dominant.	Demonstrated the suitability of moss bags for active biomonitoring of AMPs.
Jafarova et al.	2023	Central Italy	<i>Evernia prunastri</i> and <i>Pseudoscleropodium purum</i>	Comparative biomonitoring study; field collection, wet peroxide oxidation, filtration, and microscopy	Moss accumulated significantly more MPs than lichen; fibers predominated in both biomonitors.	First direct comparison between moss and lichen biomonitors for airborne MPs.
Jafarova et al.	2023	Italy	<i>Robinia pseudoacacia</i> leaflets	Passive biomonitoring study; leaf sampling, digestion, microscopy, and FTIR	Leaflets reflected spatial variability in atmospheric MP deposition; fibers and PET predominated.	Demonstrated the suitability of deciduous tree leaves as biomonitors.

Footnotes

⌘ Leonard et al. (2023) was included because airborne microplastics were directly quantified on tree leaves collected under field conditions. Although the primary focus was methodological validation and assessment of uncertainties associated with leaf-based biomonitoring, the study generated original environmental monitoring data and evaluated the suitability of leaves as biomonitoring matrices.

Ref.	Year	Location	Plant Species / Biomonitor	Study Design and Methodologies Employed	Key Findings	Other Specific Details
Capozzi et al.	2023	Italy	<i>Hypnum cupressiforme</i> (moss)	Passive biomonitoring study; moss collection, digestion, stereomicroscopy, and μ -FTIR	Higher MP deposition was observed at sites with stronger anthropogenic influence; fibers predominated.	Biomonitoring conducted in rural and semi-natural environments.
Capozzi et al.	2023	Italy	Moss and lichen transplants	Transplant biomonitoring study; transplantation, exposure, digestion, microscopy, and FTIR	Mosses generally accumulated more anthropogenic microfibers than lichens.	Optimized transplant protocols for atmospheric microfiber biomonitoring.
Canha et al.	2023	Lisbon, Portugal	<i>Lactuca sativa</i> (lettuce)	Passive biomonitoring study; leaf sampling from urban gardens, digestion, and FTIR spectroscopy	Urban-grown lettuce accumulated MPs derived from atmospheric deposition; fibers and PET predominated.	Highlighted a potential food-chain exposure pathway.
Leonard et al. [¶]	2023	Los Angeles, United States	Urban tree leaves	Methodological validation study; field leaf sampling from urban tree canopies, microscopy, and FTIR	Identified strengths, limitations, and uncertainties associated with leaf-based biomonitoring of airborne MPs.	Evaluated the suitability and methodological challenges of leaf biomonitoring.
Huang et al.	2023	Chengdu, China	<i>Ficus virens</i>	Field-based vegetation interception study; atmospheric deposition monitoring beneath tree canopy and in open areas	<i>Ficus virens</i> intercepted approximately 6.25% of airborne MPs; fibers predominated.	Demonstrated the mitigation potential of urban trees for atmospheric MP pollution.
Xu et al.	2024	China	<i>Platycladus orientalis</i> , <i>Juglans regia</i> , and <i>Ulmus pumila</i>	Field biomonitoring study with additional ecological/phylosphere assessment; leaf sampling, LDIR analysis, and phylosphere microbial assessment	Urban leaves contained significantly higher MP loads than rural leaves; PE, PA, and rubber were dominant polymers.	Linked leaf-retained MPs with phylosphere bacterial communities.
Jiao et al.	2024	China	Multiple plant leaves	Passive biomonitoring study; seasonal monitoring of leaf-retained MPs	Leaf interception of AMPs exhibited pronounced temporal and seasonal fluctuations.	Demonstrated dynamic changes in vegetation capture efficiency.

Footnotes

[¶] Leonard et al. (2023) was included because airborne microplastics were directly quantified on tree leaves collected under field conditions. Although the primary focus was methodological validation and assessment of uncertainties associated with leaf-based biomonitoring, the study generated original environmental monitoring data and evaluated the suitability of leaves as biomonitoring matrices.

Ref.	Year	Location	Plant Species / Biomonitor	Study Design and Methodologies Employed	Key Findings	Other Specific Details
Khodabakhshloo et al.	2024	Shiraz, Iran	Mosses and lichens	Passive biomonitoring study; digestion, microscopy, and polymer identification	Both mosses and lichens effectively accumulated airborne MPs and microrubbers; fibers predominated.	First biomonitoring study of airborne MPs and microrubbers in Iran.
Taurozzi et al.	2024	Italy	Lichens	Passive biomonitoring study; lichen sampling, H ₂ O ₂ digestion, and FTIR	Urban sites exhibited significantly higher MP accumulation than natural and protected areas; fibers predominated.	Compared atmospheric MP deposition across urban, natural, and protected environments.
Sunaga et al.	2024	Tokyo, Japan	<i>Quercus serrata</i> (Konara oak) leaves	Passive biomonitoring study; water washing, ultrasonication, KOH extraction, and μ -FTIR	Forest canopy leaves acted as long-term sinks for AMPs; PE predominated; KOH extraction substantially improved recovery.	Demonstrated the importance of epicuticular waxes in AMP retention.
Perera et al.	2024	Queensland, Australia	Eight natural plant species and two artificial plants	Controlled exposure and retention experiment; controlled environmental exposure, μ -FTIR, μ -Raman, and SEM	AMP retention varied according to leaf morphology; trichome-bearing and structurally complex leaves retained more MPs; fibers and PET predominated.	Investigated mechanisms underlying plant retention of airborne MPs.
Kocakaya et al.	2025	Yozgat Çamlık National Park, Türkiye	Lichens	Passive biomonitoring study; wet peroxide oxidation, FTIR, and Raman spectroscopy	Anthropogenic microfibers were detected at all sites; polyurethane, ABS, and PET predominated.	Demonstrated the applicability of lichens for monitoring atmospheric microfiber pollution in protected areas.
Li et al.	2026	Xinjiang, China	Pine needles	Passive biomonitoring study; NaBr density separation, ultrasonication, H ₂ O ₂ digestion, Raman spectroscopy, and ecological risk assessment	Mean AMP abundance was 9.63 ± 4.59 particles g ⁻¹ ; winter concentrations were highest; fibers and PE predominated.	Included Pollution Load Index (PLI) and Potential Ecological Risk Index (PERI) assessments.

Footnotes

⌘ Leonard et al. (2023) was included because airborne microplastics were directly quantified on tree leaves collected under field conditions. Although the primary focus was methodological validation and assessment of uncertainties associated with leaf-based biomonitoring, the study generated original environmental monitoring data and evaluated the suitability of leaves as biomonitoring matrices.

Ref.	Year	Location	Plant Species / Biomonitor	Study Design and Methodologies Employed	Key Findings	Other Specific Details
Işık & Yıldız	2026	Ankara, Türkiye	<i>Xanthoria parietina</i> (lichen)	Passive biomonitoring study; wet peroxide oxidation, Rose Bengal staining, stereomicroscopy, and FTIR	A total of 566 MPs were detected; industrial zones exhibited the highest contamination levels; fibers predominated.	Confirmed the suitability of <i>Xanthoria parietina</i> as a biomonitor in industrial and landfill environments.
Footnotes						
■ Leonard et al. (2023) was included because airborne microplastics were directly quantified on tree leaves collected under field conditions. Although the primary focus was methodological validation and assessment of uncertainties associated with leaf-based biomonitoring, the study generated original environmental monitoring data and evaluated the suitability of leaves as biomonitoring matrices.						

Note: One additional conference-based record (Peiris et al., 2023) met the topical eligibility criteria but was excluded from the primary evidence synthesis because it had not undergone peer review.

Preprints superseded by peer-reviewed publications and not counted separately: Sunaga et al. (2023) and Kocakaya et al. (2024).

Sample preparation typically involves wet peroxide oxidation, alkaline digestion, density separation, washing, ultrasonication, and filtration. Initial particle detection and morphological characterization were generally performed using stereomicroscopy or optical microscopy, while polymer identification was accomplished through Fourier-transform infrared spectroscopy (FTIR), μ -FTIR, Raman spectroscopy, or laser direct infrared spectroscopy. In certain studies, scanning electron microscopy was utilized to examine particle and leaf surface morphology rather than for definitive polymer identification. Considerable variation was noted across studies regarding sampling design, extraction procedures, spectroscopic confirmation, contamination-control measures, and reporting practices; these methodological differences are further examined in Sections 3.3 and 3.5.

3.3. Methodological Quality and Risk-of-Bias Assessment

The methodological quality of the 20 studies included in the analysis varied from moderate to high quality. Using the adapted eight-domain assessment framework, 10 studies (50%) were classified as high quality, achieving total scores between 15 and 17, while the remaining 10 studies (50%) were categorized as moderate quality, with scores ranging from 11–14. Notably, no study was classified as low-quality. Figure 3 illustrates the criterion-level scores, total scores, and overall classifications for each of the studies.

High-quality studies are characterized by more precise sampling designs, increased spatial or temporal replication, and more comprehensive reporting of analytical procedures. These studies also included spectroscopic confirmation of polymer identity and demonstrated stronger implementation of contamination control and quality assurance/quality control measures. Furthermore, they generally provided more transparent descriptions of particle characteristics, sampling conditions, and data processing procedures.

The most common methodological limitations include restricted spatial coverage, limited or absent seasonal replication, incomplete reporting of meteorological and vegetation-related factors, and inconsistencies in contamination control procedures. Variations were also observed in the extraction methods, particle size detection thresholds, polymer confirmation criteria, recovery assessment, and reporting formats. These differences reduced the direct comparability among studies, even when their overall methodological quality was acceptable.

Studies of moderate quality typically omit one or more components related to sampling replication, environmental covariates, contamination control, recovery validation, or transparent reporting. However, none of the studies were classified as low quality according to the predefined criteria. Overall, the assessment indicates that the existing evidence base possesses moderate to high methodological quality, although it continues to exhibit weaknesses in standardization, reproducibility, and cross-study comparability.

3.4. Plant Species Used for Biomonitoring Airborne Microplastics

The studies included in this analysis utilized various matrices such as vascular-plant foliage, edible vegetation, needles, mosses, and lichens to serve as biomonitors for airborne microplastic deposition. These matrices were either sampled in natural environments, deployed as transplants or moss bags, or assessed under controlled field-exposure conditions. A summary of study-level characteristics is provided in Table 1, while Fig. 2 illustrates the geographical distribution of biomonitor groups.

Vascular foliage emerged as the most frequently examined matrix. *Robinia pseudoacacia* leaflets were employed to characterize spatial variations in atmospheric microplastic deposition in Italy (Jafarova et al., 2023b). In Chengdu, *Ficus virens* canopies were analyzed to assess the interception of airborne particles compared to adjacent open areas (Huang et al., 2023). Additional studies evaluated multiple tree species, including *Platycladus orientalis*, *Juglans regia*, and *Ulmus pumila*, across both urban and rural settings (Xu et al., 2024), and monitored temporal and seasonal variations in particle accumulation on leaves (Jiao et al., 2024). Urban tree leaves were also utilized in a methodological validation study of leaf-based biomonitoring (Leonard et al., 2023), and controlled field exposure of both natural and artificial plants was conducted to compare retention across different leaf morphologies (Perera et al., 2024). Edible vegetation, represented by *Lactuca sativa* collected from urban gardens in Lisbon, highlighted the significance of foliar deposition in potential food-crop contamination (Canha et al., 2023).

Needles and long-lived foliage provided matrices capable of integrating deposition over extended durations. *Quercus serrata* leaves were studied in forested areas of Tokyo, where epicuticular wax played a role in retaining deposited particles (Sunaga et al., 2024). Pine needles served as passive samplers in Shihezi, China, facilitating comparisons between urban and less urbanized sites (Liu et al., 2022), and were later used in Xinjiang to evaluate seasonal variations and ecological-risk indicators (Li et al., 2026).

Moss-based biomonitoring encompassed the use of naturally occurring mosses, moss bags, and comparative transplant designs. *Hypnum cupressiforme* was collected from rural and semi-natural environments in Italy to evaluate spatial variations in atmospheric deposition (Capozzi et al., 2023a), while moss bags were utilized in urban locations across Canada (Bertrim and Aherne, 2023). A direct comparison between *Pseudoscleropodium purum* and the lichen *Evernia prunastri* revealed differences in microplastic accumulation between these matrices (Jafarova et al., 2023a). Additionally, moss and lichen transplants were jointly assessed to enhance biomonitoring procedures for anthropogenic microfibres (Capozzi et al., 2023b).

Lichens were employed in environments affected by landfills, as well as urban, industrial, natural, and protected areas. *Flavoparmelia caperata* was sampled near a landfill in Italy (Loppi et al., 2021), and transplanted *Evernia prunastri* was used along an urbanisation gradient in Milan (Jafarova et al., 2022). Further studies employed lichens to compare deposition across urban, natural, and protected settings in Italy (Taurozzi et al., 2024), within Yozgat Çamlık National Park in Türkiye (Kocakaya et al., 2025), and in industrial and landfill-affected areas of Ankara using *Xanthoria parietina* (Işık and Yıldız, 2026). In Shiraz, Iran, both mosses and lichens were evaluated for the accumulation of airborne microplastics and microrubbers (Khodabakhshloo et al., 2024).

Overall, the studies employed various plant matrices for specific monitoring objectives: vascular foliage and edible plants were used for spatial, seasonal, interception, and food-surface assessments; needles and long-lived leaves for cumulative deposition; and mosses and lichens for passive, comparative, and transplant-based monitoring. Differences in matrix performance and interpretation are discussed in Sections 3.5 and 4.2.

3.5. Plant-Specific Challenges in Sampling, Preparation, and Interpretation of Airborne Microplastics

In the reviewed studies, plant-associated airborne microplastics were primarily assessed as particles deposited on or retained by external plant surfaces. Leaves, needles, moss thalli, and lichen surfaces act as passive collectors through mechanisms such as interception, adhesion, and entrapment within cuticles, epicuticular waxes, trichomes, surface irregularities, and other external structures. Therefore, the reported particle burdens should be interpreted as indicators of surface deposition and retention, rather than evidence of internal absorption or translocation into plant tissues. This distinction is crucial when comparing plant-based biomonitoring results with measurements obtained using conventional atmospheric sampling. Biomonitor morphology significantly contributes to the variability in particle capture. A direct comparison between *Pseudoscleropodium purum* and *Evernia prunastri* revealed greater microplastic accumulation by the moss under the investigated conditions, suggesting that differences in surface structure can affect retention efficiency (Jafarova et al., 2023a). Moss-and-lichen transplant experiments similarly demonstrated matrix-specific differences in the accumulation of anthropogenic microfibers (Capozzi et al., 2023b). Among vascular plants, factors such as leaf roughness, trichome abundance, wax characteristics, surface complexity, and canopy architecture influence particle interception and persistence. Methodological assessment of urban tree leaves highlighted variability associated with leaf properties

and sampling conditions (Leonard et al., 2023), while controlled exposure experiments indicated that trichome-bearing and structurally complex leaves generally retained more airborne microplastics than smoother surfaces (Perera et al., 2024).

Particle recovery from plant surfaces introduces additional methodological uncertainty. While washing and ultrasonication can remove loosely deposited particles, they may not fully recover microplastics embedded in epicuticular waxes or those strongly attached to complex surface structures. In forest canopy leaves, the use of potassium hydroxide extraction resulted in the recovery of more particles compared to conventional washing-based procedures, highlighting that extraction efficiency can significantly influence the measured abundance (Sunaga et al., 2024). The sample preparation methods employed in the studies reviewed included various combinations of wet peroxide oxidation, alkaline digestion, density separation, washing, ultrasonication, and filtration. Consequently, variations in reagent selection, treatment intensity, filter characteristics, and minimum detectable particle size hindered direct comparison of reported concentrations. Contamination control also varied across studies. Plant samples were prone to secondary contamination during field collection, transport, preparation, filtration, microscopy, and spectroscopic analysis due to the ubiquity of microplastic fibers in both indoor and outdoor air. Although several studies reported procedural blanks and laboratory contamination-control measures, there was inconsistency in reporting blank correction, recovery testing, filtered reagents, laboratory clothing, exposed materials, and clean-air working conditions. These discrepancies contributed to uncertainty in distinguishing environmentally deposited particles from contamination introduced during sample handling and analysis.

The interpretation is further complicated by spatial and temporal factors. The microplastic loads associated with plants vary according to sampling location, urbanization intensity, canopy exposure, season, precipitation, and local environmental conditions. Temporal variations in leaf interception have been documented in seasonal monitoring studies (Jiao et al., 2024), whereas monitoring of pine needles has indicated a higher abundance during winter in Xinjiang (Li et al., 2026). Research on precipitation and underlying surface conditions suggests that atmospheric deposition and vegetation interception may vary according to local environmental processes (Huang et al., 2023). Consequently, differences in the abundance of plant-associated particles may reflect ambient atmospheric contamination and variations in exposure duration, meteorology, plant morphology, and sampling position.

Evidence indicates that airborne microplastic measurements using plant-based methods are influenced by factors such as the choice of biomonitor, surface characteristics, exposure conditions, extraction efficiency, contamination control, and analytical thresholds. These sources of variability must be considered when interpreting individual studies and comparing the results across various plant matrices and environmental contexts. Detailed recommendations for methodological harmonization are provided in the Discussion.

3.6. Occurrence, Characteristics, and Environmental Patterns of Airborne Microplastics

Airborne microplastics have been identified within plant matrices across diverse environments, including urban, industrial, rural, semi-natural, forested, and protected areas. Numerous studies have documented elevated particle concentrations in locations with significant anthropogenic impacts. Notably, increased accumulation has been recorded along an urbanization gradient in Milan (Jafarova et al., 2022), at urban sites compared to less urbanized areas in China (Liu et al., 2022; Xu et al., 2024), and in regions influenced by industrial activities, landfill operations, or other intensive human activities (Loppi et al., 2021; Capozzi et al., 2023a; Taurozzi et al., 2024; Işık and Yıldız, 2026). However, considerable variability in sampling matrices, exposure durations, extraction methods, particle size thresholds, and reporting units hindered the direct quantitative aggregation of the reported abundances.

Fibers emerged as the most commonly reported particle morphology in the studies reviewed, although fragments and other non-fibrous particles were also identified in some studies. The polymer composition varied across the studies and analytical methods. Polyethylene terephthalate has been frequently detected in lichens, tree leaves, lettuce, and plants exposed experimentally (Loppi et al., 2021; Canha et al., 2023; Jafarova et al., 2023b; Perera et al., 2024), whereas polyethylene has been predominant in several investigations of pine needles and forest canopies (Liu et al., 2022; Sunaga et al., 2024; Li et al., 2026). Other reported materials include polypropylene, polyamide, polyurethane, acrylonitrile butadiene styrene, and rubber-related particles, indicating significant variability in the polymer profiles detected across different environmental contexts (Xu et al., 2024; Kocakaya et al., 2025).

The accumulation of airborne microplastics is influenced by the characteristics of the biomonitor surface. Controlled exposure experiments have demonstrated that leaves with structural complexity and trichomes retain more particles than smoother surfaces (Perera et al., 2024). Research on forest canopies has further shown that epicuticular waxes enhance the retention of deposited particles on *Quercus serrata* leaves (Sunaga et al., 2024). In Chengdu, the canopies of *Ficus virens* have been found to intercept airborne microplastics more effectively than adjacent open areas, highlighting the potential role of urban vegetation in altering local

deposition patterns (Huang et al., 2023). Consequently, leaf-based studies reflect not only ambient contamination but also species-specific variations in surface morphology and particle retention capacity.

Evidence from edible vegetation suggests a potential pathway for atmospherically deposited microplastics to enter food systems. Microplastics have been detected on *Lactuca sativa* collected from urban gardens in Lisbon, indicating that edible leaves can serve as environmental biomonitors and matrices pertinent to potential dietary exposure (Canha et al., 2023). Nonetheless, current studies have not provided sufficient standardized evidence to quantify resultant human exposure or health risk.

Comparative studies have revealed distinctions among the cryptogamic biomonitors. Under similar exposure conditions, *Pseudoscleropodium purum* accumulated more microplastics than *Evernia prunastri* (Jafarova et al., 2023a). In contrast, transplant experiments have indicated matrix-specific variations in the retention of anthropogenic microfibers by mosses and lichens (Capozzi et al., 2023b). Furthermore, moss bags have proven to be effective for the standardized monitoring of atmospheric deposition across urban areas (Bertrim and Aherne, 2023). These findings advocate for the use of mosses and lichens as complementary biomonitoring matrices rather than directly interchangeable ones.

The evidence presented indicates that plant-associated airborne microplastic burdens differ according to environmental setting, anthropogenic influence, biomonitor type, surface morphology, exposure conditions, and analytical procedures. Consistent patterns were observed, such as the predominance of fibers and increased contamination at sites with a greater anthropogenic influence. However, methodological heterogeneity has impeded direct comparisons of absolute concentrations across studies.

3.7. Exploratory Bibliometric Analysis

The exploratory bibliometric analysis encompassed all 20 studies from this systematic review. Keyword metadata, provided by the sources, was available for 18 studies (90%), forming the foundation for the keyword co-occurrence analyses. Across these records, 102 harmonized keywords were identified, with 18 meeting the minimum occurrence threshold of two keywords. After retaining co-occurrence relationships observed at least twice and excluding five terms that became isolated following link filtering, the displayed network comprised 13 connected keywords and 27 links (Fig. 4).

Three thematic communities were identified in this study: the largest community, interpreted as microplastics and biomonitoring, contained seven terms: microplastics, biomonitoring, lichens, mosses, microfibers, atmosphere, and Italy. The second community, interpreted as environmental monitoring, comprised air pollution, environmental monitoring, particulate matter, and concentration/composition analyses. The third community, which represents analytical methods, includes FTIR and Raman spectroscopy. These labels were assigned to summarize the dominant concepts within each algorithmically identified community rather than to represent predefined research categories.

Microplastics was the most frequently connected keyword, appearing in 16 records, followed by biomonitoring (10), air pollution (seven), and lichens (six). Microplastics also occupied the most structurally prominent position in the network. The strongest co-occurrence relationships were observed between biomonitoring and microplastics, and between lichens and microplastics, each with a link weight of five. Air pollution–microplastics and biomonitoring–lichens each had a weight of four, whereas microplastics–Raman spectroscopy had a weight of three. All remaining retained relationships had a weight of two. The network was organized around a central microplastic–biomonitoring axis, with environmental monitoring concepts and analytical methods forming smaller associated groupings.

The co-authorship network included 94 authors and 294 collaboration links (Fig. 5). All authors were connected to at least one co-author; however, the network was divided into 13 mutually disconnected collaboration groups, defined analytically as connected components. The group sizes ranged from two to 18 authors. The largest component contained 18 authors, representing 19.1% of all authors, and the mean component size was 7.2 authors. No collaborative links were observed between the 13 components. Furthermore, a substantial majority of the authors, precisely 83 out of 94 (88.3%), contributed to only one publication included in the study. This suggests that a limited group of contributors accounted for multiple authorships.

Stefano Loppi and Julian Aherne emerged as the most prolific contributors, each authoring five publications included in the study. Mehriban Jafarova followed with four publications, and Lisa Grifoni contributed three. Notable co-authorship connections were identified between Aherne and Loppi and between Jafarova and Loppi, with each pair collaborating on four publications. Additionally, the pairs Aherne and Jafarova, Grifoni and Jafarova, and Grifoni and Loppi shared three publications. The presence of multiple disconnected components, the absence of inter-group links, and the predominance of single-publication authors suggest that research

activity is concentrated within distinct collaboration groups rather than being integrated across a broader evidence base. All reported numerical results were independently reproduced in the final node, edge, and component tables. Given the limited number of studies included and the absence of source keyword fields in two records, these findings should be interpreted with caution. The networks provide complementary and provisional insights into the conceptual and collaborative structure of the field rather than offering a comprehensive scientometric characterization.

4. Discussion

This systematic review analyzed 20 peer-reviewed studies published between 2021 and 2026, focusing on the application of plants as biomonitors for airborne microplastics. The aggregated evidence demonstrates that vascular plant foliage, pine needles, mosses, and lichens can retain atmospherically deposited microplastics in urban, industrial, rural, forested, and protected environments. Several consistent patterns emerged, including the predominance of fibers, generally higher particle burdens in areas with increased anthropogenic influence, and significant effects of biomonitor morphology and extraction procedures on measured abundance. However, substantial heterogeneity in sampling design, exposure duration, analytical thresholds, reporting units, and contamination control procedures limits direct quantitative comparison among studies. The findings support plant-based biomonitoring as a valuable complementary method for characterizing atmospheric deposition, while also emphasizing the lack of sufficient standardization in the field for direct cross-study comparisons or routine regulatory applications.

4.1. Prevalence and Characteristics of Airborne Microplastics

Airborne microplastics have been detected in plant matrices across all the environmental contexts examined in the included studies. Numerous investigations have demonstrated a higher accumulation in areas characterized by increased urbanization, industrial activity, landfill influence, or other anthropogenic pressures. Specifically, microplastic accumulation has been observed to increase along an urbanization gradient in Milan (Jafarova et al., 2022). This pattern is similar to that observed when comparing urban areas with less urbanized regions in China (Liu et al., 2022; Xu et al., 2024). Furthermore, elevated microplastic levels have been detected near landfill sites or in environments affected by industrial activities in Italy and Türkiye (Işık & Yıldız, 2026; Loppi et al., 2021; Taurozzi et al., 2024). These findings are consistent with studies using conventional atmospheric sampling, which have also documented spatial variations in airborne microplastic abundance relative to population density, urban activity, and local emission sources (Boakes et al., 2023; Zhu et al., 2021). However, plant-associated particle loads should not be interpreted as direct measurements of ambient air concentration. Plants accumulate atmospheric deposition over time, and the measured abundance reflects the combined effects of airborne concentration, exposure duration, meteorological conditions, canopy position, surface morphology, particle adhesion, and extraction efficiency. The higher burdens reported in more anthropogenically influenced settings thus indicate spatial differences in deposition and retention but do not, in isolation, establish specific emission sources or quantify ambient exposure. Source attribution would require integration with direct air sampling, meteorological data, chemical modelling, or receptor-modelling approaches.

Fibers were the most frequently reported morphology across the included studies, whereas fragments and other non-fibrous particles were less frequently observed. This predominance has been reported in studies utilizing lichens, mosses, pine needles, tree leaves, and edible foliage (Loppi et al., 2021; Liu et al., 2022; Bertrim and Aherne, 2023; Canha et al., 2023; Jafarova et al., 2023a, 2023b; Kocakaya et al., 2025). Fiber dominance has also been commonly reported in studies employing active and passive atmospheric sampling (Levermore et al., 2020; Wright et al., 2019). Plausible contributors include the abrasion and shedding of synthetic textiles and the fragmentation of other plastic materials, although morphology alone is insufficient for definitive source identification (Cai et al., 2021). The apparent predominance of fibers may also partly reflect the methodological factors. Fibers are often more readily recognized during visual screening than small or irregular fragments, and their elongated shape may promote entanglement with trichomes, moss structures, lichen thalli, and other complex plant surfaces. Conversely, very small particles may be underrepresented because of limitations in filtration, microscopy, spectral resolution, and minimum particle size thresholds. Consequently, differences in the reported morphology among studies may reflect both environmental variation and analytical selectivity. The polymer compositions varied considerably across the studies. Polyethylene terephthalate has been frequently identified in lichens, mosses, lettuce, and tree foliage (Loppi et al., 2021; Canha et al., 2023; Jafarova et al., 2023b; Perera et al., 2024), whereas polyethylene has been prominent in several studies on pine needles and forest canopies (Liu et al., 2022; Sunaga et al., 2024; Li et al., 2026). Other reported materials include polypropylene, polyamide, polyurethane, acrylonitrile butadiene styrene, and rubber-related particles (Xu et al., 2024; Khodabakhshloo et al., 2024; Kocakaya et al., 2025). This variability may reflect differences in local sources, environmental transport, biomonitor retention properties, spectroscopic methods, and library-matching criteria. Therefore, polymer identity alone should be

interpreted cautiously and not treated as definitive evidence of a particular source without supporting contextual or chemical information.

The extensive detection of fibers and common consumer polymers aligns with the broader understanding that atmospheric transport plays a significant role in the environmental plastic cycle. Small and lightweight particles can remain airborne or be transported beyond their immediate source areas before settling on vegetation and other surfaces (Brahney et al., 2021). Consequently, plant biomonitors may provide a time-integrated record of local and regional deposition, complementing the shorter sampling periods of conventional active air samplers. Nonetheless, calibration studies directly comparing plant-associated particle burdens with standardized atmospheric measurements are scarce.

Evidence indicates that airborne microplastic deposition on vegetation is prevalent in the studied geographical regions, with a higher prevalence in areas with significant anthropogenic influence. Fibers were the most frequently reported morphology, while polymer profiles varied depending on location and analytical methods. These patterns align with those from conventional atmospheric monitoring. However, methodological heterogeneity and the absence of standardized reporting impede the calculation of a reliable pooled abundance or universal particle-composition estimate.

4.2. Effectiveness and Complementarity of Plant-Based Biomonitoring

Mosses and lichens have significant potential as biomonitors of atmospheric microplastic deposition. Current evidence does not support the universal superiority of any group. In a direct comparison between *Pseudoscleropodium purum* and *Evernia prunastri*, the moss exhibited a higher accumulation of microplastics than the lichen under the studied conditions. This suggests that variations in the surface area and thallus structure may influence the retention efficiency (Jafarova et al., 2023a). Similarly, transplantation experiments have revealed matrix-specific differences in the accumulation of anthropogenic microfibers by mosses and lichens (Capozzi et al., 2023b). Field sampling of *Hypnum cupressiforme* further demonstrated its ability to reflect spatial differences in atmospheric deposition across rural and semi-natural environments (Capozzi et al., 2023a), whereas moss bags provided a standardized method for assessing deposition in urban areas (Bertrim and Aherne, 2023). These findings advocate for the use of mosses and lichens as complementary biomonitoring matrices rather than as interchangeable ones.

Higher plants also exhibit considerable utility, particularly in the evaluation of spatial patterns, interception processes, seasonal variability, and potential exposure pathways. *Robinia pseudoacacia* leaflets demonstrate spatial variations in atmospheric microplastic deposition, with their waxy surfaces aiding particle retention (Jafarova et al., 2023b). Pine needles offer a persistent foliar matrix capable of integrating deposition over extended periods (Liu et al., 2022; Li et al., 2026), whereas *Quercus serrata* leaves retain particles within epicuticular waxes, highlighting the significance of leaf surface characteristics (Sunaga et al., 2024). Controlled comparisons of natural and artificial plants further indicated that trichome-bearing and structurally complex leaves generally retained more microplastics than smoother surfaces (Perera et al. 2024). Additionally, the detection of atmospherically deposited microplastics in *Lactuca sativa* underscores the potential relevance of edible vegetation in assessing food-chain exposure (Canha et al., 2023).

The effectiveness of plant biomonitors depends on the specific aims of the monitoring process. Mosses and lichens are particularly beneficial for standardized transplantation studies and spatial comparisons because of their reliance on atmospheric deposition and complex surface structures. In contrast, leaves and needles are more appropriate when the objectives include evaluating canopy interception, seasonal accumulation, land-use gradients, or contamination of edible vegetation. However, differences in surface morphology, exposure duration, growth stage, canopy position, and extraction efficiency indicate that particle burdens measured across various plant matrices are not directly comparable.

Plant-based biomonitoring fundamentally differs from traditional atmospheric sampling methods. Active air samplers measure particles within a defined air volume over a specified sampling period, providing relatively high temporal resolution. Depending on the filter characteristics and analytical methods, they may also be more effective in detecting smaller suspended particles (Wright et al., 2019; Levermore et al., 2020; Xu et al., 2023). In contrast, plant biomonitors integrate deposition and retention over extended and sometimes less precisely defined exposure periods. Consequently, they offer a spatially integrated depiction of atmospheric deposition but cannot be directly converted into ambient air concentrations because of the lack of standardization in effective sampling area, sampled air volume, and particle retention efficiency.

The particle assemblage retained by vegetation may differ from that captured by active or conventional passive samplers. Fibers and larger particles are often preferentially intercepted or entangled by trichomes, waxes, moss structures, and lichen thalli, whereas very small particles may be underrepresented because of weak adhesion, environmental removal, extraction losses, or analytical detection limits. Therefore, agreement in dominant particle forms or polymers between plant and conventional sampling methods should not be interpreted as evidence that both approaches characterize the same fraction of atmospheric microplastics.

Plant-based biomonitoring should be regarded as a complementary environmental monitoring approach rather than a substitute for direct air sampling. Its primary advantages include the potential for relatively low-resource deployment, extensive spatial coverage, repeated monitoring, and assessment of cumulative deposition across diverse environments. However, its current limitations include the lack of standardized calibration, significant species-specific variability, and limited comparability of results expressed using different plant mass, surface area, or exposure-based units. Future studies should integrate plant biomonitors with co-located active or passive atmospheric samplers, meteorological measurements, and standardized extraction and analytical protocols. Such integrated designs would enable the calibration of biomonitor responses, clarify the atmospheric particle fractions represented by different plant matrices, and enhance the interpretation of spatial and temporal deposition patterns.

4.3. Methodological Heterogeneity and Quality-Assurance Challenges

Despite the increasing use of plants as biomonitors for airborne microplastics, significant methodological heterogeneity remains, posing substantial challenges in comparing and synthesizing findings across studies. Variations are evident in biomonitor selection, sampling height and duration, exposure conditions, spatial replication, seasonal coverage, sample preparation, analytical confirmation, particle size thresholds, and reporting units. Plant-specific characteristics, such as surface morphology, epicuticular wax composition, trichome density, canopy position, and particle retention efficiency, further contribute to this variability. Consequently, differences in reported particle abundance may reflect not only environmental contamination but also variations in biomonitor performance, exposure history and analytical procedures. A central limitation is the absence of calibration between plant-associated particle burdens and measurements obtained through standardized, active, or passive atmospheric sampling. Plants function as time-integrated indicators of deposition and retention; however, parameters such as the effective sampling area, exposure duration, retention efficiency, and equivalent volume of sampled air are typically not well defined. Results expressed in terms of dry mass, fresh mass, leaf area, or sampled surface cannot be directly translated into ambient air concentrations or deposition fluxes. Co-located studies that integrate vegetation sampling with conventional atmospheric monitoring and meteorological measurements are necessary to establish quantitative relationships between plant-associated particulate loads and their airborne concentrations. Quality assurance and quality control practices also exhibited considerable variability. Although several studies have reported procedural blanks and contamination prevention measures, the use and documentation of field blanks, laboratory blanks, filtered reagents, nonsynthetic clothing, clean-air workspaces, recovery experiments, and blank correction were inconsistent. Method-specific limits of detection and quantification have rarely been reported. Given the ubiquity of airborne fibers in sampling and laboratory environments, inadequate contamination control may significantly influence the reported particle counts, particularly in studies involving small samples or low environmental burdens. Transparent and harmonized QA/QC reporting is therefore essential for evaluating data reliability and supporting cross-study comparisons (Hermesen et al., 2018; Shruti & Kutralam-Muniasamy, 2023).

Analytical heterogeneity presents an additional challenge. Although FTIR, μ -FTIR, Raman spectroscopy, and LDIR were utilized for polymer identification, studies differed in the proportion of visually identified particles subjected to spectroscopic confirmation, the selection of spectral libraries, matching thresholds, minimum detectable particle sizes, and the handling of uncertain spectra. Scanning electron microscopy offered valuable insights into particle and plant surface morphology but did not independently confirm polymer identity. Such variations can significantly affect reported particle abundance, morphology, size distribution, and polymer composition. Extraction efficiency is particularly critical for vascular plant matrices. While washing and ultrasonication may recover loosely deposited particles, they can underestimate particles embedded within epicuticular waxes or retained by complex surface structures. The increased recovery observed following alkaline extraction of forest canopy leaves illustrates how extraction procedures can materially influence measured abundance (Sunaga et al., 2024). Recovery experiments using representative polymer types, particle sizes, and plant matrices are therefore necessary to evaluate method performance and distinguish analytical losses from actual environmental variation. Temporal and environmental coverage also remains limited. Many studies relied on a single sampling campaign or geographically restricted study area, with relatively few incorporating repeated seasonal measurements. Meteorological conditions, precipitation, wind, exposure duration, vegetation characteristics, and canopy position were not consistently considered, despite their potential impact on deposition and retention. These limitations constrain the interpretation of temporal variability and complicate the differentiation between changes in atmospheric contamination and changes in plant-surface

accumulation. The methodological assessment classified 10 studies as high-quality and 10 as moderate-quality, with no studies categorized as low-quality. This suggests that the evidence base is generally credible but not methodologically uniform. Moderate-quality studies most commonly lacked extensive spatial or temporal replication, comprehensive contamination control, recovery validation, or detailed consideration of environmental covariates. Therefore, methodological quality should not be interpreted as evidence that findings are directly comparable across studies.

4.4. Key Recommendations for Plant-Based AMP Biomonitoring

Future advancements in plant-based airborne microplastic biomonitoring should focus on harmonizing sampling methods and data interpretation. Research must clearly distinguish between surface deposition and retention versus internal uptake, while also reporting on exposure duration, sampling height, plant organ, canopy position, season, sampled area or mass, and relevant meteorological conditions. The adoption of standardized reporting units and minimum metadata requirements would enhance transparency and facilitate comparisons across different biomonitoring species and environmental contexts.

Analytical standardization should encompass contamination control, extraction efficiency, polymer confirmation, and particle size reporting. Routine study design components should include field and laboratory blanks, recovery experiments, blank correction, and method-specific detection and quantification limits. It is crucial to report the proportion of particles subjected to spectroscopic confirmation and the spectral-matching criteria employed. Extraction protocols must be validated for the specific plant matrix, as methods effective for mosses or lichens may not adequately recover particles embedded within waxy or structurally complex vascular plant surfaces.

The selection of biomonitors should be guided by specific monitoring objectives rather than the assumption of the universal superiority of one plant group. Mosses and lichens may be particularly advantageous for transplantation studies and comparative assessments of atmospheric deposition, whereas leaves and needles may be more suitable for evaluating canopy interception, seasonal accumulation, land-use gradients, and contamination of edible vegetation. Comparative studies that expose different biomonitoring species to identical environmental conditions would help define matrix-specific performance and support the development of application-specific protocols.

There is also a need for greater integration with conventional atmospheric sampling. Co-located active and passive air samplers can be employed to calibrate plant-associated burdens against airborne concentrations and deposition fluxes. Integrating biomonitoring with meteorological measurements, geospatial analysis, source-apportionment methods, and atmospheric transport modelling would enhance the interpretation of spatial patterns and strengthen source identification. Such integration is essential before plant-derived measurements can be reliably used for quantitative exposure assessment or routine environmental surveillance.

The geographical evidence base needs to be expanded. Current studies are predominantly concentrated in Europe and Asia, with no eligible investigations from Africa or South America. Research in underrepresented climatic, socioeconomic, and land-use contexts is necessary to determine whether the findings from the existing evidence base are globally transferable. An exploratory co-authorship analysis further revealed that research activity was concentrated within disconnected collaboration groups. International and interdisciplinary partnerships can facilitate protocol harmonization, data sharing, interlaboratory comparisons, and the development of coordinated monitoring networks.

4.5 Environmental and Public Health Implications

The detection of airborne microplastics on vegetation suggests that atmospheric transport and deposition can introduce plastic particles into terrestrial environments. Plant surfaces may temporarily retain these particles, which can later be redistributed through mechanisms such as rainfall wash-off, leaf fall, surface runoff, or incorporation into soils. However, the reviewed studies primarily concentrated on the occurrence and biomonitoring performance, without directly quantifying the subsequent fate of retained particles, their transfer through terrestrial food webs, or their effects on ecosystem functioning. Consequently, while the ecological implications are plausible, they remain insufficiently characterized. The detection of microplastics on edible lettuce from urban gardens indicates that atmospheric deposition may contribute to the contamination of food-crop surfaces (Canha et al., 2023). This finding suggests a potential dietary exposure pathway but does not establish the ingestion dose, bioavailability, internal plant uptake, or human health risk. Similarly, the presence of particles on leaves should not be interpreted as evidence of translocation into edible tissues unless internal uptake has been specifically demonstrated. Exposure and risk assessments will require standardized measurements of particle abundance, size, polymer type, adherence, removal during washing or food preparation, and actual consumption. Plant-based biomonitoring may nonetheless offer practical environmental-health value by identifying areas of elevated atmospheric deposition and

supporting spatial surveillance where conventional monitoring is limited. Such information can aid in prioritizing locations for direct air sampling, source investigation, and ecological or human-exposure assessment. Plant biomonitoring should be regarded as a supplementary method for screening and surveillance, rather than a direct assessment of inhalation exposure, dietary intake, or health risk.

4.6. Limitations and Future Directions

This review is subject to several limitations. First, the inclusion criteria were restricted to peer-reviewed articles published in English, which may introduce language and publication bias. Although gray literature sources and preprint repositories were consulted to enhance retrieval comprehensiveness, non-peer-reviewed records were excluded from the primary synthesis.

Second, significant heterogeneity in biomonitor species, sampling designs, exposure periods, extraction procedures, analytical methods, particle-size thresholds, and reporting units precluded formal meta-analysis and limited direct quantitative comparison. Consequently, the synthesis primarily relied on narrative interpretation, and the observed differences among studies cannot be solely attributed to environmental conditions.

Thirdly, the evidence base is limited and geographically uneven. Most studies were conducted in Europe and Asia, with no representation from Africa and South America. Additionally, several studies relied on geographically restricted or single-period sampling, which constrained the assessment of seasonal variation, long-term trends, and transferability across climatic regions.

Fourth, the methodological quality was assessed using an adapted framework, as no universally accepted risk-of-bias instrument exists specifically for plant-based airborne microplastic biomonitoring. Although the criteria address sampling, analytical confirmation, contamination control, reporting, and reproducibility, the resulting quality classifications should be interpreted as structured comparative assessments rather than as definitive measures of study validity.

The bibliometric analysis, which was exploratory in nature, was conducted using a sample of only 20 studies, with keyword metadata available for 18 of these studies. The thematic and co-authorship networks produced should be considered provisional representations of the existing evidence base rather than stable or comprehensive depictions of the broader research field.

Future research should prioritize longitudinal and multi-season designs, co-located comparisons with conventional atmospheric samplers, validated extraction and recovery procedures, and comprehensive QA/QC reporting. Expanding into underrepresented regions and conducting coordinated multi-center studies would enhance geographical representativeness and support interlaboratory evaluation. Integration with source-apportionment methods, atmospheric transport modelling, and carefully designed ecological and human exposure studies would further elucidate the sources, fate, and implications of airborne microplastics retained by vegetation.

5. Conclusion

This systematic review of 20 peer-reviewed studies indicates that vascular plant leaves and needles, mosses, and lichens serve as complementary biomonitors for airborne microplastic (AMP) deposition across various environments, including urban, industrial, rural, forested, and protected areas. These matrices provide time-integrated data on spatial deposition patterns and particle retention. Nevertheless, particle burdens associated with plants do not directly correspond to ambient air concentrations, internal plant uptake, or human exposure.

The current evidence base is limited in scope and exhibits an uneven geographical distribution. Additionally, there is considerable heterogeneity in the selection of biomonitors, sampling and exposure conditions, extraction procedures, particle size thresholds, spectroscopic confirmation, contamination control and reporting units. These inconsistencies impede cross-study comparability, hinder reliable quantitative synthesis, and currently obstruct the direct translation of plant-associated particle burdens into atmospheric exposure and risk estimates.

The exploratory bibliometric analysis further revealed that the field remains conceptually focused on microplastics, biomonitoring, environmental monitoring, and analytical identification, whereas collaboration is fragmented among disconnected research groups. Future research should prioritize harmonized protocols, matrix-specific recovery validation, comprehensive QA/QC procedures, co-located calibration against conventional atmospheric samplers, and longitudinal multi-center monitoring in underrepresented regions. Establishing comparable methods and datasets will require international and interlaboratory collaboration. Currently, plant-based

biomonitoring is regarded as a complementary surveillance approach with the potential for broader environmental-monitoring applications once its performance has been more thoroughly standardized and validated.

Declarations

Ethics approval

Ethical approval for this study was granted by the Research Ethics Committee of the Ahvaz Jundishapur University of Medical Sciences (IR.AJUMS.REC.1402.548).

Consent to publish

Not applicable

Note

One additional conference-based record (Peiris et al., 2023) met the topical eligibility criteria but was excluded from the primary evidence synthesis because it had not undergone peer review.

Preprints superseded by peer-reviewed publications and not counted separately

Sunaga et al. (2023) and Kocakaya et al. (2024).

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Competing Interests

The authors declare the absence of any known competing financial interests or personal relationships that could have influenced the work reported in this study.

Author Contribution

Neda Kaydi and Farhad Safdari were responsible for conducting the investigation, validating the results, managing and curating the data, creating visualizations, preparing the initial draft, and contributing to the manuscript writing. Morteza Abdullatif Khafaie developed the methodology, provided supervision, and contributed to the review and editing of the manuscript. Mehdi Ahmadi Moghadam led the conceptualization and provided supervision. Fakher Rahim, Ajay Ojha and Mona Sharififard contributed to the review and editing of the manuscript. Samaneh Motalebi, Behzad Khafaei and Najmeh Yazdanparast performed data screening and extraction. All authors read and approved the final manuscript.

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Availability of data and materials

Data underpinning the findings of this study can be obtained from the corresponding author upon reasonable request.

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Figures

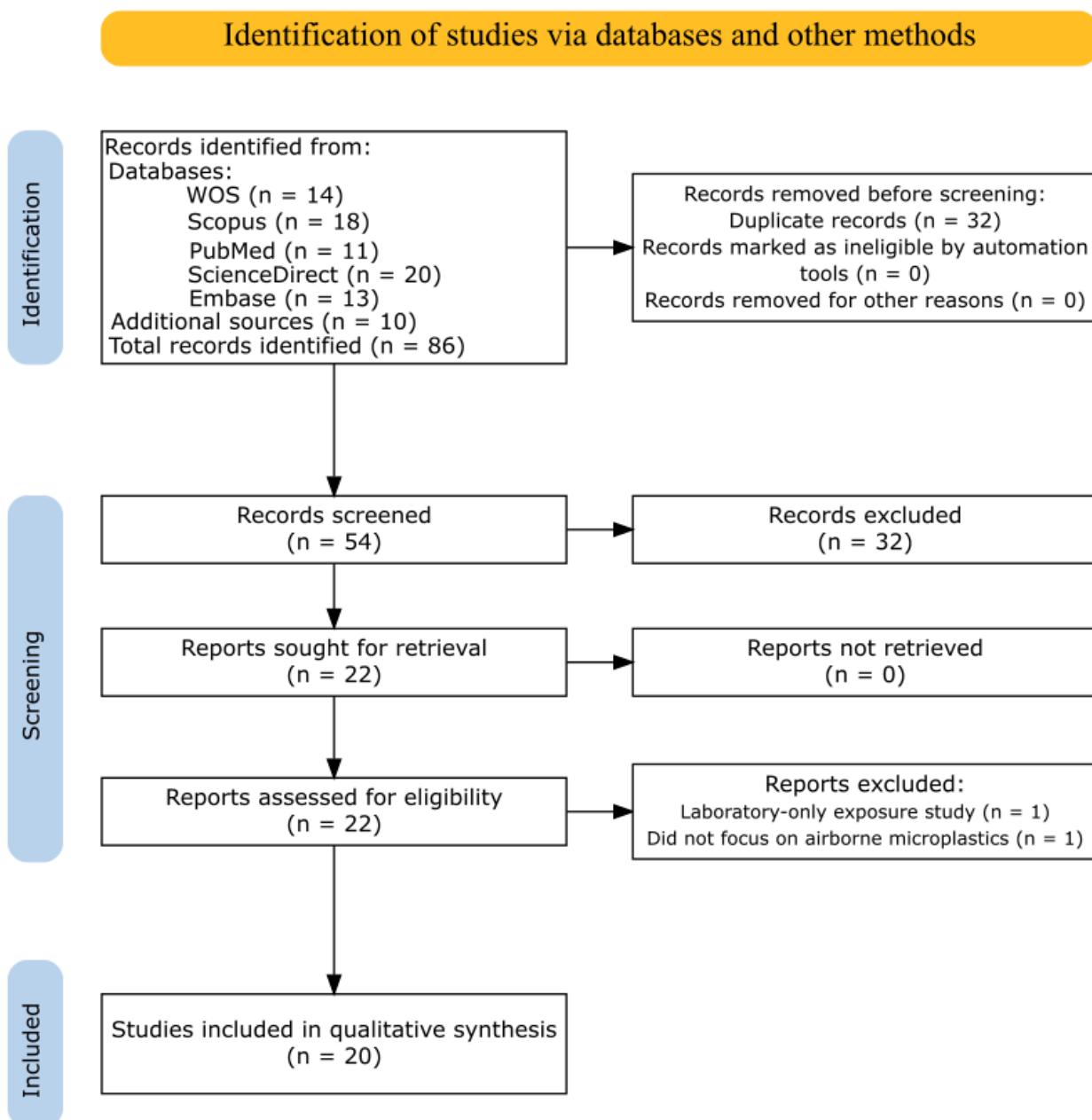
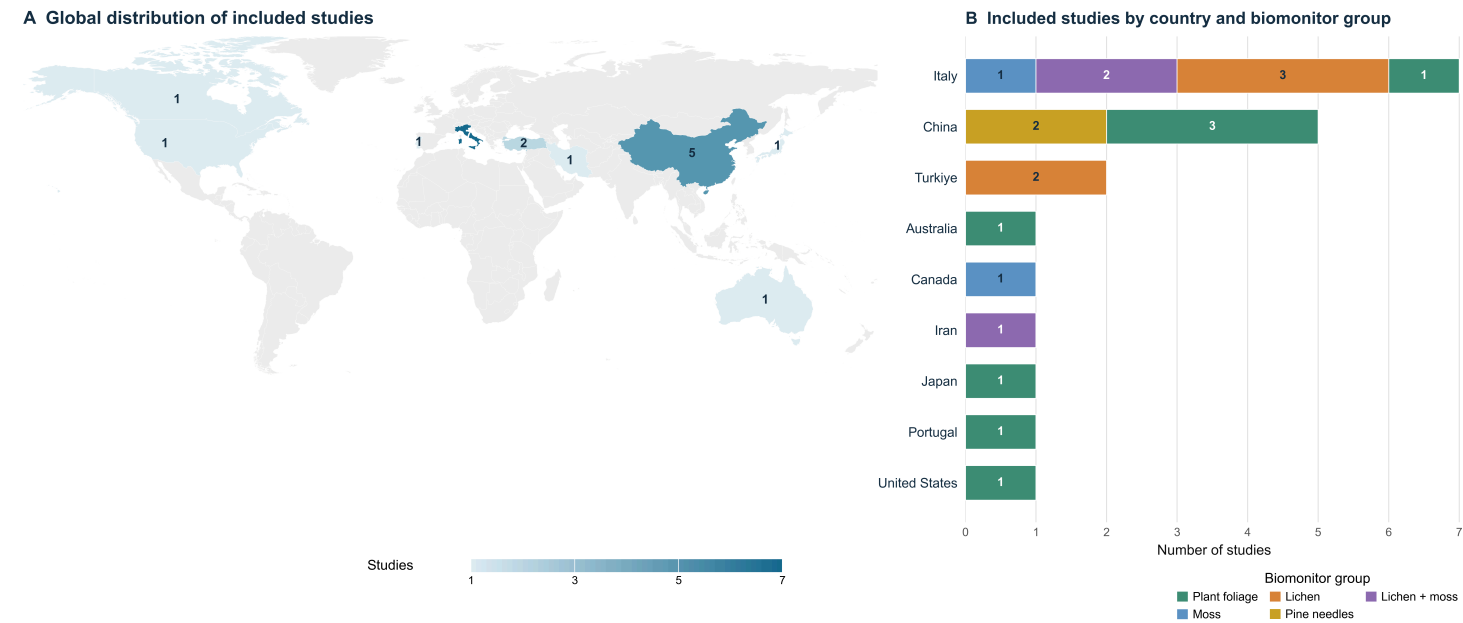


Figure 1

PRISMA 2020 flow diagram illustrating the study selection process for this systematic review.

Twenty included studies across nine countries; locations represent study sites rather than author affiliations. Dual-biomonitor studies are counted once in the combined category.



Source: Revision 3, Table 1, cross-checked against study abstracts; one location correction is documented in the audit table.

Figure 2

Country-level distribution and biomonitor groups of the studies included in the systematic review.

Full-text methodological quality assessment of included studies

Independent application of the modified Newcastle-Ottawa rubric; high = 15–17; moderate = 11–14; low ≤ 10.

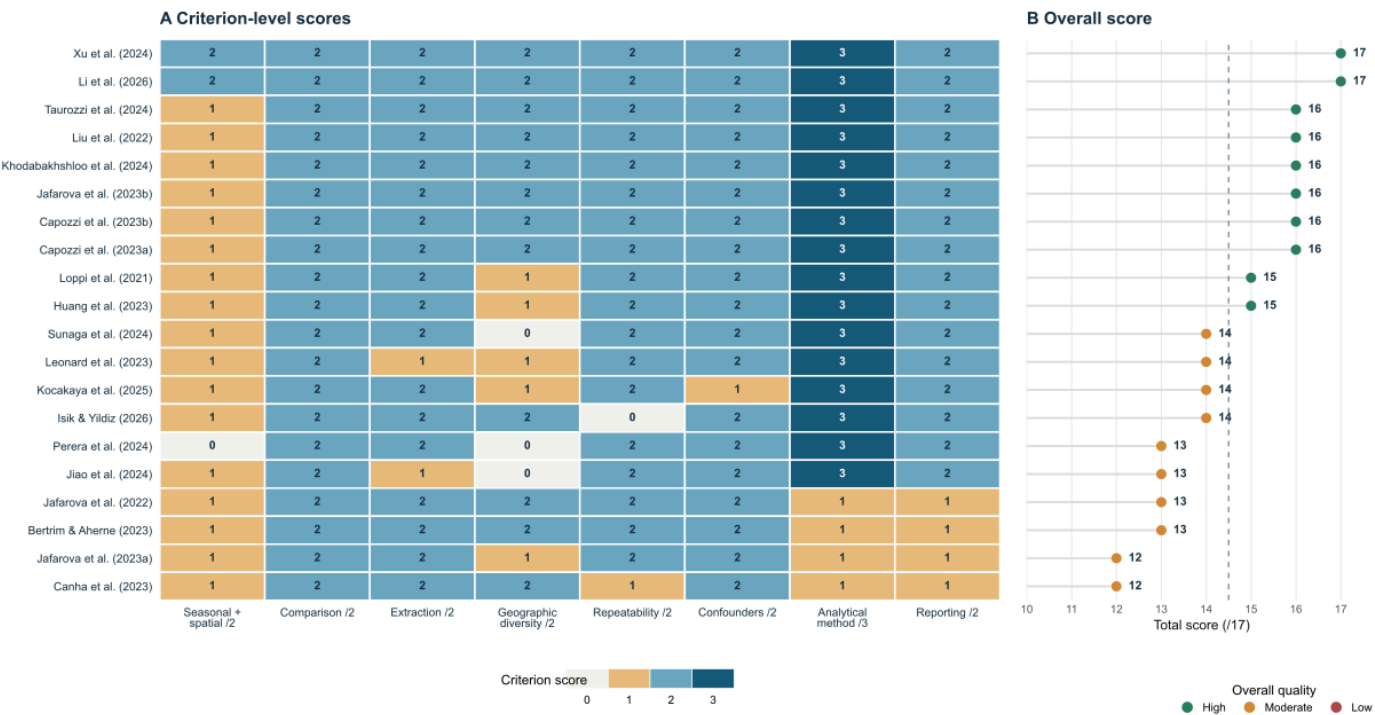


Figure 3

Full-text methodological quality assessment of the studies included in the systematic review.

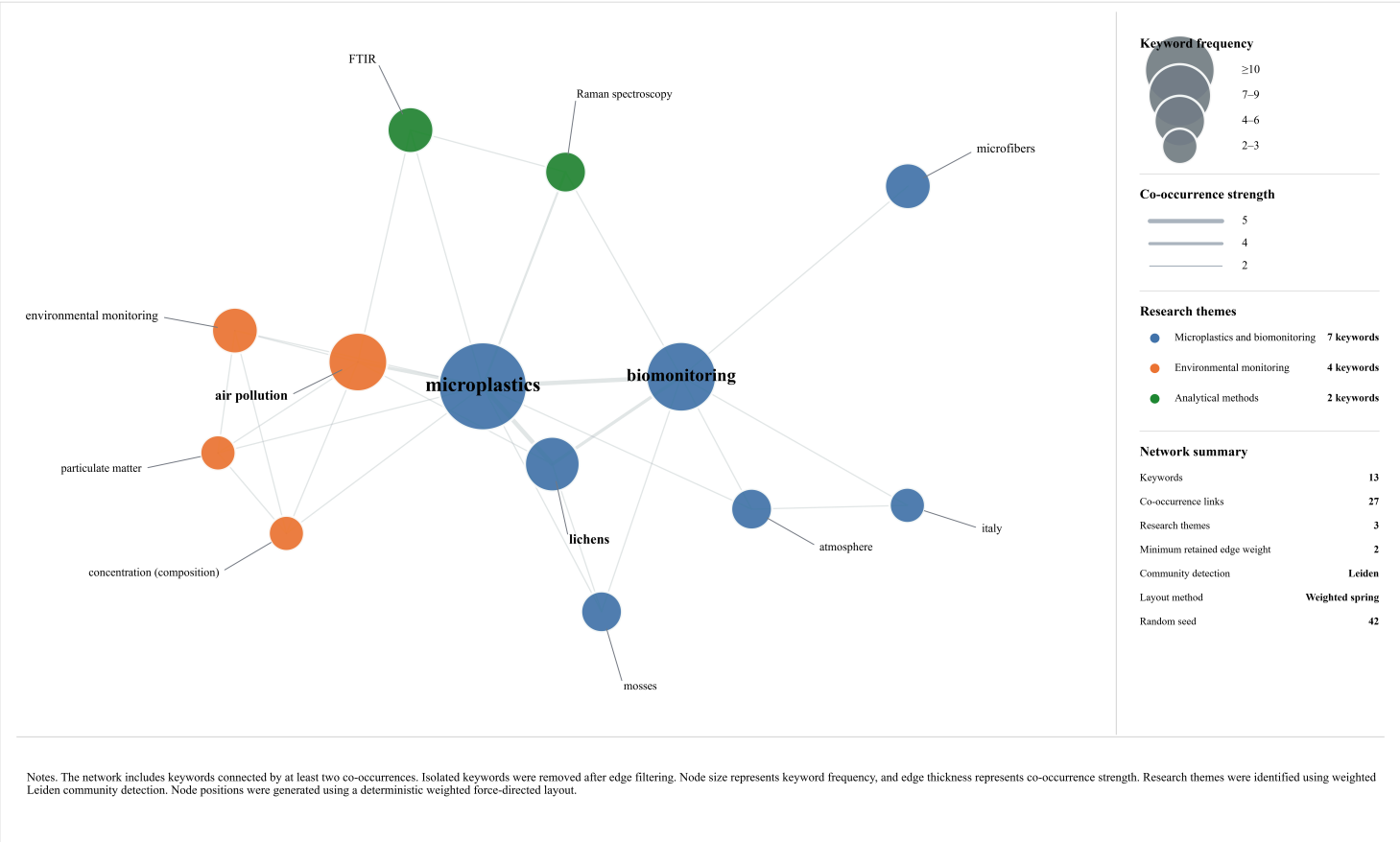


Figure 4

Keyword co-occurrence analysis of studies investigating plant-based biomonitoring of airborne microplastics (n = 20).

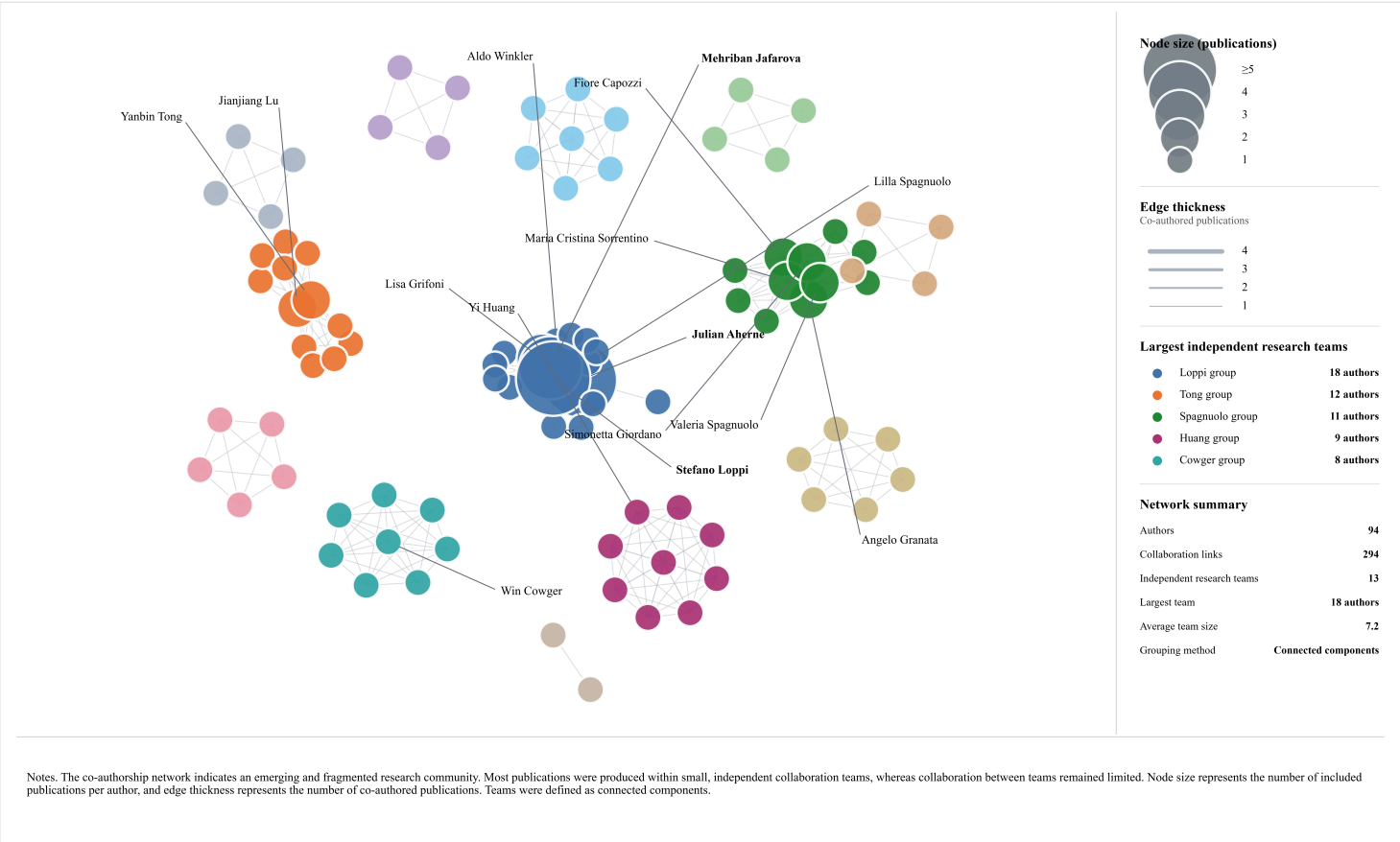


Figure 5

Bibliographic coupling network of studies investigating plant-based biomonitoring of airborne microplastics (n = 20).

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