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Review Article

Plastic Pollution Meets Biological Invasions: A Systematic Review of Emerging Interactions

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Abstract

Plastic pollution and biological invasions are two of the most pervasive and persistent drivers of ecological change. Although both have been widely studied in isolation, their potential interactions remain poorly understood. This review synthesises 146 peer-reviewed scientific articles published up to December 2024, providing the first global assessment of research at the intersection between plastic pollution and biological invasions. We found that the literature is taxonomically narrow, geographically skewed, and methodologically fragmented. Research focuses on aquatic invertebrates, especially Mollusca and Arthropoda, and is largely restricted to microplastics, with limited attention to mesoplastics, nanoplastics, or terrestrial systems. Most studies use standardised ecotoxicological assays under laboratory or field conditions, leaving broader ecological processes such as context-dependent interactions at the population, community, and ecosystem levels, habitat modification by non-native species interacting with plastic debris, and plastic-driven disruptions to ecosystem functioning and services largely underexplored. Despite these limitations, we identified three recurrent pathways through which plastics and biological invasions interact: (1) non-native species dispersal and colonization via plastic debris, (2) altered biotic interactions, and (3) the experimental use of non-native species to assess plastic toxicity, with a focus on species-specific physiological responses. These interactions may influence bioaccumulation dynamics, contaminant transfer across trophic levels, and compromise the resilience of invaded ecosystems. Our findings highlight key research gaps (e.g. the predominance of laboratory studies with limited integration of ecological responses in natural ecosystems, the underrepresentation of many taxonomic groups, and the lack of comparative analyses exploring how non-native species may act as vectors for plastic transport and bioaccumulation) and call for mechanistic, context-sensitive, and cross-disciplinary approaches. We also emphasise the urgent need to incorporate plastic pollution into non-native risk assessments and management frameworks. Strengthening methodological standardisation and public engagement, for instance through citizen science, will be critical for addressing the combined impacts of these two global stressors and mitigating their impacts.

Keywords: Non-native species, microplastic, Vectoring of contaminants, Species–pollutant interactions

1. Introduction

Plastics have become central to contemporary society, representing a defining hallmark of the Anthropocene (Stoett et al., 2024). Their global production, fuelled by properties such as durability and resistance to degradation, has grown exponentially over recent decades, far outpacing any other manufactured material. While these properties make plastics indispensable in many sectors, they also contribute to long-term environmental contamination across ecosystems (Geyer et al., 2017).

Global plastic production doubled in less than two decades, from 234 million metric tonnes (Mt) in 2000 to 460 Mt in 2019 (OECD, 2022). This increase was accompanied by a proportional rise in waste generation, with an estimated 353 Mt of plastic waste produced in 2019 alone. Of this, only 9% was effectively recycled, 19% incinerated, approximately 50% landfilled, and the remaining 22% discarded under uncontrolled conditions, including direct release into the environment (OECD, 2022). It should be noted that these numbers are primarily based on data from countries with robust monitoring and may not fully reflect the global reality.

Plastic pollution has thus emerged as one of the most persistent and pervasive forms of environmental contamination (Cowger et al., 2024; J. Li et al., 2021; J. Yang et al., 2025) Its mass production and unsustainable disposal have led to widespread accumulation of plastic debris across marine, freshwater, terrestrial, and even atmospheric ecosystems, posing a global threat that transcends both geographic and ecological boundaries (Richard et al., 2024; Walker & Fequet, 2023; Williams & Rangel-Buitrago, 2022; J. Yang et al., 2025). Yet, its ecological consequences remain far from fully understood, from the individual to the ecosystem level (Horton et al., 2017; Stoett et al., 2024; J. Yang et al., 2025).

In natural environments, plastics degrade through a combination of physical, chemical, and biological processes (Andrady & Neal, 2009; Chamas et al., 2020; Hollerová et al., 2021). This degradation results in a broad spectrum of particles that can be classified by size – nanoplastics (1 to <1000 nm), microplastics (1 to <1000 µm), mesoplastics (1 to <10 mm), and macroplastics (≥1 cm) (Hartmann et al., 2019) - each with distinct physicochemical characteristics, subjected to different transport dynamics, and ecological behaviours (Andrady, 2017).

Alongside plastic pollution, biological invasions have emerged as both a driver and a passenger of global environmental change (MacDougall & Turkington, 2005), drawing increasing scientific attention (Pyšek et al., 2020; Roy et al., 2024). Biological invasions are human-mediated processes responsible for the intentional or unintentional introduction of organisms into areas beyond their native range, where they lack an evolutionary history (Prentis et al., 2008; Soto et al., 2024). Historically, species distributions were shaped by their inherent dispersal (and recruitment) capacity and by natural geographic and environmental barriers. The permeability of these barriers changes only slowly, on timescales of thousands to millions of years, resulting in the independent evolution of endemic lineages within distinct biogeographical regions (Leroy et al., 2023). However, with the advent of long-distance human transport and modern global trade, particularly over the past two centuries, these natural patterns have been profoundly disrupted (Havel et al., 2015; Meyerson & Mooney, 2007; Mooney & Cleland, 2001; Seebens et al., 2017). Once introduced, some species establish self-sustaining populations and successfully spread in their new environments (Pyšek et al., 2020; Ricciardi, 2013).

These established non-native species can exert a diverse array of ecological, economic and social impacts — often highly context-dependent — due to direct biotic interactions such as predation, competition, parasitism, and hybridisation with native taxa, to indirect effects involving substantial changes to habitat structure and function, hydrological cycles, nutrient fluxes, and trophic interactions (Andersen et al., 2004; Ehrenfeld, 2010; Simberloff, 2010; Simberloff et al., 2013). These effects may cause biodiversity loss and irreversible ecological shifts (Simberloff, 2010). From an anthropocentric perspective, such impacts may further translate into ecosystem service degradation, reduced quality of life, substantial economic losses, and public health concerns, all of which are themselves frequently context-dependent (Diagne et al., 2021; Gallardo et al., 2024; Pejchar & Mooney, 2009).

Although differing in origin and consequences of their impacts, both plastic pollution and biological invasions can be viewed as pervasive anthropogenic stressors that interact with other environmental pressures across different ecological levels, altering the physiology and behaviour of organisms, species interactions, environmental conditions and ecosystem functioning (Rochman, 2013; Vye et al., 2015). Although non-native species have been shown to interact with various pollutants, such as metals and pesticides (El Haj et al., 2019; J. Li et al., 2022; Piola & Johnston, 2009; S. Wang et al., 2020; R.-

Y. Yang et al., 2007), studies are often fragmented and rarely extended to plastics. Yet, potential interactions (including ingestion, transport, or altered bioaccumulation) could have significant ecological consequences and merit further investigation. In particular, plastic debris can act as a vector for the passive transport of non-native species across distant ecosystems, especially via water currents and oceanic drift, enabling their introduction into new habitats where they might not otherwise establish (García-Gómez et al., 2021). Other studies have begun to address whether non-native species exhibit differential tolerance or sensitivity to plastics and how plastic contamination may influence their establishment success, competitive interactions, or broader ecological impacts (Gao et al., 2024; Tian et al., 2024; Z. Wang et al., 2024).

Interactions between plastic pollution and biological invasions can be complex, producing additive, synergistic, or antagonistic outcomes that may exacerbate threats to biodiversity and ecosystem functioning (Iqbal, 2024; Rodrigues et al., 2022). Yet, to date, no global synthesis has assessed the extent or nature of these interactions, nor identified the most affected taxonomic groups or ecosystems. In this context, the present review aims to critically evaluate the current state of knowledge at the intersection of plastics and biological invasions, identify emergent patterns, and highlight key priorities for future integrated ecological research.

2. Materials and Methods

2.1 Bibliographical Search

A systematic literature search was conducted in the Scopus database to identify studies at the intersection of plastic pollution and non-native species (**Figure 1**). The search strategy was designed to capture a wide range of relevant literature using a comprehensive combination of keywords related to biological invasions, plastic contaminants, and specific non-native taxa of global concern. A detailed search string, encompassing all taxonomic names and thematic keywords used in the systematic review, is provided in the Supplementary Material (Section S1).

In addition to general terms related to biological invasions, we give emphasis to the 100 most invasive species in the world, as identified by expert-based risk assessments and authoritative databases (e.g., IUCN, the European Union's list of Invasive Alien Species of Union Concern, DAISIE). Additional species were included to capture relevant taxonomic and ecological diversity, with emphasis on taxa known to occur in both aquatic and terrestrial environments.

The initial search returned 2,534 records. After removing duplicates and screening titles and abstracts for relevance, followed by full-text review when necessary, a total of 146 articles were retained for analysis. Only articles published up to December 31, 2024, were considered. The search was restricted to articles written in English, aiming to provide a global overview. Articles were included if they explicitly addressed the interactions, co-occurrence, or potential impacts of plastic pollution on one or more non-native species.

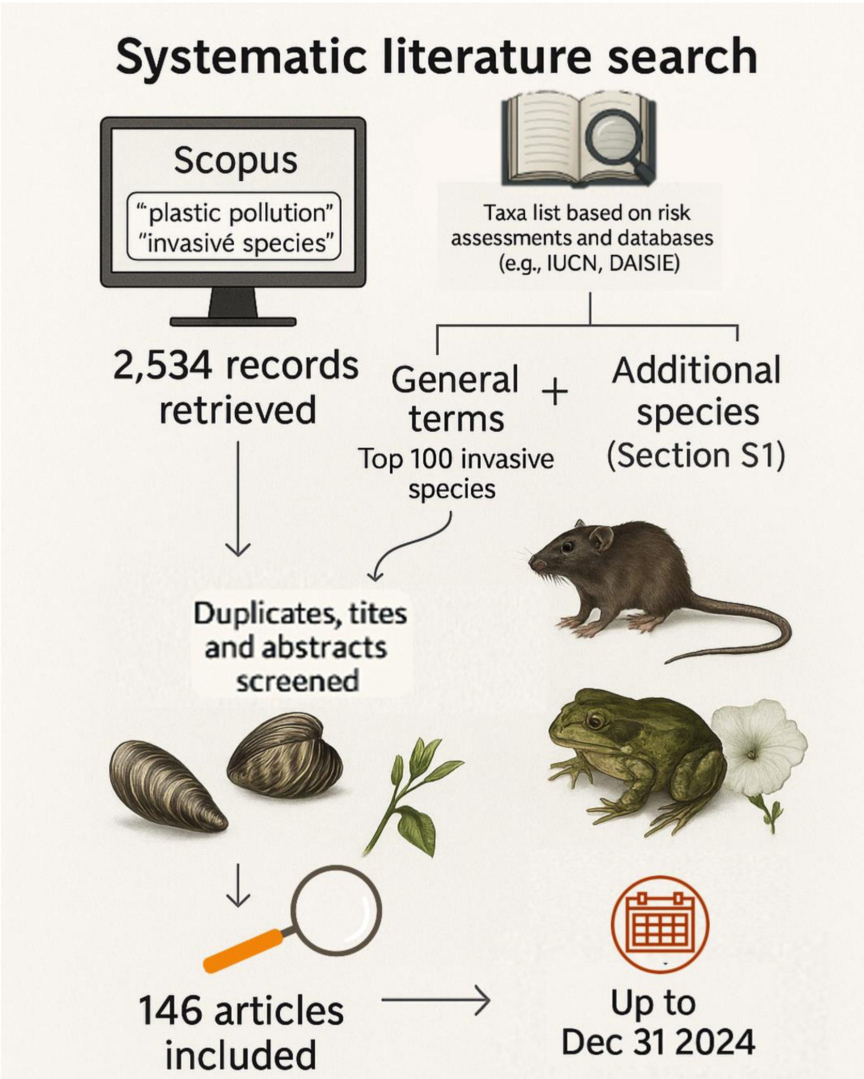

Figure 1. Overview of the systematic literature search and screening process. A total of 2,534 records were retrieved from Scopus; after screening and full-text review, 146 articles were included for analysis.

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2.2 Data Analysis

All data cleaning, processing, and visualization were performed using R version 4.3.1. A choropleth map was generated to visualize the number of studies per continent, using the sf, rnaturalearth, rnaturalearthdata, dplyr, and ggplot2 packages. The map was projected using the Equal Earth projection (EPSG:8857) and color-coded by study count using a continuous gradient scale. In addition, a Sankey diagram was constructed using the networkD3 package to illustrate the relationships among four categorical variables: Continent, Taxonomic Group, Study Type, and Plastic Type. Before building the diagram, the dataset was preprocessed to filter and recode values using stringr, tidyr, and dplyr. All plots were exported in HTML and PNG formats using the htmlwidgets and webshot packages for outputs.

3. Results

3.1 Temporal Trends

The number of scientific publications addressing both plastic pollution and biological invasions has increased sharply in recent years (**Figure 2**). Between 2000 and 2016, the number of publications combining these topics remained low, indicating limited scientific attention to their intersection. From 2017 onwards, there has been an apparent acceleration in the number of articles published. In 2021, a noticeable decline occurred. However, this slowdown was short-lived, and from 2022 onwards, the number of publications increased markedly, reaching the highest levels to date.

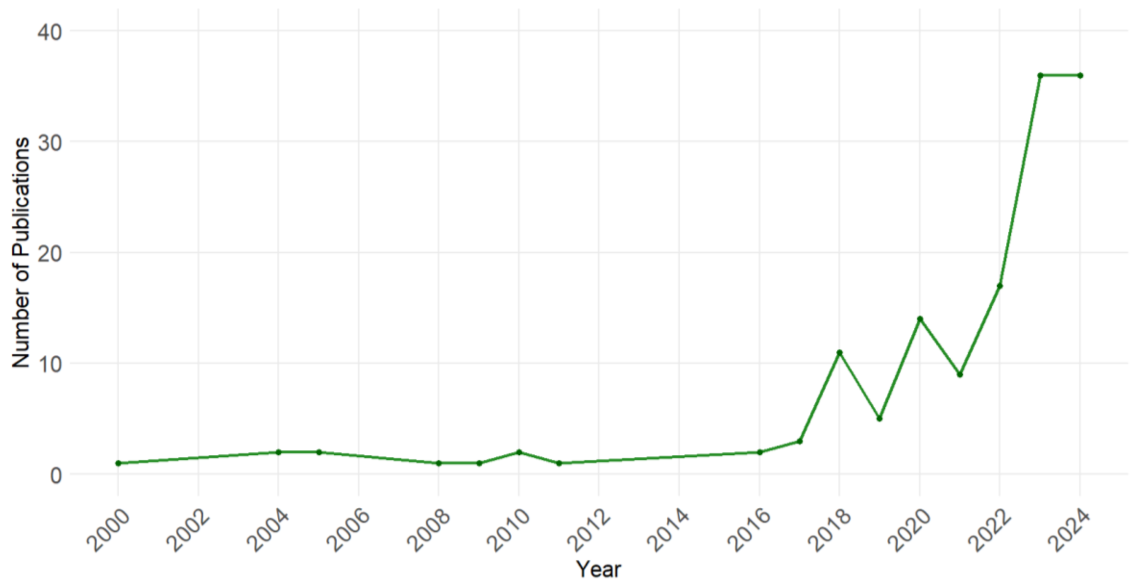


Figure 2. Number of publications produced per year on the topic of non-native species and plastics according Scopus database until 2024.

3.2 Spatial Distribution

As illustrated in Figure 3, the studies included in this review were conducted across all continents, but with marked geographic disparities. Scientific output is concentrated primarily in North America, Europe, and Asia, with the United States, China, and Italy standing out as the three countries with the highest number of publications. Other countries, such as India and Brazil, also make a significant contribution to this body of literature. In contrast, regions such as Africa, Southeast Asia, Central America, and Eastern Europe remain underrepresented.

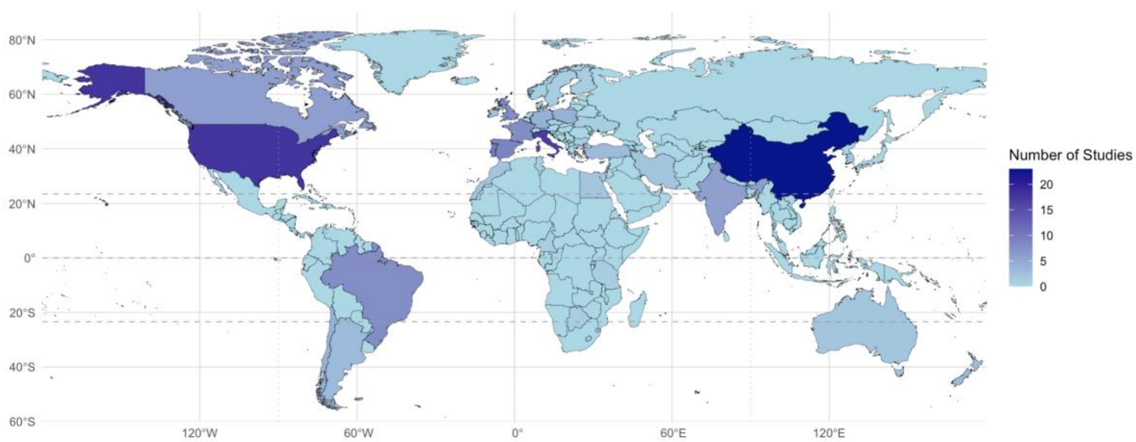
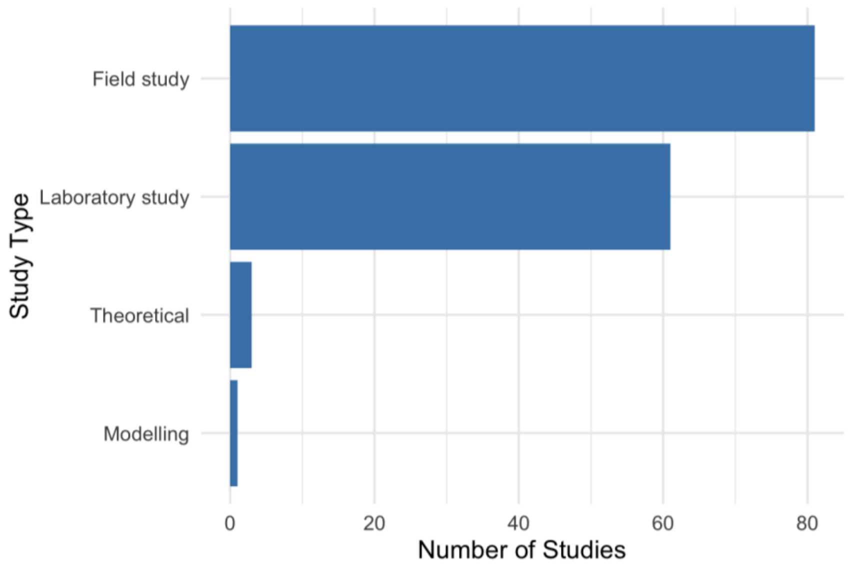


Figure 3. Geographic distribution of studies by country (n = 146).

3.3 Study types and Techniques used

As illustrated in Figure 4a, field studies were slightly more represented than laboratory-based research, followed at a considerable distance by theoretical and modelling approaches. Concerning the techniques used (**Figure 4b**), Fourier-transform infrared (FTIR) spectroscopy — particularly micro-FTIR, ATR-FTIR, and FPA-FTIR — was the most frequently reported method. Microscopy was also widely applied, encompassing light, fluorescence, scanning electron (SEM), and transmission electron (TEM) techniques, which were grouped under the category “Microscopy” due to their shared analytical functions. Other techniques appeared more sporadically, including Raman spectroscopy, pyrolysis-GC/MS, differential scanning calorimetry (DSC), dynamic and static light scattering (DLS/SLS), inductively coupled plasma mass spectrometry (ICP-MS), energy-dispersive X-ray spectroscopy (EDX), fluorimetry, and asymmetric flow field-flow fractionation (AF4).

a)



b)

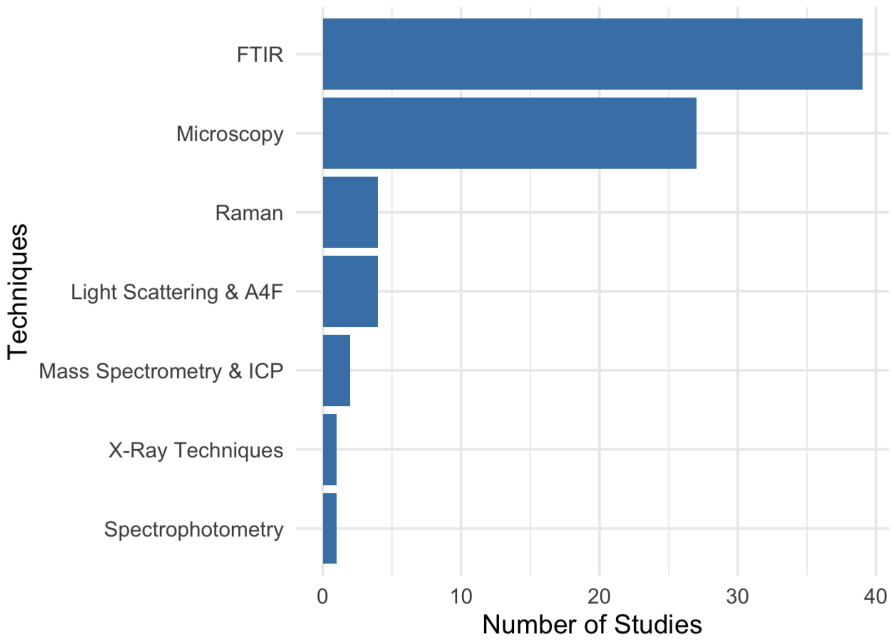


Figure 4. Most commonly used a) study types and b) analytical techniques in studies at the intersection of plastic pollution and non-native species (n = 146). Techniques were grouped into categories such as FTIR-based methods, microscopy (including optical, fluorescence, SEM, and TEM), Raman spectroscopy, light scattering and field-flow fractionation (AF4), mass spectrometry and ICP-MS, X-ray-based techniques, spectrophotometry, and computational modelling.

3.4 Plastic Size Classes and Detection Biases

As illustrated in Figure 5, most studies focused on microplastics, followed by macroplastics, with considerably fewer studies on nanoplastics or mesoplastics.

Microplastics were the most frequently addressed in the reviewed literature. Macroplastics were primarily considered in studies examining physical interactions with organisms, such as entanglement, habitat alteration, or rafting of marine non-native species (González-Ortegón et al., 2024; Gregory, 2009; Pawar et al., 2016; Rech et al., 2018; Ryan, 2018). Nanoplastics and Mesoplastics were rarely the central focus of studies.

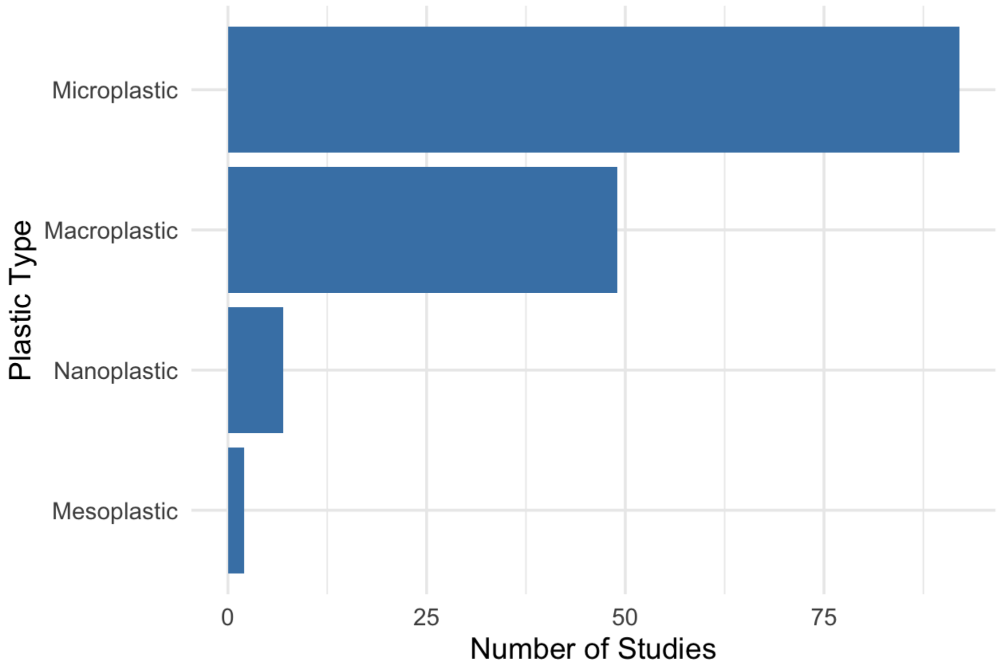


Figure 5. Distribution of plastic size classes reported in studies examining the intersection between plastic pollution and non-native species (n = 146).

3.5 Polymer types

The most frequently studied polymers were polyethylene (PE), polystyrene (PS), and polypropylene (PP), jointly accounting for over 70% of all polymers reported **(Figure 6**). In contrast, other polymers such as polybutylene succinate, polylactic acid, phenolic resins, and cellophane were rarely represented.

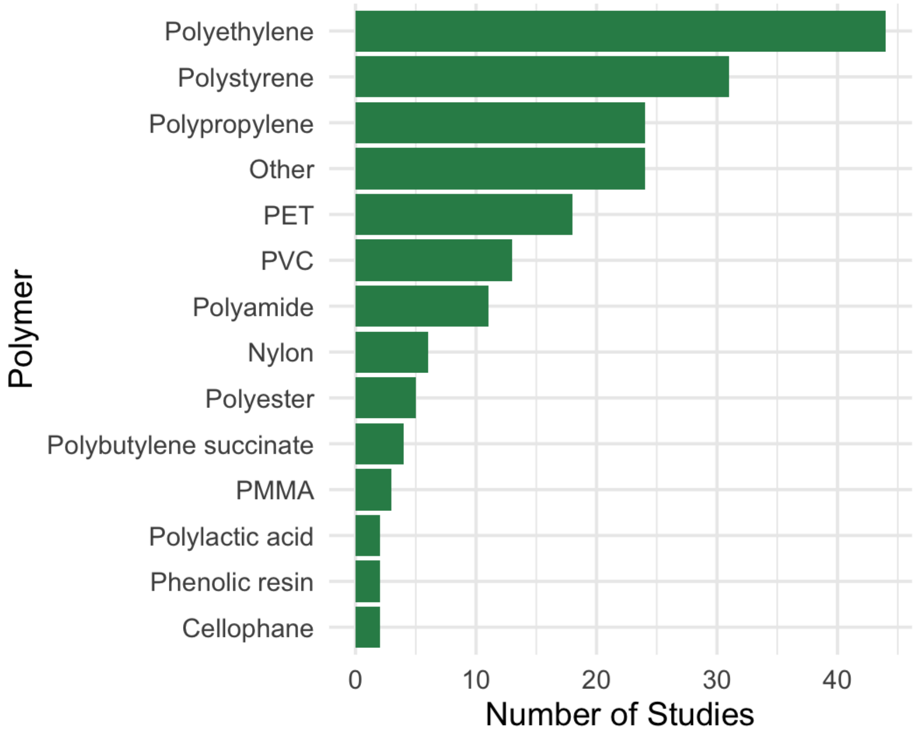


Figure 6. The most common polymers identified in studies addressing the intersection between plastic pollution and non-native species (n = 146 articles). All polymer types cited only once were grouped under "Other."

3.6 Overview of Research, Distribution, and Thematic Connections

To integrate the dimensions analysed in the previous sections and explore how they co-occur across the literature, a thematic synthesis was developed using a Sankey diagram (**Figure 7**). This visualisation links four key axes: continent, taxonomic group, study type, and plastic type. The thickness of each flow is proportional to the number of studies connecting the respective categories, providing a structural overview of dominant research pathways.

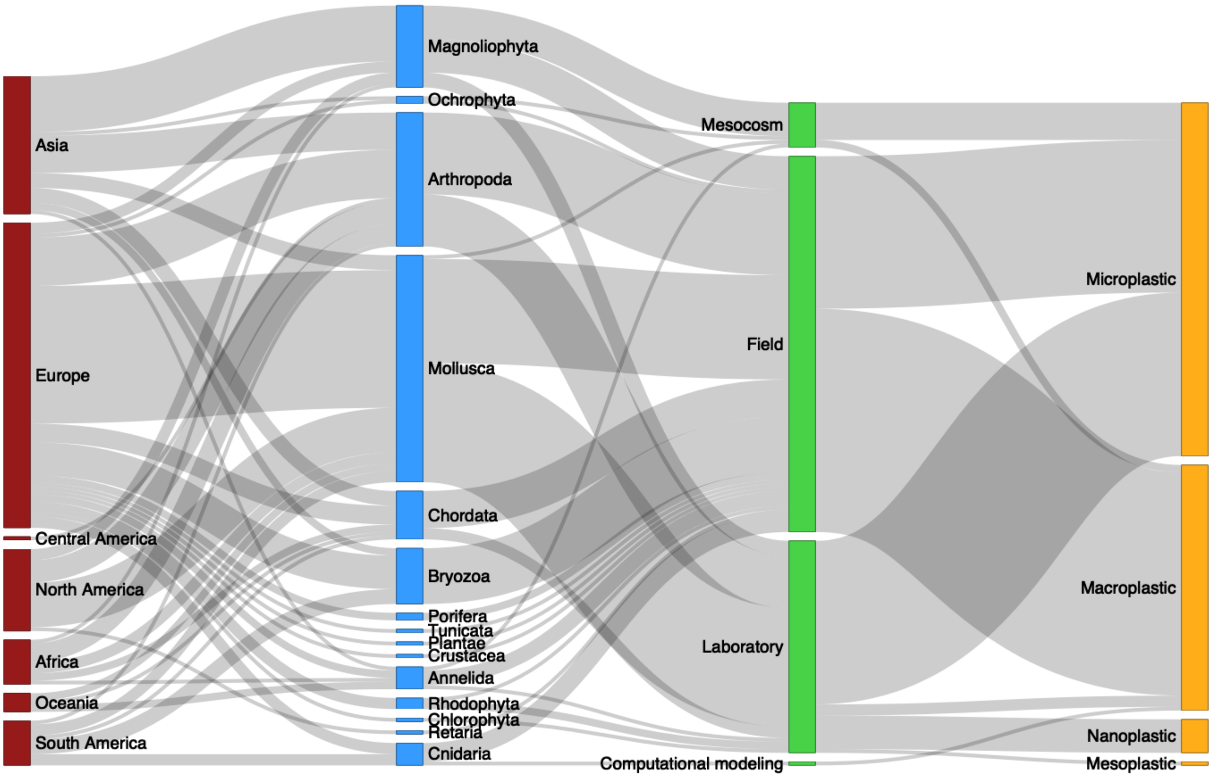


Figure 7. Sankey diagram showing the relationships between continent, invasive taxonomic group, study type, and plastic type across the selected studies. The flow thickness is proportional to the number of studies linking each category. Colours represent the four node groups: continent (dark red), invasive taxonomic group (blue), study type (green), and plastic type (orange).

Taken together, these connections illustrate not only the diversity of approaches across regions and taxa but also the methodological preferences and plastic types most frequently studied in each context. This structural overview provides a foundation for interpreting broader patterns and identifying knowledge gaps, which are addressed in the following discussion.

4. Discussion

Plastic pollution and biological invasions are among the most pressing and persistent anthropogenic stressors threatening ecosystems worldwide. While both topics have been extensively studied in isolation, their intersection remains surprisingly underexplored. Our systematic review of 146 scientific articles reveals that research at this interface is taxonomically narrow, geographically uneven, and methodologically fragmented.

Nonetheless, we identify three main pathways through which plastics and non-native species interact: dispersal via plastic debris, altered biotic interactions, and species-specific responses to plastic exposure. These findings underscore the urgent need for integrative approaches that consider how plastics may facilitate invasions, reshape ecological processes, and amplify environmental risks. By illuminating overlooked connections, this review highlights critical gaps and offers a roadmap for future research and management strategies aimed at mitigating the compounded effects of these global drivers.

4.1 Temporal Trends

Although plastic pollution and biological invasions are now recognised as major global change drivers, the broader field of plastic pollution only began to expand rapidly after 2008, particularly in marine ecosystems, following increased awareness of microplastics and their environmental impacts (Blettler et al., 2018; Law, 2017). In contrast, the field of biological invasions gained prominence mainly since the 1990s (Richard et al., 2024; Simberloff, 2004). Given this historical background, it is reasonable to understand that only in recent years has awareness grown regarding the potential intersection of these two topics. The consistent rise in recent publications suggests that the interaction between plastic pollution and biological invasions is rapidly gaining scientific traction, driven by the recognition of complex ecological interactions and the urgency of understanding multiple global change stressors. Although a decrease in publications during 2021, probably linked to the worldwide disruption of research activities caused by the COVID-19 pandemic, the post-pandemic surge may reflect both the release of delayed research outputs and a renewed interest in the combined effects of these environmental threats.

4.2 Spatial Distribution

The concentration of studies in countries such as the United States, China, and Italy reflects broader trends already observed in other areas of ecology and can be attributed to structural factors, including access to competitive research funding, advanced laboratory infrastructure, established research institutions, and integration into international scientific networks (Martin et al., 2012). The availability of specialised analytical equipment, such as FTIR or Raman spectroscopy, and participation in global research consortia further facilitate interdisciplinary studies, advantages not equitably distributed worldwide.

In countries like China, India, and Brazil, increased scientific output may stem from rapid urbanisation, significant environmental pressures, and high biodiversity, which generate demand for applied and locally relevant research. These efforts are supported by growing investments in science and technology, and stronger international collaboration (Turbelin et al., 2017).

By contrast, underrepresentation in regions such as Africa, Southeast Asia, Central America, and Eastern Europe does not suggest a lesser relevance of plastic pollution or biological invasions in these areas. Instead, it stems from structural inequalities in global science, including limited funding, institutional capacity, infrastructure, and access to international networks. Linguistic and editorial barriers also contribute: relevant studies may be published in local languages or non-indexed journals, rendering them invisible to the broader scientific community and to systematic reviews (Amano & Berdejo-Espinola, 2025).

These disparities highlight not only production gaps but also deep asymmetries in how scientific knowledge is validated and valued globally. As discussed by Salager-Meyer, 2008 and Turba et al., 2025 , researchers from the Global South face systemic disadvantages shaped by linguistic, financial, and institutional barriers. Dominant academic models and publishing norms rooted in the Global North reinforce a partial and exclusionary system of science, limiting the ecological and sociopolitical representativeness of global knowledge on pressing issues such as plastic pollution and biological invasions.

Interestingly, underrepresentation is also observed in countries with strong research capacity and a long-standing tradition in invasion biology, such as Australia, New Zealand, and South Africa. In these cases, the gap appears to stem more from thematic focus than financial limitations. For example, in New Zealand and Australia, research and policy have historically prioritized native species conservation and invasive vertebrate control in terrestrial systems (Firn et al., 2015; Towns et al., 2019). Large-scale programmes like Predator-Free NZ 2050 channel significant investments toward specific conservation goals, but often overlook the combined effects of multiple stressors. In Australia, major funding streams into the management of non-native species remain decoupled mainly from research on plastic pollution (Hoffmann & Broadhurst, 2016).

Overall, these geographic imbalances underscore that scientific production is influenced not only by environmental urgency but also by institutional priorities, political agendas, and structural inequities in knowledge production — factors that must be critically considered when interpreting patterns and gaps in the literature.

4.3 Study types and Techniques used

Field studies are essential for in situ observation of the interactions between plastics and non-native species. They have revealed diverse mechanisms such as the colonisation of artificial substrates and the rafting of non-native organisms. For instance, in Brazil, *Tubastraea* corals have been documented on floating plastic debris, highlighting plastics as effective dispersal vectors (Mantelatto et al., 2020). In Northern Europe, non-native barnacles were found attached to the plastic leg bands (rings) of migratory birds, demonstrating how plastic items can indirectly facilitate the long-distance transport of non-native species (Tøttrup et al., 2010). In Swedish port areas, debris accumulation supported higher richness and density of non-native species compared to adjacent litter-free zones (Garcia-Vazquez et al., 2018). In terrestrial systems, species such as *Carpobrotus acinaciformis* have been shown to trap plastic debris in coastal dunes (Calderisi et al., 2023), and discarded tyres have facilitated the spread of *Aedes albopictus* by providing breeding microhabitats (Simard et al., 2005). These studies underscore the value of fieldwork in identifying ecological processes relevant to plastic-mediated biological invasions.

Laboratory experiments, meanwhile, provide controlled conditions for mechanistic understanding. In agroecological simulations, *Solidago canadensis* and microplastics together reduced root growth in rice (*Oryza sativa*), indicating synergistic effects (G. Li et al., 2023). Likewise, *Sphagneticola trilobata* exhibited greater tolerance to pollutants than native species, suggesting plastic-contaminated environments may confer competitive advantages to particular non-native species (Javed et al., 2023). Laboratory-based toxicological assays have also revealed sublethal and chronic effects: for example, *Corbicula fluminea* in Portugal showed oxidative and histopathological changes when exposed to MPs and cadmium (Parra et al., 2024), while *Dreissena polymorpha* in Ireland suffered cellular damage under nanoplastic exposure (Reynolds et al., 2024).

Theoretical and modelling studies, although underrepresented, play a crucial role in conceptual synthesis and predictive capacity. In Brazil, a review by Soares et al., 2022 identified dozens of introduced and cryptogenic marine species associated with plastic debris, reinforcing the role of plastics as long-distance dispersal mechanisms. Modelling work, like that of Barry et al., 2023, used predictive simulations to trace a piece of marine debris carrying non-native species from the western Atlantic to the UK coast, demonstrating how computational tools can support risk assessments and management strategies.

Overall, while empirical approaches dominate the field, the growing integration of experimental, theoretical, and modelling frameworks — alongside a diverse array of analytical tools — reflects an increasingly sophisticated and interdisciplinary effort to understand the complex interplay between plastic pollution and biological invasions.

In relation to the techniques used, FTIR spectroscopy was the most common, widely employed to confirm the identity of plastic polymers in both environmental and biological matrices. Its popularity is linked to its robustness, relative affordability, and broad methodological standardisation (Al Alwan et al., 2024; Käppler et al., 2016; W. Wang & Wang, 2018). FTIR works by detecting changes in dipole moment, producing infrared absorption spectra that are matched against reference libraries. It is most effective for particles >10–20 µm, depending on the analytical configuration. Variants such as ATR-FTIR are commonly used for larger or irregular particles, while FPA-FTIR enables automated, high-throughput analysis (Al Alwan et al., 2024). In Italy and Poland, non-native crayfish *Procambarus clarkii* and *Pacifastacus leniusculus* were analysed using FTIR to determine the polymer composition of ingested MPs, supporting their use as bioindicators of plastic contamination in freshwater ecosystems (Dobrzycka-Krahel et al., 2024; Pastorino et al., 2023). In Turkiye, *Carassius gibelio* was studied for its potential role as a vector of MPs within freshwater food webs (Terzi, 2023).

Microscopy was applied in 15 of the reviewed studies, either as a standalone tool or in combination with spectroscopic or physical validation methods. This category includes a wide range of techniques, from basic stereomicroscopy to advanced polarised light, fluorescence, and electron microscopy. In some cases, visual inspection alone was used to identify suspected plastic fibres or fragments, particularly in gastrointestinal contents. For example, in *Eriocheir sinensis* from Poland and Portugal, identification was based on morphology and resemblance to fishing gear (Wójcik-Fudalewska et al., 2016). In other cases, microscopy was combined with chemical or physical validation. A study in the Mendoza River (Argentina) used both stereomicroscopy and polarised light microscopy to identify synthetic fibres in the gastrointestinal tracts of native (*Hatcheria macraei*) and non-native freshwater fish such as *Oncorhynchus mykiss* and *Salmo trutta*. Suspected particles were validated via anisotropy under polarised light or by applying the "hot needle" test (Ríos et al., 2022). These examples demonstrate the versatility of microscopy as a cost-effective, first-pass screening method, particularly in contexts where access to advanced spectroscopic tools is limited. However, the lower specificity of microscopy relative to spectroscopic methods highlights the need for complementary validation steps, especially when concluding polymer type or origin.

Raman spectroscopy, although used sporadically, played a key role in the high-resolution identification of small MPs, particularly in the micro- and nano-size ranges. Complementing FTIR, Raman detects changes in molecular polarizability, enabling spectral fingerprinting of particles as small as <1 μm (Al Alwan et al., 2024; Käppler et al., 2016; W. Wang & Wang, 2018). It was used, for example, to confirm the presence of plastic polymers in non-native species such as *Faxonius cristavarius* in the USA (Gray et al., 2024), *Corbicula fluminea* in Argentina (Giarratano et al., 2024), *Carassius gibelio* in Iran (Saemi-Komsari et al., 2023), and *Piaractus brachypomus* in India (Devi et al., 2020). Despite technical constraints such as fluorescence interference, high cost, and lower signal-to-noise ratios, Raman remains invaluable for analysing small or embedded particles in complex biological matrices (Al Alwan et al., 2024; Käppler et al., 2016).

Less frequently reported approaches were grouped under broader categories in Figure 4b to enhance clarity and avoid fragmentation. These included techniques such as dynamic and static light scattering (DLS/SLS) and asymmetric flow field-flow fractionation (AF4), which are typically employed for sizing and characterising nanoplastics in aqueous samples. The category "Mass spectrometry & ICP" encompasses methods like pyrolysis coupled with gas chromatography and mass spectrometry (Py-GC/MS), as well as inductively coupled plasma mass spectrometry (ICP-MS), which were applied to detect additives or trace elements associated with plastic particles. X-ray techniques, including energy-dispersive X-ray spectroscopy (EDX), were primarily used alongside electron microscopy to determine the elemental composition of suspected plastics. Finally, spectrophotometry was rarely used, but occasionally applied in the optical quantification of coloured plastics or associated dyes.

The diversity of analytical methods identified across the reviewed studies reflects both the range of research objectives and the complex ecological questions surrounding plastic–biological invasions interactions. Nevertheless, the lack of methodological standardisation and integration across disciplines remain a barrier, limiting the comparability of results across studies and hindering the development of generalisable conclusions. Addressing this limitation through more harmonised protocols and cross-validation between techniques could strengthen future research efforts in this field.

4.4 Size-Based Detection Biases and Methodological Constraints

Microplastics were by far the most studied size class in the reviewed literature. This prominence is likely due to a combination of practical factors, such as the availability of validated analytical protocols (e.g., FTIR, Raman spectroscopy, stereomicroscopy), and ecological relevance, as microplastics are abundant across terrestrial, freshwater, and marine environments. Furthermore, their size allows for interaction with a wide range of organisms, from filter-feeding invertebrates to fish and amphibians, making them an accessible and versatile subject of study. However, this strong emphasis may also reflect a research bias, whereby studies disproportionately focus on what is easiest to detect, rather than on what may be most ecologically disruptive. As a result, the potential contributions of other particle sizes to invasion dynamics may remain underexplored.

Nanoplastics are particularly challenging to isolate from environmental matrices and require advanced instrumentation such as electron microscopy or dynamic light scattering, which are not commonly accessible in ecological research settings. The lack of consistent definitions for these particles further complicates their study and reporting. **Mesoplastics** occupy an ambiguous analytical space; they are too large for most microplastic characterisation workflows and too small to be the target of macroplastic surveys. As a result, they remain an overlooked category, despite their potential ecological relevance.

These patterns underscore a clear size-based detection bias in the literature. The dominance of microplastic studies reflects both practical constraints and scientific priorities, but this focus may obscure the roles that other size classes play in dispersal, exposure pathways, and ecological interactions involving invasive species. Expanding analytical frameworks to include underrepresented size classes, especially nanoplastics and mesoplastics, will be crucial for developing a more comprehensive understanding of plastic-biological invasions dynamics.

4.5 Polymer types

The predominance of polyethylene (PE), polystyrene (PS), and polypropylene (PP) in the reviewed studies is consistent with global trends observed across **marine, freshwater**, and **terrestrial** compartments. These polymers are frequently reported in riverine waters, coastal sediments, agricultural soils, sewage sludge, and biotic samples (Andrady, 2017; Jones et al., 2020; C. Li et al., 2020; Lofty et al., 2023; Scherer et al., 2020; Schwarz et al., 2019). Their widespread detection likely reflects broader global production and consumption trends. These polymers dominate the plastic industry due to their extensive use in packaging, single-use items, and other consumer products, which are particularly susceptible to environmental leakage (Geyer et al., 2017). This trend aligns with global and regional production data. According to the OECD, 2022, PE, PP, and PS are among the most widely produced polymers worldwide, primarily used in packaging, construction, and consumer products. In Europe, PE and PP together accounted for nearly 29% of total plastic production in 2022, while PS contributed an additional 5% (Plastics Europe, 2024).

Comparable patterns have been observed in terrestrial systems. Field studies and recent review articles confirm that PE and PP—and to a lesser extent PS—are also the most prevalent polymers identified in agricultural soils, floodplain sediments, and sewage sludge (Cai et al., 2023; En-Nejmy et al., 2024; Kim et al., 2021; Q. Li et al., 2019; Sa'adu & Farsang, 2023; Sajjad et al., 2022; L. Yang et al., 2021). Their presence is commonly linked to sources such as plastic mulching films, irrigation systems, organic waste applications, and atmospheric deposition. Although terrestrial matrices remain less studied than aquatic ones, the available evidence strongly supports the dominance of these polymers across soil environments.

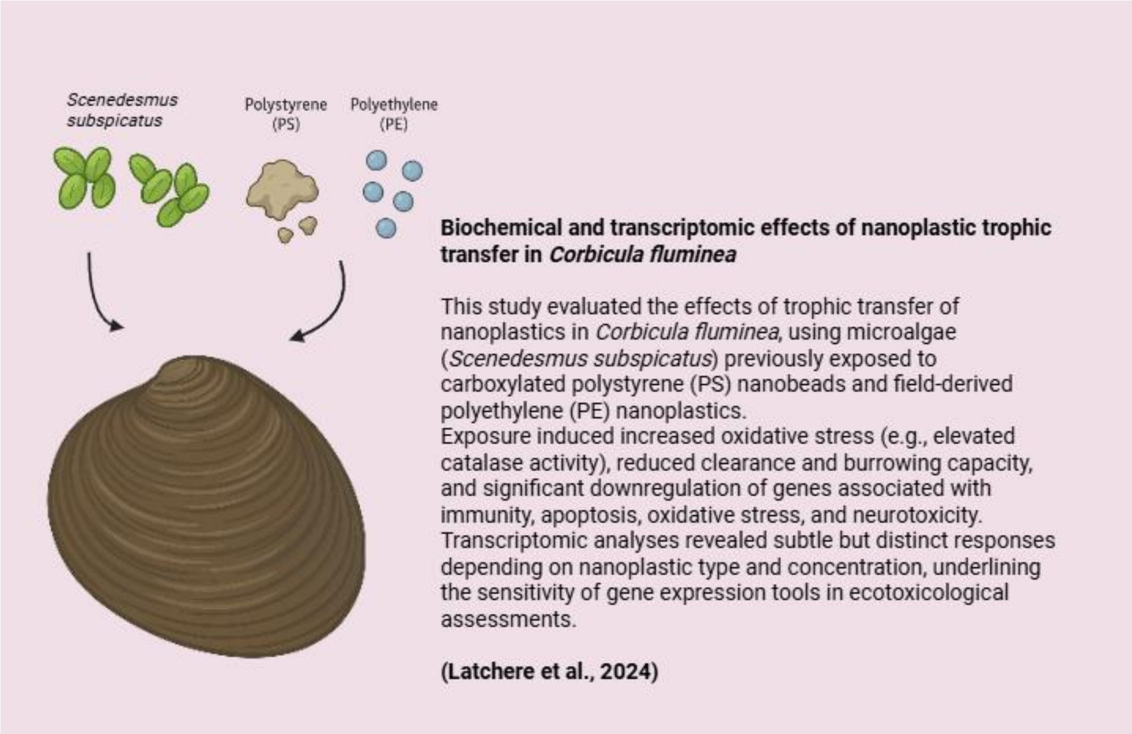
As previously mentioned, a substantial number of studies included in this review were based on experimental approaches, which were identified as the most frequently employed study type. Many of these experiments, conducted both in the field and under controlled laboratory conditions, relied on commercially available polymers selected for their relevance to experimental design, such as polypropylene (PP) (the most commonly used), polyethylene (PE), and polystyrene (PS). This experimental bias may partly explain the recurrent detection of PE, PP, and PS across study designs, reinforcing their prominence in both environmental and controlled contexts.

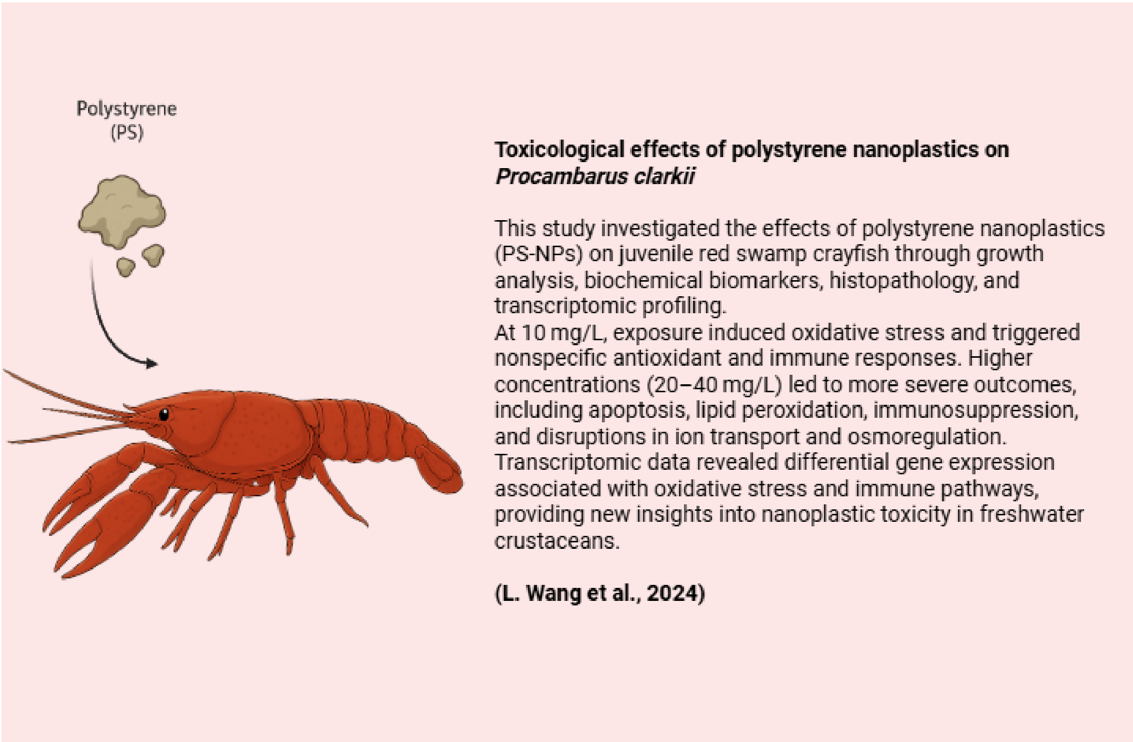
4.6 Overview of Research, Distribution, and Thematic Connections

Despite the apparent diversity of studies, several knowledge gaps exist. A clear taxonomic bias emerges: most studies focus on a narrow range of phyla, often due to the availability of standardised protocols, greater ease of sampling, or ethical considerations (i.e, few studies on mammals and birds). This tendency compromises ecological representativeness and limits our understanding of how functionally distinct groups may respond differently to plastic exposure. At the ecosystem level, a predominance of aquatic environments, particularly freshwater, is also evident, with terrestrial and marine habitats remaining comparatively underexplored, despite their unique community dynamics and exposure pathways. This thematic structure also reveals a degree of conceptual inertia: researchers tend to rely on familiar taxa, experimental settings, and endpoints. While this contributes to methodological consistency and comparability, it may also restrict innovation and delay the recognition of emerging ecological questions and overlooked dimensions of species–plastic interactions. In particular, the field remains strongly skewed towards aquatic invertebrates, especially Mollusca and Arthropoda, with limited attention given to terrestrial taxa, vertebrates, and lesser-studied phyla. This narrow focus risks overlooking relevant biological responses and constrains the ecological scope of current knowledge.

4.7 Mechanistic Insights from Case Studies

To illustrate the diversity of mechanisms linking plastic pollution and biological invasions, we present a few selected case studies involving non-native species across different ecosystems, taxa, plastic types, and experimental contexts. These examples highlight how plastics can facilitate invasion processes through multiple pathways, including dispersal, habitat modification, altered biotic interactions, and differential species responses to plastic exposure. Together, they emphasize the multifaceted nature of plastic–invasion interactions and the importance of integrating these dynamics into ecological and management frameworks.





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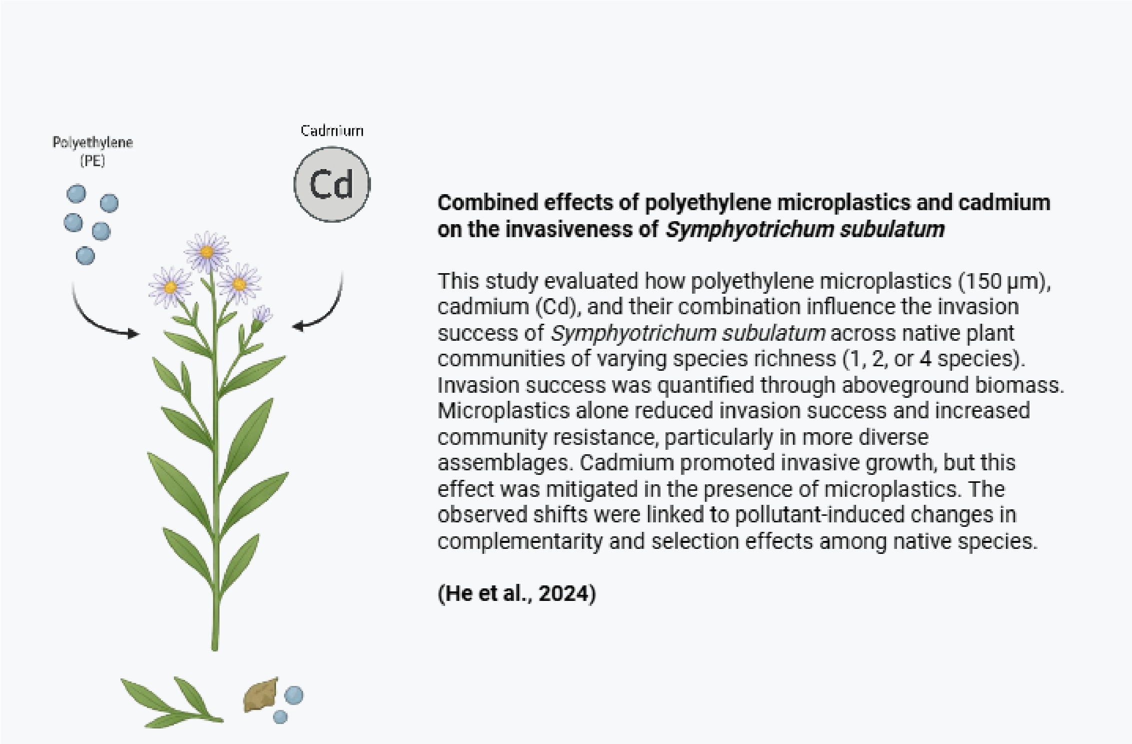

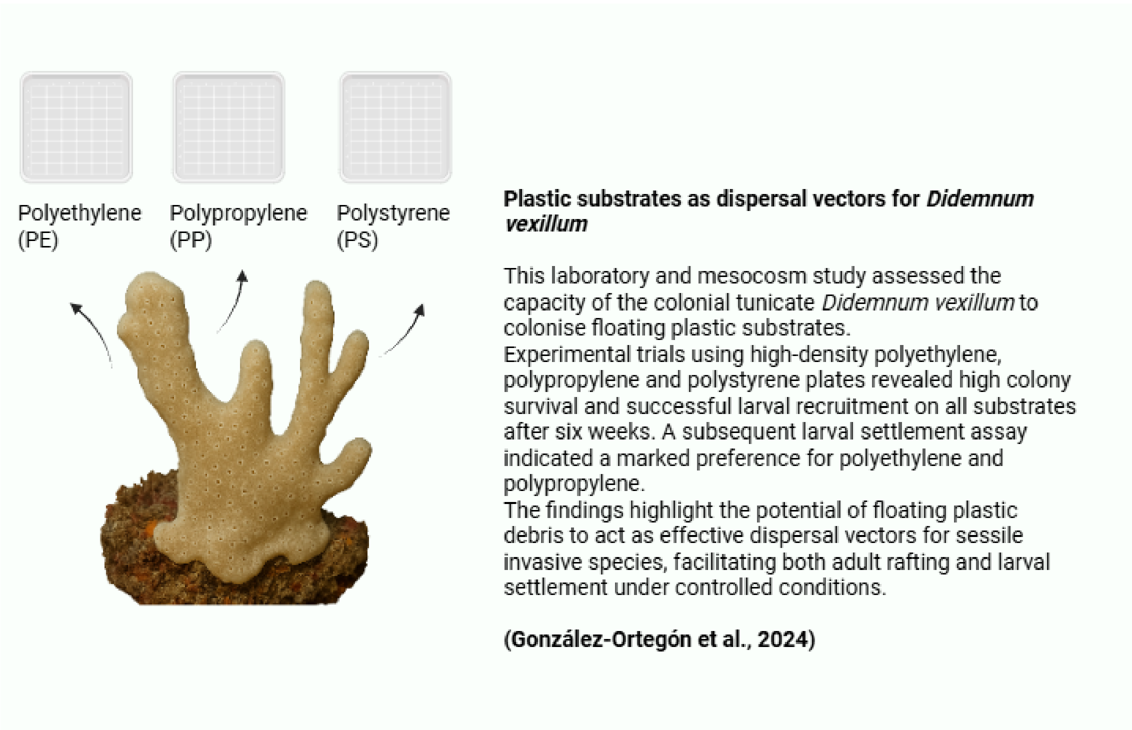

5. Future directions

Despite growing recognition of the potential interplay between plastic pollution and biological invasions, the intersection of both fields remains in its infancy. Our review reveals significant knowledge gaps that must be addressed to understand better and mitigate the combined impacts of these two pervasive environmental stressors.

First, there is a pressing need for mechanistic studies that go beyond correlation and explore the causal links between plastic pollution and the success of non-native species. Plastics may act not only as vectors for dispersal by providing physical substrates for rafting species, but also as novel habitats that selectively favour non-native taxa over native ones. However, most rafting-related studies to date have focused exclusively on marine environments, with little to no investigation into rafting in freshwater ecosystems. Moreover, aerial dispersal of plastic-associated organisms, whether via birds (e.g., ringed birds; (Tøttrup et al., 2010)) or windborne transport of lightweight or early life-stage organisms, remains virtually undocumented.

These overlooked pathways may play a critical role in inland and cross-ecosystem biological invasions and deserve greater empirical attention due to their management implications. Experimental and field-based research should quantify these dynamics under realistic environmental conditions, considering factors such as substrate preference, plastic degradation, and competition for space or food.

Second, the trophic transfer and bioaccumulation of plastics mediated by non-native species remain poorly understood. Some non-native species may accumulate plastics at higher rates due to their feeding strategies, trophic positions, or dominance in polluted ecosystems, potentially acting as entry points for microplastics and associated contaminants into food webs. Longitudinal and multi-trophic studies are essential to evaluate whether non-native species serve as key vectors for the biological transfer of plastics and whether they increase the risk of exposure to predators, including top consumers and humans.

Third, future research must account for the context-dependency of plastic–biological invasion interactions. The outcomes of these interactions may vary significantly depending on the ecosystem type (e.g., terrestrial vs. freshwater vs. marine), the traits of the non-native species involved, the composition of native communities, environmental conditions, and the local intensity and type of plastic pollution. Comparative studies across biomes and geographic regions, ideally using standardised methodologies, will be key to identifying general patterns or context-specific dynamics.

Fourth, research is needed to expand the taxonomic scope of current studies, which remain overwhelmingly focused on Mollusca and Arthropoda. Underrepresented groups may exhibit distinct ecological and physiological responses to plastic exposure, and should be included to improve taxonomic representativeness.

Fifth, current methodological biases also warrant attention. The predominance of FTIR-based analyses, while useful, has contributed to the underdetection of nanoplastics and limited the use of advanced techniques such as Py-GC/MS, Raman spectroscopy, or AF4. The broaderder adoption of high-resolution analytical tools will enhance comparability and facilitate detection across different size classes.

Sixth, research remains largely siloed between ecotoxicology and field ecology. Integrated frameworks that combine laboratory toxicological assessments with field-based ecological observations will be essential to capture the full spectrum of species–plastic interactions.

Seventh, to ensure comparability across studies, it is also crucial to develop standardised metrics of invasion success and ecological impact in the context of plastic pollution. Such metrics may include colonisation rates, fitness proxies, or community-level responses.

Eighth, the consistent presence of particular non-native species in contaminated habitats suggests that they may also serve as biomonitors of plastic pollution. Their ubiquity, high tolerance to environmental stress, and propensity to ingest or accumulate plastics make them promising candidates for future monitoring programmes.

Ninth, a more equitable and globally inclusive research agenda is urgently needed. Regions such as Africa, Southeast Asia, and Central America remain underrepresented in the literature due to entrenched structural barriers. Strengthening international collaborations, investing in local analytical capacity, and promoting open-access dissemination of research outputs will be key to bridging these gaps and supporting informed, locally relevant conservation actions.

Tenth, from a management perspective, there is a critical need to integrate plastic pollution into non-native species risk assessments, as well as vice versa. Predictive modelling tools that incorporate variables related to both plastic distribution and species dispersal can help identify areas of overlap and guide management priorities. With advances in computational tools and the increasing application of artificial intelligence, such approaches may become central to forecasting invasion pathways and assessing ecological risk at a global scale. This is particularly important in ecologically sensitive regions such as biodiversity hotspots, migratory corridors, and protected areas, where compounding effects may be most pronounced.

Eleventh, policy frameworks should be updated to reflect the co-occurrence of these stressors, promoting holistic, ecosystem-based management approaches. Citizen science initiatives can play a crucial role in environmental education and public engagement. Efforts focused on increasing awareness of non-native species and plastic pollution can promote more sustainable behaviours, foster a deeper understanding of cumulative ecological impacts, and support community-based conservation strategies.

Finally, progress in this field will depend on methodological standardisation and innovation. Harmonising sampling protocols for detecting and quantifying plastics in association with non-native species is essential to ensure data comparability and reliability. In parallel, emerging technologies such as remote sensing, eDNA analysis, machine learning, and advanced spectroscopic tools offer new opportunities for large-scale, integrated monitoring of species–pollutant interactions. These innovations, if made accessible across different regions and research contexts, could revolutionise the way we monitor and mitigate the dual threats of plastic pollution and biological invasions.

By addressing these research priorities, the scientific community will be better equipped to anticipate, quantify, and mitigate the cumulative impacts of plastic pollution and biological invasions in a rapidly changing world. Recognising and tackling these interactions is not only a scientific imperative, but also an ethical and political responsibility, crucial to safeguarding ecological integrity under mounting anthropogenic pressure.

6. Conclusion

This systematic review reveals that the intersection between plastic pollution and biological invasions remains an underexplored yet increasingly relevant frontier in research on global change. Despite the growing number of publications in recent years, the literature remains taxonomically narrow, methodologically fragmented, and geographically skewed. The majority of studies are concentrated in high-income regions, focus disproportionately on aquatic invertebrates (particularly mollusks and arthropods), and rely heavily on microplastics and standardized ecotoxicological assays. As a result, our current understanding is limited to a narrow set of species, polymers, and endpoints, failing to capture the full ecological complexity of these interactions.

Nevertheless, our synthesis identifies three recurrent pathways through which plastics and non-native species intersect: (1) as dispersal vectors via plastic debris, (2) as modulators of biotic interactions, and (3) through the experimental use of non-native species in ecotoxicological assays, with a focus on species-specific physiological responses and plastic tolerance. These patterns suggest that the interactions between plastics and biological invasions are not merely incidental but potentially systemic, with consequences that ripple through ecosystems and food webs.

The consistent association of certain non-native species with high levels of plastic ingestion or transport raises concerns about their potential role as vectors or bioaccumulators of contaminants, not only plastics themselves, but also the hazardous chemicals they carry.

Critically, this review highlights how two of the most widespread and persistent anthropogenic stressors can interact in complex, and sometimes overlooked, ways. The lack of integration between these fields has likely hindered the development of holistic ecological models, risk assessments, and management strategies. Our findings underscore the need to break down disciplinary silos and embrace a more integrative framework to understand and mitigate the compounding effects of multiple stressors in a rapidly changing world.

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6. References

Al Alwan, B., Ismail, B., El Jery, A., & Badawi, A. K. (2024). State-of-the-art strategies for microplastics mitigation in aquatic environments: Identification, technological innovations, and prospects for advancement. *Journal of Water Process Engineering*, *61*, 105336. https://doi.org/10.1016/j.jwpe.2024.105336

Amano, T., & Berdejo-Espinola, V. (2025). Language barriers in conservation: Consequences and solutions. *Trends in Ecology & Evolution*, *40*(3), 273–285. https://doi.org/10.1016/j.tree.2024.11.003

Andersen, M. C., Adams, H., Hope, B., & Powell, M. (2004). Risk Assessment for Invasive Species. *Risk Analysis*, *24*(4), 787–793. https://doi.org/10.1111/j.0272-4332.2004.00478.x

Andrady, A. L. (2017). The plastic in microplastics: A review. *Marine Pollution Bulletin*, *119*(1), 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977–1984. https://doi.org/10.1098/rstb.2008.0304

Barry, P. J., Beraud, C., Wood, L. E., & Tidbury, H. J. (2023). Modelling of marine debris pathways into UK waters: Example of non-native crustaceans transported across the Atlantic Ocean on floating marine debris. *Marine Pollution Bulletin*, *186*, 114388. https://doi.org/10.1016/j.marpolbul.2022.114388

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., & Espinola, L. A. (2018). Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps.

Water Research, *143*, 416–424. https://doi.org/10.1016/j.watres.2018.06.015

Cai, L., Zhao, X., Liu, Z., & Han, J. (2023). The abundance, characteristics and distribution of microplastics (MPs) in farmland soil—Based on research in China. *Science of The Total Environment*, *876*, 162782. https://doi.org/10.1016/j.scitotenv.2023.162782

Calderisi, G., Cogoni, D., Loni, A., & Fenu, G. (2023). Difference between invasive alien and native vegetation in trapping beach litter: A focus on a typical sandy beach of W-Mediterranean Basin. *Marine Pollution Bulletin*, *192*, 115065. https://doi.org/10.1016/j.marpolbul.2023.115065

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering*, *8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Cowger, W., Willis, K. A., Bullock, S., Conlon, K., Emmanuel, J., Erdle, L. M., Eriksen, M., Farrelly, T. A., Hardesty, B. D., Kerge, K., Li, N., Li, Y., Liebman, A., Tangri, N., Thiel, M., Villarrubia-Gómez, P., Walker, T. R., & Wang, M. (2024). Global producer responsibility for plastic pollution. *Science Advances*, *10*(17), eadj8275. https://doi.org/10.1126/sciadv.adj8275

Devi, S. S., Sreedevi, A. V., & Kumar, A. B. (2020). First report of microplastic ingestion by the alien fish Pirapitinga (Piaractus brachypomus) in the Ramsar site Vembanad Lake, south India. *Marine Pollution Bulletin*, *160*, 111637. https://doi.org/10.1016/j.marpolbul.2020.111637

Diagne, C., Leroy, B., Vaissière, A.-C., Gozlan, R. E., Roiz, D., Jarić, I., Salles, J.-M., Bradshaw, C. J. A., & Courchamp, F. (2021). High and rising economic costs of biological invasions worldwide. *Nature*, *592*(7855), 571–576. https://doi.org/10.1038/s41586-021-03405-6

Dobrzycka-Krahel, A., Skóra, M. E., & Pladzyk, A. (2024). Plastic Debris in the Stomach of the Invasive Signal Crayfish Pacifastacus leniusculus from a Baltic Coastal River. *Water*, *16*(6), 903. https://doi.org/10.3390/w16060903

Ehrenfeld, J. G. (2010). Ecosystem Consequences of Biological Invasions. *Annual Review of Ecology, Evolution, and Systematics*, *41*(1), 59–80. https://doi.org/10.1146/annurev-ecolsys-102209-144650

El Haj, Y., Bohn, S., & Souza, M. M. (2019). Tolerance of native and invasive bivalves under herbicide and metal contamination: An ex vivo approach. *Environmental Science and Pollution Research*, *26*(30), 31198–31206. https://doi.org/10.1007/s11356-019-06256-x

En-Nejmy, K., El Hayany, B., Al-Alawi, M., Jemo, M., Hafidi, M., & El Fels, L. (2024). Microplastics in soil: A comprehensive review of occurrence, sources, fate, analytical techniques and potential impacts. *Ecotoxicology and Environmental Safety*, *288*, 117332. https://doi.org/10.1016/j.ecoenv.2024.117332

Firn, J., Maggini, R., Chadès, I., Nicol, S., Walters, B., Reeson, A., Martin, T. G., Possingham, H. P., Pichancourt, J., Ponce-Reyes, R., & Carwardine, J. (2015). Priority threat management of invasive animals to protect biodiversity under climate change. *Global Change Biology*, *21*(11), 3917–3930. https://doi.org/10.1111/gcb.13034

Gallardo, B., Bacher, S., Barbosa, A. M., Gallien, L., González-Moreno, P., Martínez-Bolea, V., Sorte, C., Vimercati, G., & Vilà, M. (2024). Risks posed by invasive species to the provision of ecosystem services in Europe. *Nature Communications*, *15*(1), 2631. https://doi.org/10.1038/s41467-024-46818-3

Gao, X., Li, X., Wang, Y., Lin, C., Zuo, Y., Li, X., & Xing, W. (2024). Does invasive submerged macrophyte diversity affect dissimilatory nitrate reduction processes in sediments with varying microplastics? *Journal of Hazardous Materials*, *472*, 134510.

https://doi.org/10.1016/j.jhazmat.2024.134510

García-Gómez, J. C., Garrigós, M., & Garrigós, J. (2021). Plastic as a Vector of Dispersion for Marine Species With Invasive Potential. A Review. *Frontiers in Ecology and Evolution*, *9*, 629756. https://doi.org/10.3389/fevo.2021.629756

Garcia-Vazquez, E., Cani, A., Diem, A., Ferreira, C., Geldhof, R., Marquez, L., Molloy, E., & Perché, S. (2018). Leave no traces – Beached marine litter shelters both invasive and native species. *Marine Pollution Bulletin*, *131*, 314–322. https://doi.org/10.1016/j.marpolbul.2018.04.037

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Giarratano, E., Trovant, B., & Hernández-Moresino, R. D. (2024). Asian clam Corbicula fluminea as potential biomonitor of microplastics and metal(oid)s in a Patagonian River. *Marine Environmental Research*, *198*, 106548. https://doi.org/10.1016/j.marenvres.2024.106548

González-Ortegón, E., Demmer, J., Robins, P., & Jenkins, S. (2024). Floating plastics as a potential dispersal vector for rafting marine non-native species. *Marine Pollution Bulletin*, *207*, 116919. https://doi.org/10.1016/j.marpolbul.2024.116919

Gray, A., Mayer, K., Gore, B., Gaesser, M., & Ferguson, N. (2024). Microplastic burden in native (Cambarus appalachiensis) and non-native (Faxonius cristavarius) crayfish along semi-rural and urban streams in southwest Virginia, USA. *Environmental Research*, *258*, 119494. https://doi.org/10.1016/j.envres.2024.119494

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings—Entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2013–2025. https://doi.org/10.1098/rstb.2008.0265

Hartmann, N. B., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M. P., Hess, M. C., Ivleva, N. P., Lusher, A. L., & Wagner, M. (2019). Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris. *Environmental Science & Technology*, *53*(3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297

Havel, J. E., Kovalenko, K. E., Thomaz, S. M., Amalfitano, S., & Kats, L. B. (2015). Aquatic invasive species: Challenges for the future. *Hydrobiologia*, *750*(1), 147–170. https://doi.org/10.1007/s10750-014-2166-0

Hoffmann, B. D., & Broadhurst, L. M. (2016). The economic cost of managing invasive species in Australia. *NeoBiota*, *31*, 1–18. https://doi.org/10.3897/neobiota.31.6960

Hollerová, A., Hodkovicová, N., Blahová, J., Faldyna, M., Maršálek, P., & Svobodová, Z. (2021). Microplastics as a potential risk for aquatic environment organisms – a review. *Acta Veterinaria Brno*, *90*(1), 99–107. https://doi.org/10.2754/avb202190010099

Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of The Total Environment*, *586*, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190

Iqbal, B. (2024). Microplastics meet invasive plants: Unraveling the ecological hazards to agroecosystems. *Science of the Total Environment*.

Javed, Q., Sun, J., Rutherford, S., Li, J., Iqbal, B., Xiang, Y., Ren, G., He, F., Pan, L., Bo, Y., Khattak, W. A., & Du, D. (2023). Soil pollution and the invasion of congener Sphagneticola in crop lands. *Journal of Environmental Management*, *340*, 118013. https://doi.org/10.1016/j.jenvman.2023.118013

Jones, J. I., Vdovchenko, A., Cooling, D., Murphy, J. F., Arnold, A., Pretty, J. L., Spencer, K. L., Markus, A. A., Vethaak, A. D., & Resmini, M. (2020). Systematic Analysis of the Relative Abundance of Polymers Occurring as Microplastics in Freshwaters and Estuaries. *International Journal of Environmental Research and Public Health*, *17*(24), 9304. https://doi.org/10.3390/ijerph17249304

Käppler, A., Fischer, D., Oberbeckmann, S., Schernewski, G., Labrenz, M., Eichhorn, K.-J., & Voit, B. (2016). Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both? *Analytical and Bioanalytical Chemistry*, *408*(29), 8377–8391. https://doi.org/10.1007/s00216-016-9956-3

Kim, S.-K., Kim, J.-S., Lee, H., & Lee, H.-J. (2021). Abundance and characteristics of microplastics in soils with different agricultural practices: Importance of sources with internal origin and environmental fate. *Journal of Hazardous Materials*, *403*, 123997. https://doi.org/10.1016/j.jhazmat.2020.123997

Law, K. L. (2017). Plastics in the Marine Environment. *Annual Review of Marine Science*, *9*(1), 205–229. https://doi.org/10.1146/annurev-marine-010816-060409

Leroy, B., Bellard, C., Dias, M. S., Hugueny, B., Jézéquel, C., Leprieur, F., Oberdorff, T., Robuchon, M., & Tedesco, P. A. (2023). Major shifts in biogeographic regions of freshwater fishes as evidence of the Anthropocene epoch. *Science Advances*, *9*(46), eadi5502. https://doi.org/10.1126/sciadv.adi5502

Li, C., Busquets, R., & Campos, L. C. (2020). Assessment of microplastics in freshwater systems: A review. *Science of The Total Environment*, *707*, 135578. https://doi.org/10.1016/j.scitotenv.2019.135578

Li, G., Zhao, X., Iqbal, B., Zhao, X., Liu, J., Javed, Q., & Du, D. (2023). The effect of soil microplastics on Oryza sativa L. root growth traits under alien plant invasion. *Frontiers in Ecology and Evolution*, *11*, 1172093. https://doi.org/10.3389/fevo.2023.1172093

Li, J., Leng, Z., Wu, Y., Du, Y., Dai, Z., Biswas, A., Zheng, X., Li, G., Mahmoud, E. K., Jia, H., & Du, D. (2022). Interactions between invasive plants and heavy metal stresses: A review. *Journal of Plant Ecology*, *15*(3), 429–436. https://doi.org/10.1093/jpe/rtab100

Li, J., Wang, Z., Rotchell, J. M., Shen, X., Li, Q., & Zhu, J. (2021). Where are we? Towards an understanding of the selective accumulation of microplastics in mussels. *Environmental Pollution*, *286*, 117543. https://doi.org/10.1016/j.envpol.2021.117543

Li, Q., Wu, J., Zhao, X., Gu, X., & Ji, R. (2019). Separation and identification of microplastics from soil and sewage sludge. *Environmental Pollution*, *254*, 113076. https://doi.org/10.1016/j.envpol.2019.113076

Lofty, J., Ouro, P., & Wilson, C. A. M. E. (2023). Microplastics in the riverine environment: Meta-analysis and quality criteria for developing robust field sampling procedures. *Science of The Total Environment*, *863*, 160893. https://doi.org/10.1016/j.scitotenv.2022.160893

MacDougall, A. S., & Turkington, R. (2005). ARE INVASIVE SPECIES THE DRIVERS OR PASSENGERS OF CHANGE IN DEGRADED ECOSYSTEMS? *Ecology*, *86*(1), 42–55. https://doi.org/10.1890/04-0669

Mantelatto, M. C., Póvoa, A. A., Skinner, L. F., Araujo, F. V. D., & Creed, J. C. (2020). Marine litter and wood debris as habitat and vector for the range expansion of invasive corals (Tubastraea spp.). *Marine Pollution Bulletin*, *160*, 111659. https://doi.org/10.1016/j.marpolbul.2020.111659

Martin, L. J., Blossey, B., & Ellis, E. (2012). Mapping where ecologists work: Biases in the global distribution of terrestrial ecological observations. *Frontiers in Ecology and the Environment*, *10*(4), 195–201. https://doi.org/10.1890/110154

Meyerson, L. A., & Mooney, H. A. (2007). Invasive alien species in an era of globalization.

Frontiers in Ecology and the Environment, *5*(4), 199–208. https://doi.org/10.1890/1540-9295(2007)5[199:IASIAE]2.0.CO;2

Mooney, H. A., & Cleland, E. E. (2001). The evolutionary impact of invasive species. *Proceedings of the National Academy of Sciences*, *98*(10), 5446–5451. https://doi.org/10.1073/pnas.091093398

OECD. (2022). *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. OECD. https://doi.org/10.1787/de747aef-en

Parra, S., Santos, D., Luzio, A., Cabecinha, E., Saavedra, M. J., Gago, J., Varandas, S., & Monteiro, S. M. (2024). Impacts of Microplastics, Cadmium, and Their Mixtures on Biochemical Biomarkers in the Freshwater Bivalve Corbicula fluminea (Bivalvia, Corbiculidea). *Diversity*, *16*(12), 750. https://doi.org/10.3390/d16120750

Pastorino, P., Anselmi, S., Zanoli, A., Esposito, G., Bondavalli, F., Dondo, A., Pucci, A., Pizzul, E., Faggio, C., Barceló, D., Renzi, M., & Prearo, M. (2023). The invasive red swamp crayfish (Procambarus clarkii) as a bioindicator of microplastic pollution: Insights from Lake Candia (northwestern Italy). *Ecological Indicators*, *150*, 110200. https://doi.org/10.1016/j.ecolind.2023.110200

Pawar, P. R., Shirgaonkar, S. S., & Patil, R. B. (2016). *Plastic marine debris: Sources, distribution and impacts on coastal and ocean biodiversity*.

Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. *Trends in Ecology & Evolution*, *24*(9), 497–504. https://doi.org/10.1016/j.tree.2009.03.016

Piola, R. F., & Johnston, E. L. (2009). Comparing differential tolerance of native and non-indigenous marine species to metal pollution using novel assay techniques. *Environmental Pollution*, *157*(10), 2853–2864. https://doi.org/10.1016/j.envpol.2009.04.007

Plastics Europe. (2024). *The Circular Economy for Plastics: A European Analysis – 2024* *edition*. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-analysis-2024/

Prentis, P. J., Wilson, J. R. U., Dormontt, E. E., Richardson, D. M., & Lowe, A. J. (2008). Adaptive evolution in invasive species. *Trends in Plant Science*, *13*(6), 288–294. https://doi.org/10.1016/j.tplants.2008.03.004

Pyšek, P., Hulme, P. E., Simberloff, D., Bacher, S., Blackburn, T. M., Carlton, J. T., Dawson, W., Essl, F., Foxcroft, L. C., Genovesi, P., Jeschke, J. M., Kühn, I., Liebhold, A. M., Mandrak, N. E., Meyerson, L. A., Pauchard, A., Pergl, J., Roy, H. E., Seebens, H., … Richardson, D. M. (2020). Scientists' warning on invasive alien species. *Biological Reviews*, *95*(6), 1511–1534. https://doi.org/10.1111/brv.12627

Rech, S., Borrell Pichs, Y. J., & García-Vazquez, E. (2018). Anthropogenic marine litter composition in coastal areas may be a predictor of potentially invasive rafting fauna. *PLOS ONE*, *13*(1), e0191859. https://doi.org/10.1371/journal.pone.0191859

Reynolds, A., Cody, E., Giltrap, M., & Chambers, G. (2024). Toxicological and Biomarker Assessment of Freshwater Zebra Mussels (Dreissena polymorpha) Exposed to Nano-Polystyrene. *Toxics*, *12*(11), 774. https://doi.org/10.3390/toxics12110774

Ricciardi, A. (2013). Invasive Species. Em R. Leemans (Ed.), *Ecological Systems: Selected Entries from the Encyclopedia of Sustainability Science and Technology* (pp. 161–178). Springer New York. https://doi.org/10.1007/978-1-4614-5755-8_10

Richard, C. M. C., Dejoie, E., Wiegand, C., Gouesbet, G., Colinet, H., Balzani, P., Siaussat, D., & Renault, D. (2024). Plastic pollution in terrestrial ecosystems: Current knowledge on impacts of micro and nano fragments on invertebrates. *Journal of Hazardous Materials*, *477*, 135299. https://doi.org/10.1016/j.jhazmat.2024.135299

Ríos, J. M., Teixeira De Mello, F., De Feo, B., Krojmal, E., Vidal, C., Loza-Argote, V. A., &

Scheibler, E. E. (2022). Occurrence of microplastics in Fish from Mendoza River: First Insights into Plastic Pollution in the Central Andes, Argentina. *Water*, *14*(23), 3905. https://doi.org/10.3390/w14233905

Rochman, C. M. (2013). Plastics and Priority Pollutants: A Multiple Stressor in Aquatic Habitats. *Environmental Science & Technology*, *47*(6), 2439–2440. https://doi.org/10.1021/es400748b

Rodrigues, F., Vieira, H., Campos, D., Pires, S., Rodrigues, A., Silva, A., Soares, A., Oliveira, J., & Bordalo, M. (2022). Co-Exposure with an Invasive Seaweed Exudate Increases Toxicity of Polyamide Microplastics in the Marine Mussel Mytilus galloprovincialis. *Toxics*, *10*(2), 43. https://doi.org/10.3390/toxics10020043

Roy, H. E., Pauchard, A., Stoett, P. J., Renard Truong, T., Meyerson, L. A., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Kavileveettil, S., McGeoch, M. A., Nuñez, M. A., Ordonez, A., Rahlao, S. J., Schwindt, E., Seebens, H., Sheppard, A. W., Vandvik, V., Aleksanyan, A., … Ziller, S. R. (2024). Curbing the major and growing threats from invasive alien species is urgent and achievable. *Nature Ecology & Evolution*, *8*(7), 1216–1223. https://doi.org/10.1038/s41559-024-02412-w

Ryan, P. G. (2018). Entanglement of birds in plastics and other synthetic materials. *Marine Pollution Bulletin*, *135*, 159–164. https://doi.org/10.1016/j.marpolbul.2018.06.057

Sa'adu, I., & Farsang, A. (2023). Plastic contamination in agricultural soils: A review. *Environmental Sciences Europe*, *35*(1), 13. https://doi.org/10.1186/s12302-023-00720-9

Saemi-Komsari, M., Esmaeili, H. R., Keshavarzi, B., Abbasi, K., Birami, F. A., Nematollahi, M. J., Tayefeh, F. H., & Busquets, R. (2023). Characterization of ingested MPs and their relation with growth parameters of endemic and invasive fish from a coastal wetland. *Science of The Total Environment*, *860*, 160495. https://doi.org/10.1016/j.scitotenv.2022.160495

Sajjad, M., Huang, Q., Khan, S., Khan, M. A., Liu, Y., Wang, J., Lian, F., Wang, Q., & Guo, G. (2022). Microplastics in the soil environment: A critical review. *Environmental Technology & Innovation*, *27*, 102408. https://doi.org/10.1016/j.eti.2022.102408

Salager-Meyer, F. (2008). Scientific publishing in developing countries: Challenges for the future. *Journal of English for Academic Purposes*, *7*(2), 121–132. https://doi.org/10.1016/j.jeap.2008.03.009

Scherer, C., Weber, A., Stock, F., Vurusic, S., Egerci, H., Kochleus, C., Arendt, N., Foeldi, C., Dierkes, G., Wagner, M., Brennholt, N., & Reifferscheid, G. (2020). Comparative assessment of microplastics in water and sediment of a large European river. *Science of The Total Environment*, *738*, 139866. https://doi.org/10.1016/j.scitotenv.2020.139866

Schwarz, A. E., Ligthart, T. N., Boukris, E., & Van Harmelen, T. (2019). Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. *Marine Pollution Bulletin*, *143*, 92–100. https://doi.org/10.1016/j.marpolbul.2019.04.029

Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., Pagad, S., Pyšek, P., Winter, M., Arianoutsou, M., Bacher, S., Blasius, B., Brundu, G., Capinha, C., Celesti-Grapow, L., Dawson, W., Dullinger, S., Fuentes, N., Jäger, H., ... Essl, F. (2017). No saturation in the accumulation of alien species worldwide. *Nature Communications*, *8*(1), 14435. https://doi.org/10.1038/ncomms14435

Simard, F. D. R., Nchoutpouen, E. E., Toto, J. C., & Fontenille, D. (2005). Geographic Distribution and Breeding Site Preference of Aedes albopictus and Aedes aegypti (Diptera: Culicidae) in Cameroon, Central Africa. *JOURNAL OF MEDICAL ENTOMOLOGY*, *42*(5).

Simberloff, D. (2004). Community Ecology: Is It Time to Move On?: (An American Society of Naturalists Presidential Address). *The American Naturalist*, *163*(6), 787–799. https://doi.org/10.1086/420777

Simberloff, D. (2010). Invasive species. *Conservation biology for all*, *1*, 131–152.

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., & Vilà, M. (2013). Impacts of biological invasions: What's what and the way forward. *Trends in Ecology & Evolution*, *28*(1), 58–66. https://doi.org/10.1016/j.tree.2012.07.013

Soares, M. O., Xavier, F. R. D. L., Dias, N. M., Silva, M. Q. M. D., Lima, J. P. D., Barroso, C. X., Vieira, L. M., Paiva, S. V., Matthews-Cascon, H., Bezerra, L. E. A., Oliveira-Filho, R. R., Salani, S., & Bandeira, Ê. V. P. (2022). Alien hotspot: Benthic marine species introduced in the Brazilian semiarid coast. *Marine Pollution Bulletin*, *174*, 113250. https://doi.org/10.1016/j.marpolbul.2021.113250

Soto, I., Balzani, P., Carneiro, L., Cuthbert, R. N., Macêdo, R., Serhan Tarkan, A., Ahmed, D. A., Bang, A., Bacela-Spychalska, K., Bailey, S. A., Baudry, T., Ballesteros-Mejia, L., Bortolus, A., Briski, E., Britton, J. R., Buřič, M., Camacho-Cervantes, M., Cano-Barbacil, C., Copilaş-Ciocianu, D., … Haubrock, P. J. (2024). Taming the terminological tempest in invasion science. *Biological Reviews*, *99*(4), 1357–1390. https://doi.org/10.1111/brv.13071

Stoett, P., Scrich, V. M., Elliff, C. I., Andrade, M. M., De M. Grilli, N., & Turra, A. (2024). Global plastic pollution, sustainable development, and plastic justice. *World Development*, *184*, 106756. https://doi.org/10.1016/j.worlddev.2024.106756

Terzi, Y. (2023). Microplastic ingestion by invasive Prussian carp (Carassius gibelio) used in fishmeal production in Türkiye. *Environmental Monitoring and Assessment*, *195*(10), 1232. https://doi.org/10.1007/s10661-023-11844-z

Tian, M., Qiao, B., Xu, Z., Liang, Q., Xie, X., Chen, K., Zhang, Y., Zhao, C., & Li, C. (2024).

Invasion of Trifolium repens L. aggravated by biodegradable plastics: Adjustable strategy for foraging N and P. *Journal of Hazardous Materials*, *474*, 134777. https://doi.org/10.1016/j.jhazmat.2024.134777

Tøttrup, A. P., Chan, B. K. K., Koskinen, H., & Høeg, J. T. (2010). 'Flying barnacles': Implications for the spread of non-indigenous species. *Biofouling*, *26*(5), 577–582. https://doi.org/10.1080/08927014.2010.489203

Towns, D. R., Daugherty, C. H., Broome, K., Timmins, S., & Clout, M. (2019). The thirty-year conservation revolution in New Zealand: An introduction. *Journal of the Royal Society of New Zealand*, *49*(3), 243–258. https://doi.org/10.1080/03036758.2019.1652192

Turba, R., Thoré, E. S. J., Bertram, M. G., Bridg, H., Sabet, S. S., Gamboa, M., Ríos-Orjuela, J. C., Takola, E., Capa Salinas, J., Sampaio Franco, A. C., & Marín, C. (2025). *Global North-South science inequalities due to language and funding barriers*. Zenodo. https://doi.org/10.5281/ZENODO.14902147

Turbelin, A. J., Malamud, B. D., & Francis, R. A. (2017). Mapping the global state of invasive alien species: Patterns of invasion and policy responses. *Global Ecology and Biogeography*, *26*(1), 78–92. https://doi.org/10.1111/geb.12517

Vye, S. R., Emmerson, M. C., Arenas, F., Dick, J. T. A., & O'Connor, N. E. (2015). Stressor intensity determines antagonistic interactions between species invasion and multiple stressor effects on ecosystem functioning. *Oikos*, *124*(8), 1005–1012. https://doi.org/10.1111/oik.01583

Walker, T. R., & Fequet, L. (2023). Current trends of unsustainable plastic production and micro(nano)plastic pollution. *TrAC Trends in Analytical Chemistry*, *160*, 116984. https://doi.org/10.1016/j.trac.2023.116984

Wang, S., Wei, M., Cheng, H., Wu, B., Du, D., & Wang, C. (2020). Indigenous plant species and invasive alien species tend to diverge functionally under heavy metal pollution and drought stress. *Ecotoxicology and Environmental Safety*, *205*, 111160. https://doi.org/10.1016/j.ecoenv.2020.111160

Wang, W., & Wang, J. (2018). Investigation of microplastics in aquatic environments: An overview of the methods used, from field sampling to laboratory analysis. *TrAC Trends in Analytical Chemistry*, *108*, 195–202. https://doi.org/10.1016/j.trac.2018.08.026

Wang, Z., He, M., Meng, Z., Lang, J., Lu, X., Xue, Q., Liang, L., & Mo, X. (2024). Nitrogen deposition modulates invasibility and stability of plant communities in microplastic-contaminated wetlands. *Global Ecology and Conservation*, *56*, e03314. https://doi.org/10.1016/j.gecco.2024.e03314

Williams, A. T., & Rangel-Buitrago, N. (2022). The past, present, and future of plastic pollution. *Marine Pollution Bulletin*, *176*, 113429. https://doi.org/10.1016/j.marpolbul.2022.113429

Wójcik-Fudalewska, D., Normant-Saremba, M., & Anastácio, P. (2016). Occurrence of plastic debris in the stomach of the invasive crab Eriocheir sinensis. *Marine Pollution Bulletin*, *113*(1–2), 306–311. https://doi.org/10.1016/j.marpolbul.2016.09.059

Yang, J., Hu, X., & Tan, F. (2025). The Mapping of Global Plastic Pollution Research: A Bibliometric Analysis of the Progress and Thematic Trends. *Sustainability*, *17*(5), 1859. https://doi.org/10.3390/su17051859

Yang, L., Zhang, Y., Kang, S., Wang, Z., & Wu, C. (2021). Microplastics in soil: A review on methods, occurrence, sources, and potential risk. *Science of The Total Environment*, *780*, 146546. https://doi.org/10.1016/j.scitotenv.2021.146546

Yang, R.-Y., Tang, J.-J., Yang, Y.-S., & Chen, X. (2007). Invasive and non-invasive plants differ in response to soil heavy metal lead contamination. *Botanical Studies*, *48*.