A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 108: 251–276 (2026)
DOI: 10.3897/neobiota.108.163842

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 colonisation 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 that include the limited integration of ecological responses in natural ecosystems, the under-representation of many taxonomic groups and the lack of comparative analyses exploring how non-native species may act as vectors for plastic transport and bioaccumulation. This situation implies the need for more 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.

Key words: Microplastic, non-native species, species–pollutant interactions, vectoring of contaminants

OPEN ACCESS

Academic editor: Zarah Pattison
Received: 2 July 2025
Accepted: 23 December 2025
Published: 5 August 2026

Citation: Sousa D, Sousa R, Padilha J (2026) Plastic pollution meets biological invasions: a systematic review of emerging interactions. NeoBiota 108: 251–276. https://doi.org/10.3897/neobiota.108.163842

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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 (Li et al. 2021; Cowger et al. 2024; Yang et al. 2025). 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 (Li et al. 2021; Cowger et al. 2024; 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 realms, posing a global threat that transcends both geographic and ecological boundaries (Williams and Rangel-Buitrago 2022; Walker and Fequet 2023; Richard et al. 2024). Yet, its ecological consequences remain far from fully understood, from the individual to the ecosystem level (Williams and Rangel-Buitrago 2022,;Walker and Fequet 2023; Richard et al. 2024).

In natural environments, plastics degrade through a combination of physical, chemical and biological processes (Andrady and 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 behaviour (Andrady 2017).

Plastic debris is composed of a wide range of polymers, each with distinct physical and chemical characteristics that influence their environmental behaviour, persistence and toxicity across ecosystems. Common polymers include polyethylene (PE) and polypropylene (PP), which are lightweight and highly persistent; polyethylene terephthalate (PET), which is denser and tends to accumulate in soils, sediments and benthic compartments; and polystyrene (PS), which readily fragments into smaller particles and can release potentially toxic monomers and additives (Andrady 2017). The environmental fate and biological interactions of these polymers vary across marine, freshwater and terrestrial systems, depending on factors, such as density, surface properties, degradation pathways and local environmental conditions (Pyšek and Richardson 2010; Roy et al. 2024).These polymers persist for decades, act as vectors for other pollutants, such as metals and organic contaminants and can be ingested by organisms, leading to physical obstruction, oxidative stress and altered energy metabolism (Horton and Dixon 2018). Understanding their specific characteristics is therefore essential to assess their ecological risks and interactions with other stressors, including non-native species.

Alongside plastic pollution, biological invasions have emerged as both a driver and a passenger of global environmental change (MacDougall and Turkington 2005), drawing increasing scientific attention (Pyšek and Richardson 2010; 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 (Mooney and Cleland 2001; Meyerson and Mooney 2007; Havel et al. 2015; Seebens et al. 2017). Once introduced, some species have established self-sustaining populations and successfully spread in their new environments (Pyšek et al. 2020; Ricciardi et al. 2021).

These established non-native species can exert a diverse array of ecological, economic and socio-cultural impacts – often highly context-dependent – due to direct biotic interactions, such as predation, competition, parasitism and hybridisation with native taxa and effects involving substantial changes to habitat structure and function, hydrological cycles, nutrient fluxes and trophic interactions (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 services degradation, reduced quality of life, substantial economic losses and public health concerns, all of which are themselves frequently context-dependent (Pejchar and Mooney 2009; Diagne et al. 2021; Gallardo et al. 2024).

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 plastics, metals and pesticides (Yang et al. 2007; Piola and Johnston 2009; El Haj et al. 2019; Wang et al. 2020), studies are often fragmented. Yet, potential interactions (including ingestion, transport or altered bioaccumulation) 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, their biotic interactions, amongst other possibilities (Gao et al. 2024; Tian 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 (Rodrigues et al. 2022; Iqbal 2024). 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.

Materials and methods

Bibliographical search

A systematic literature search was conducted in the Scopus database to identify studies at the intersection of plastic pollution and biological invasions (Fig. 1; Suppl. material 1: section S1). The search focused exclusively on peer-reviewed publications indexed in Scopus; grey literature, such as reports, theses or non-peer-reviewed materials, was not included. 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. The search was performed using a structured combination of keywords related to plastic pollution and non-native species, applied to titles, abstracts and keywords. The core search string was: (plastic OR microplastic OR nanoplastic OR macroplastic OR mesoplastic) AND (non-native OR alien OR invasive OR introduced species OR biological invasion).

This core string was expanded using taxon-specific terms and species names derived from authoritative global and regional reference lists, including the IUCN Global Invasive Species Database, the list of the 100 worst non-native species worldwide (Lowe et al. 2000), the European Union's list of Invasive Alien Species of Union Concern and the Inventory of Alien Invasive Species in Europe (DAISIE). Additional species were included to capture taxonomic and ecological diversity across both aquatic and terrestrial environments.

Although these sources provide robust and standardised references, reliance on EU-based frameworks may not fully capture non-native species dynamics in countries outside the EU or in tropical regions, where invasion histories, reporting effort and regulatory frameworks differ substantially. This represents a limitation when aiming to synthesise patterns at a global scale. The full set of search strings and taxon-specific queries is provided in Suppl. material 1: section S1.

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. No specific start date was defined for the search, which was left open to include the earliest available records. Articles were included if they explicitly addressed the interactions, co-occurrence or potential impacts of plastic pollution on one or more non-native species. Only articles published up to 31 December 2024, were considered. These studies covered diverse taxa, including viruses, fungi, plants and animals, ensuring representation of different biological groups involved in interactions with plastics. The search was restricted to articles written in English, aiming to provide a global overview. However, restricting the search to English-language publications may lead to an under-representation of studies published in other languages, particularly from regions where relevant research is commonly disseminated in local or regional journals. This language bias represents a recognised limitation of systematic reviews and may constrain the completeness of a truly global overview.

Data analysis

All data cleaning, processing and visualisation were performed using R version 4.3.1. A choropleth map was generated to visualise the number of studies per continent, using the sf, rnaturalearth, rnaturalearthdata, dplyr and ggplot2 packages.

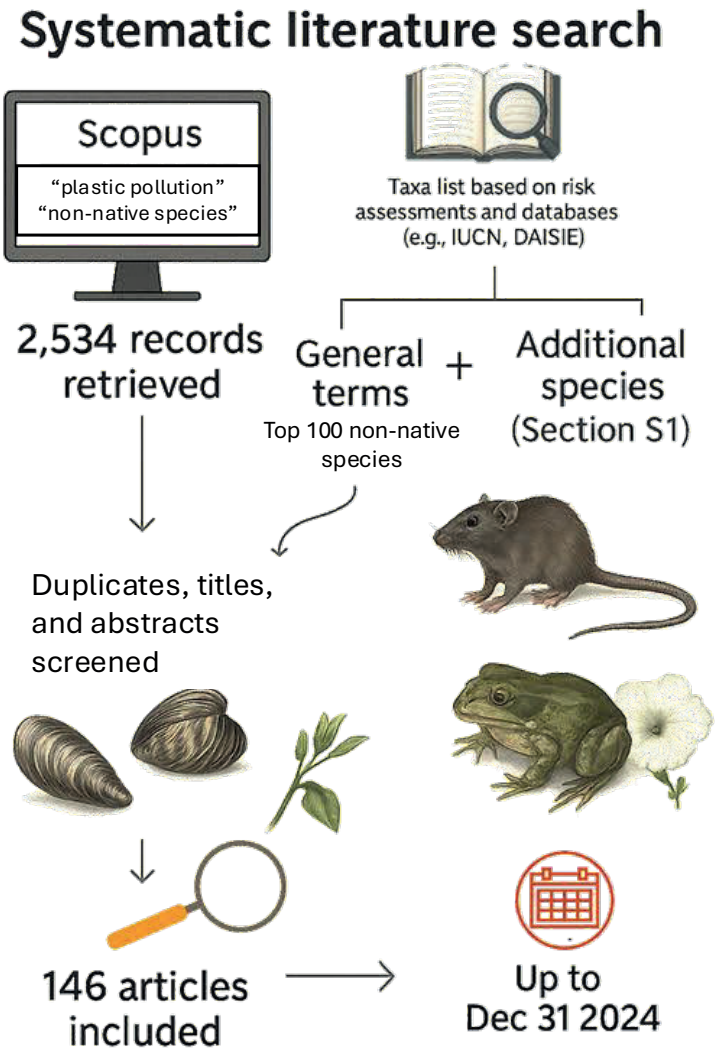


Figure 1. Overview of the systematic literature search and screening process. A total of 2,534 records were retrieved from Scopus; after screening and full-text review, 146 articles were included for analysis. This figure was created with the assistance of AI-based tools and all content was reviewed and verified by the authors.

The map was projected using the Equal Earth projection (EPSG:8857) and colour-coded by study count using a continuous gradient scale.

Analytical techniques were extracted from each article (as reported in the Materials and Methods and/or Suppl. material 1) and harmonised into broader categories to reduce fragmentation and improve comparability across studies. Techniques were grouped into FTIR-based methods, microscopy (including optical, fluorescence, SEM and TEM), Raman spectroscopy, light scattering and field-flow fractionation (including AF4), mass spectrometry and ICP-MS, X-ray-based techniques, spectrophotometry and computational modelling. When a study applied multiple techniques, all reported techniques were recorded and counted accordingly. Polymer types were recorded as reported by the authors; polymers mentioned only once across the dataset were pooled into an "Other" category for visualisation purposes. Plastic size classes were standardised following Hartmann et al. (2019) and recorded, based on the size definitions reported in each study.

In addition, a Sankey diagram was constructed using the networkD3 package to illustrate the relationships amongst four categorical variables: Continent,

Taxonomic Group, Study Type and Plastic Type. Before building the diagram, the dataset was pre-processed to filter and recode values using stringr, tidyr and dplyr. All plots were exported in HTML and PNG formats using the html widgets and webshot packages for outputs. The thickness of each flow is proportional to the number of studies connecting the respective categories, providing a structural overview of dominant research pathways.

Results

Temporal trends

The number of scientific publications addressing both plastic pollution and biological invasions has increased sharply in recent years (Fig. 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 2019 and 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.

Spatial distribution

As illustrated in Fig. 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 under-represented.

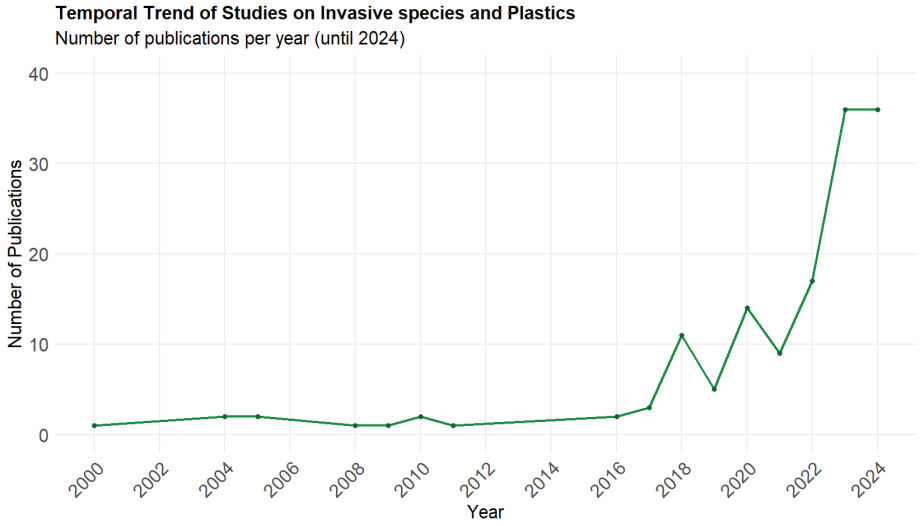


Figure 2. Number of publications produced per year on the topic of plastic pollution and biological invasions according Scopus database until 2024 (n = 146).

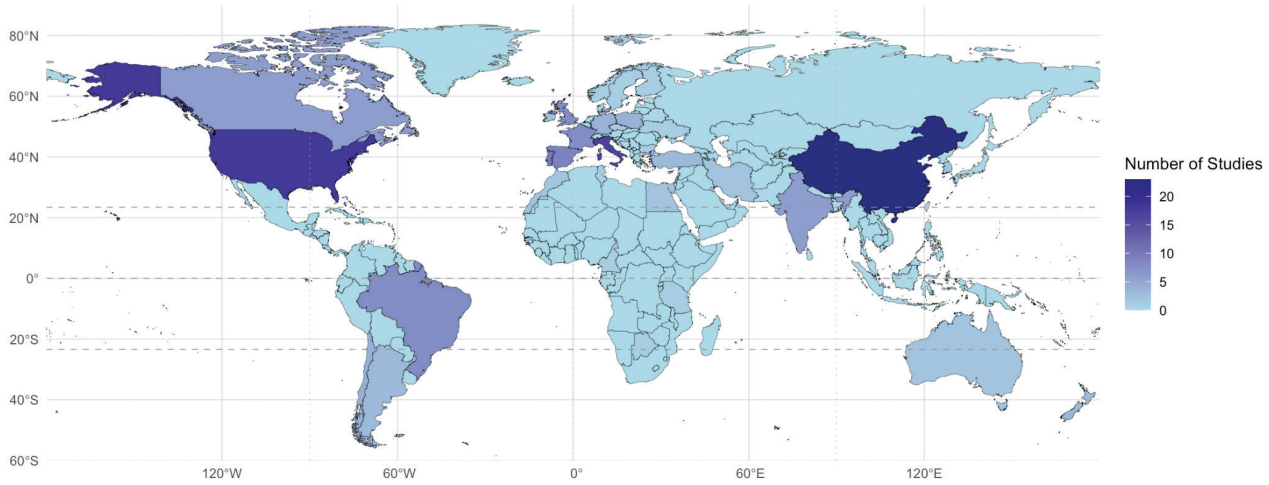


Figure 3. Geographic distribution of studies by country on the topic of plastic and biological invasions according Scopus database until 2024 (n = 146).

Study types and techniques used

As illustrated in Fig. 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 (Fig. 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).

Plastic size classes and detection biases

As illustrated in Fig. 5, most studies focused on microplastics (MPs), 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 (Gregory 2009; Pawar et al. 2016; Rech et al. 2018; Ryan 2018; González-Ortegón et al. 2024). Nanoplastics and Mesoplastics were rarely the central focus of studies.

Polymer types

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

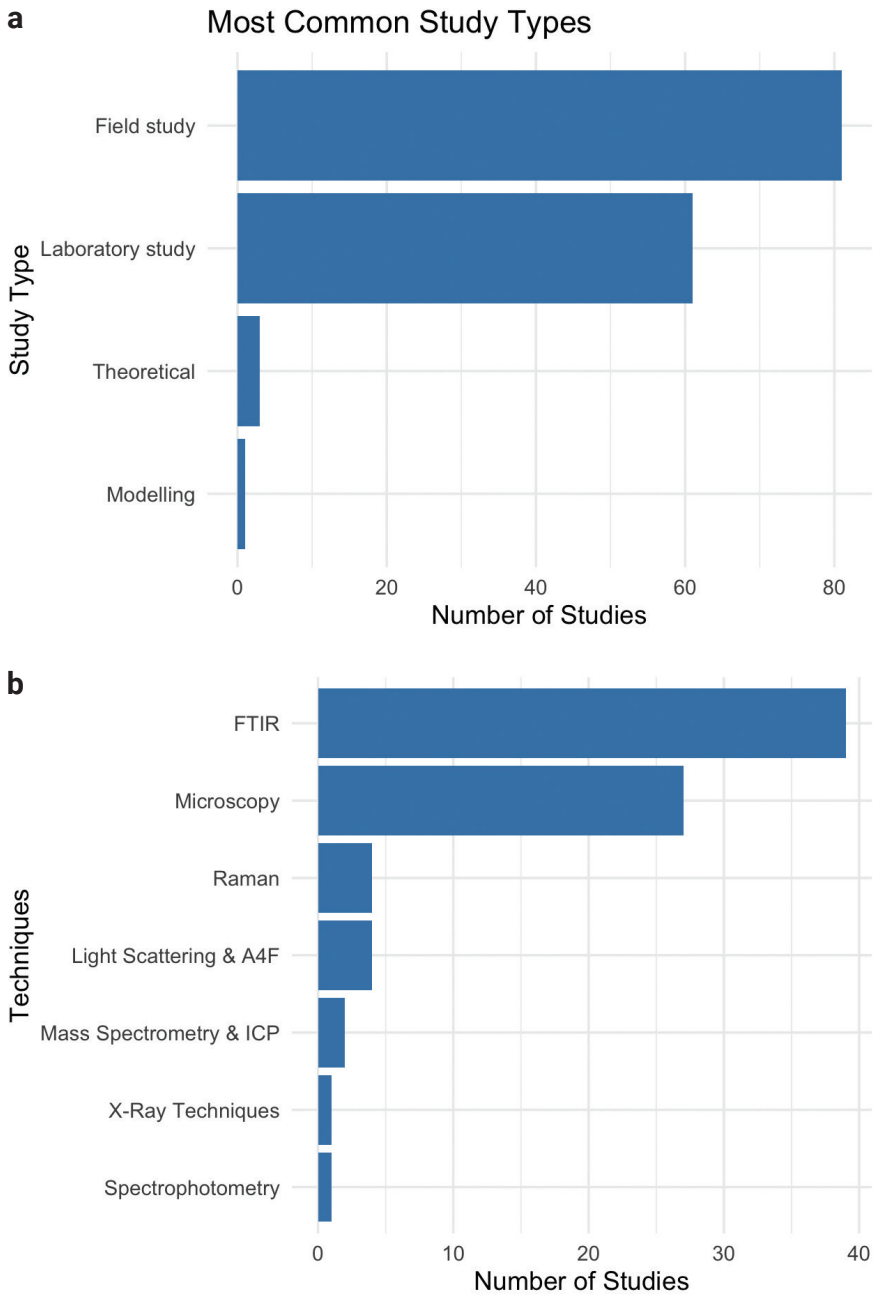


Figure 4. Most commonly used **a.** study types and **b.** analytical techniques in studies at the intersection of plastic pollution and biological invasions (n = 146).

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 (Fig. 7). This visualisation links four key axes: continent, taxonomic group, study type and plastic type.

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.

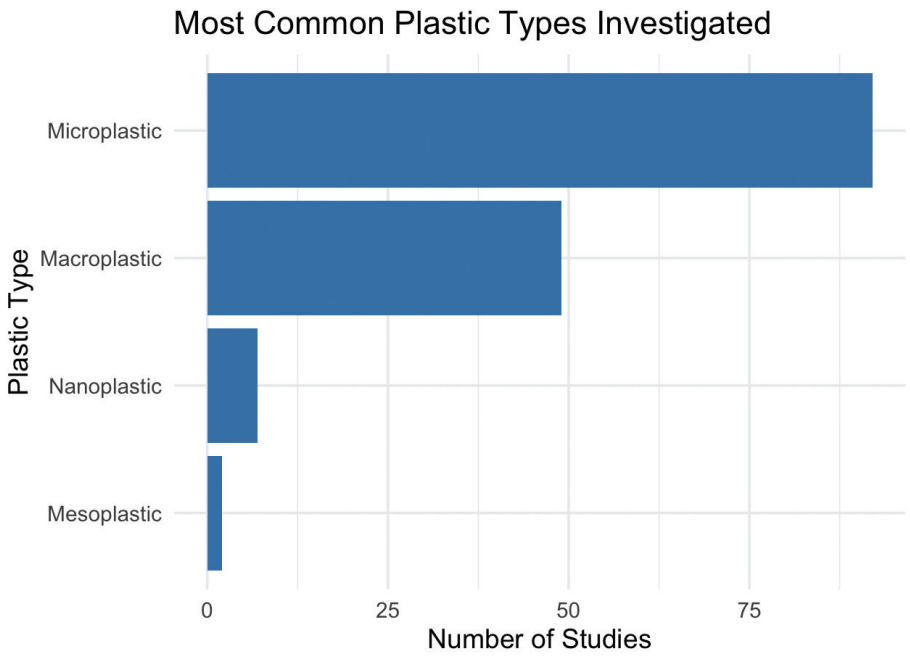


Figure 5. Distribution of plastic size classes reported in studies examining the intersection between plastic pollution and biological invasions (n = 146).

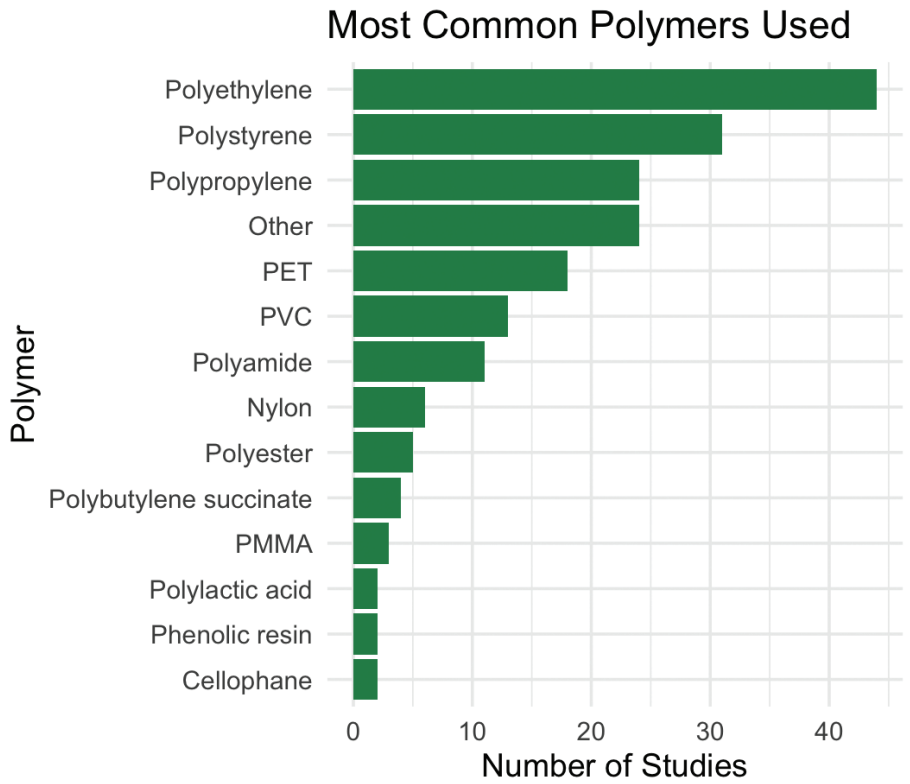


Figure 6. The most common polymers identified in studies addressing the intersection between plastic pollution and biological invasions (n = 146 articles). All polymer types cited only once were grouped under "Other".

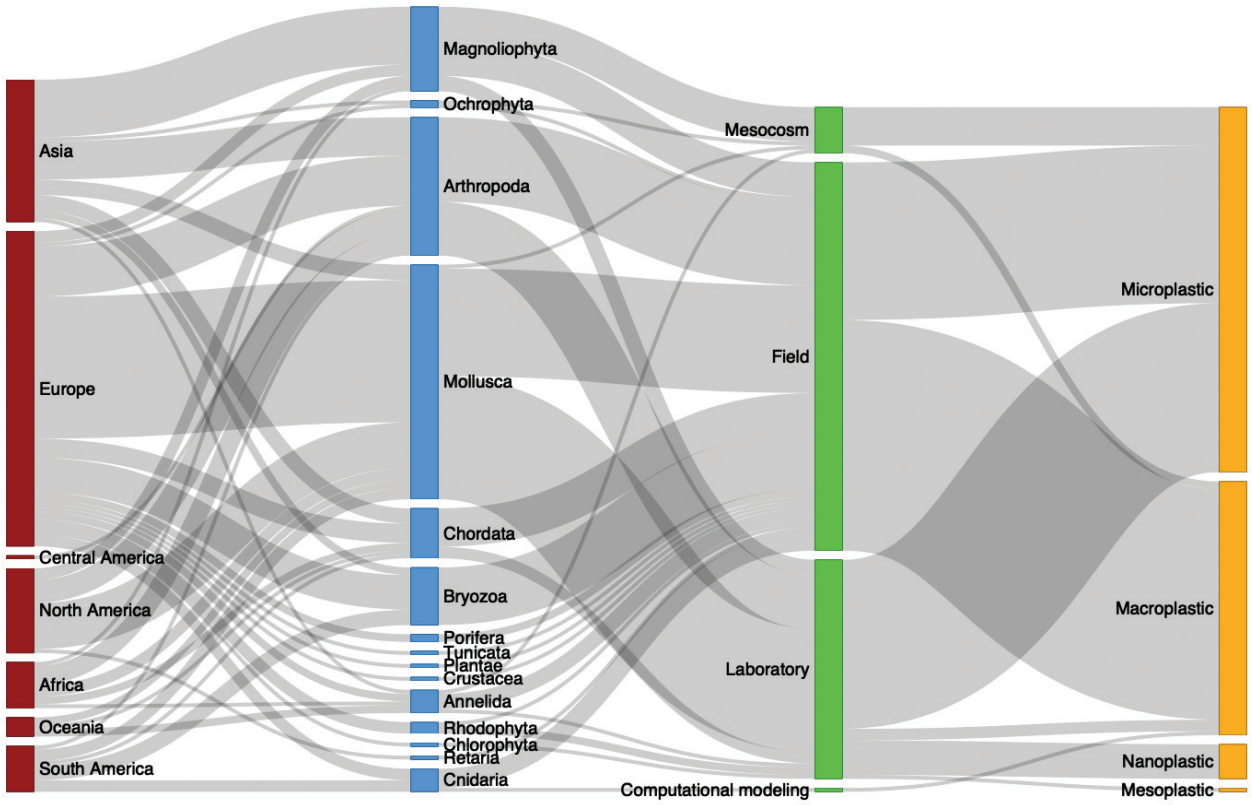


Figure 7. Sankey diagram showing the relationships between continent, non-native taxonomic group, study type and plastic type across the selected studies. The flow thickness is proportional to the number of studies linking each category. Colours represent the four node groups: continent (dark red), non-native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

Discussion

Plastic pollution and biological invasions are amongst 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 is taxonomically narrow, geographically uneven and methodologically fragmented. Nonetheless, we identify three main pathways through which plastics and biological invasions 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 biological 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.

Temporal trends

Although plastic pollution and biological invasions are now recognised as major global environmental change drivers, the broader field of plastic pollution only began to expand rapidly after 2008, particularly in marine ecosystems, following increased awareness of MPs and their environmental impacts (Law 2017). In contrast, the field of biological invasions has gained prominence mainly since the 1990s (Simberloff 2004; Richard et al. 2024). Given this historical background, it is rea-

sonable 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 there was 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.

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, under-representation 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 and 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 socio-political representativeness of global knowledge on pressing issues, such as plastic pollution and biological invasions.

Interestingly, under-representation is also observed in countries with strong research capacity and a long-standing tradition in invasion science, 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 prioritised native species conservation and non-native vertebrate control in terrestrial systems (Firn et al. 2015; Towns et al. 2019). Large-scale programmes like Predator-Free NZ 2050 channel significant investments towards specific conservation goals, but often overlook the combined effects of multiple stressors. In Australia, major funding streams into the man-

agement of non-native species remain decoupled mainly from research on plastic pollution (Hoffmann and 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.

Study types and techniques used

Field studies are essential for in situ observation of the interactions between plastics and biological invasions. 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* (L. Bolus, 1927), have been shown to trap plastic debris in coastal dunes (Calderisi et al. 2023) and discarded tyres have facilitated the spread of *Aedes albopictus* (Skuse, 1894) 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* (L., 1753) and MPs together reduced root growth in rice (*Oryza sativa*, L., 1753), indicating synergistic effects (Li et al. 2023). Likewise, *Sphagneticola trilobata* (L. Pruski, 1996) 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* (O. F. Müller, 1774) in Portugal showed oxidative and histopathological changes when exposed to MPs and cadmium (Parra et al. 2024), while *Dreissena polymorpha* (Pallas, 1771) in Ireland suffered cellular damage under nanoplastic exposure (Reynolds et al. 2024).

Theoretical and modelling studies, although under-represented, 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 in long-distance dispersal. 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 better understand the complex interplay between plastic pollution and biological invasions.

In relation to the techniques used, FTIR spectroscopy was the most common (n = 39), widely employed to confirm the identity of plastic polymers in both envi-

ronmental and biological matrices. Its popularity is linked to its robustness, relative affordability and broad methodological standardisation (Käppler et al. 2016; Wang and Wang 2018; Al Alwan et al. 2024). 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 crayfishes *Procambarus clarkii* (Girard, 1852) and *Pacifastacus leniusculus* (Dana, 1852) were analysed using FTIR to determine the polymer composition of ingested MPs, supporting their use as bioindicators of plastic contamination in freshwater ecosystems (Pastorino et al. 2023; Dobrzycka-Krahel et al. 2024). In Turkiye, *Carassius gibelio* (Bloch, 1782) 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 sinens*is (H. Milne Edwards, 1853) 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* (Girard, 1855) and non-native freshwater fish, such as *Oncorhynchus mykiss* (Walbaum, 1792) and *Salmo trutta* (Linnaeus, 1758). 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 polarisability, enabling spectral fingerprinting of particles as small as < 1 μm (Käppler et al. 2016; Wang and Wang 2018; Al Alwan et al. 2024). It was used, for example, to confirm the presence of plastic polymers in non-native species, such as *Faxonius cristavarius* (Taylor, 2000) in the USA (Gray et al. 2024), *Corbicula fluminea* in Argentina (Giarratano et al. 2024), *Carassius gibelio* (Bloch, 1782) in Iran (Saemi-Komsari et al. 2023) and *Piaractus brachypomus* (Cuvier, 1818) 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 (Käppler et al. 2016; Al Alwan et al. 2024).

Less frequently reported approaches were grouped under broader categories in Fig. 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 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.

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 MPs 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 relevant. As a result, the potential contributions of other particle sizes to invasion dynamics may remain underexplored. For example, 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. In addition, mesoplastics occupy an ambiguous analytical space; they are too large for most MPs 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 MPs 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 non-native species. Expanding analytical frameworks to include under-represented size classes, especially nanoplastics and mesoplastics, will be crucial for developing a more comprehensive understanding of plastic-biological invasions dynamics.

Polymer types

The predominance of PE, PS and 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, ag-

ricultural soils, sewage sludge and biotic samples (Andrady 2017; Schwarz et al. 2019; Jones et al. 2020; Li et al. 2020; Scherer et al. 2020; Lofty et al. 2023). 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 amongst the most widely produced polymers worldwide. 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 (Li et al. 2019; Kim et al. 2021; Sajjad et al. 2022; Cai et al. 2023; En-Nejmy et al. 2024). 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.

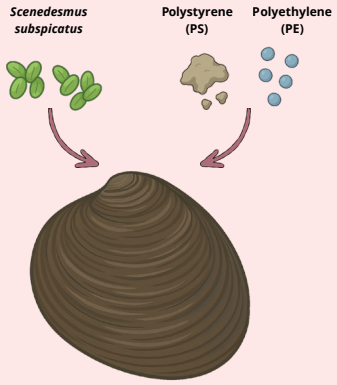
As previously mentioned, a substantial number of studies included in this review were based on experimental approaches (n = 60), which were identified as the most frequently employed study type. Many of these experiments, conducted both in the field and under controlled laboratory conditions, relied on commercially available polymers selected for their relevance to experimental design, such as PP (the most commonly used), PE and 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.

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 taxonomic groups, often due to the availability of standardised protocols, greater ease of sampling or ethical considerations (i.e. few studies on mammals and birds) (Bucci et al. 2020). 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.

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 (Figs 8–11). 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 emphasise the multifaceted nature of plastic and biological invasions interactions and the importance of integrating these dynamics into ecological and management frameworks.

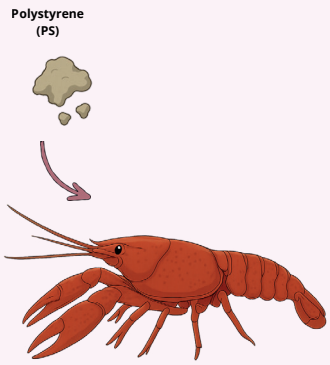


8

Biochemical and transcriptomic effects of nanoplastic trophic transfer in *Corbicula fluminea*

This study evaluated the effects of trophic transfer of nanoplastics in *Corbicula fluminea*, using microalgae (*Scenedesmus subspicatus*) previously exposed to carboxylated polystyrene (PS) nanobeads and field-derived polyethylene (PE) nanoplastics. Exposure induced increased oxidative stress (e.g., elevated catalase activity), reduced clearance and burrowing capacity, and significant downregulation of genes associated with immunity, apoptosis, oxidative stress, and neurotoxicity. Transcriptomic analyses revealed subtle but distinct responses depending on nanoplastic type and concentration, underlining the sensitivity of gene expression tools in ecotoxicological assessments.

(Latchere et al., 2024)



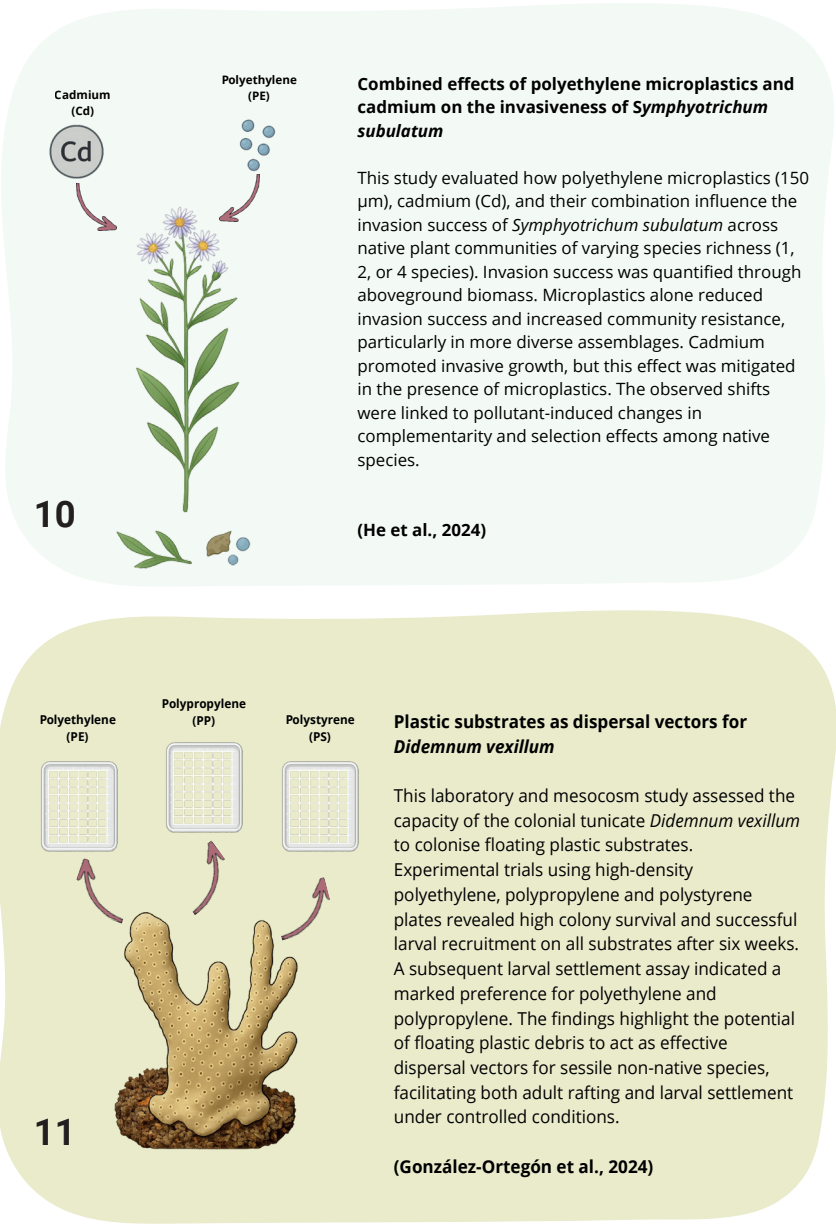
9

Toxicological effects of polystyrene nanoplastics on *Procambarus clarkii*

This study investigated the effects of polystyrene nanoplastics (PS-NPs) on juvenile red swamp crayfish (*Procambarus clarkii*) through growth analysis, biochemical biomarkers, histopathology, and transcriptomic profiling.
At 10 mg/L, exposure induced oxidative stress and triggered nonspecific antioxidant and immune responses. Higher concentrations (20–40 mg/L) led to more severe outcomes, including apoptosis, lipid peroxidation, immunosuppression, and disruptions in ion transport and osmoregulation. Transcriptomic data revealed differential gene expression associated with oxidative stress and immune pathways, providing new insights into nanoplastic toxicity in freshwater crustaceans.

(L. Wang et al., 2024)

Figures 8–11. Case study boxes. **8.** Selected case studies illustrating different pathways linking plastic pollution and non-native species, including trophic transfer and molecular responses to nanoplastics in *Corbicula fluminea* via exposure through microalgae; **9.** Toxicological and physiological effects of polystyrene nanoplastics on the red swamp crayfish *Procambarus clarkii*.



Figures 8–11. Continued. **10.** Combined effects of polyethylene microplastics and cadmium on the invasiveness of the plant *Sphagneticola trilobata*; **11.** The role of plastic substrates as dispersal vectors facilitating the transport and colonisation of the colonial tunicate *Didemnum vexillum*.

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 better understand and mitigate the combined impacts of these two pervasive environmental stressors (Table 1).

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.

Table 1. Key research priorities to advance understanding of plastics–biological invasions interactions.

Priority	Main focus	Key research directions
1. Mechanistic studies	Move beyond correlations to explore causality.	Conduct controlled and field-based experiments linking plastic exposure to invasion success; test how plastic-derived substrates or chemicals influence dispersal, settlement, fitness or reproductive success of non-native species.
2. Rafting and aerial dispersal	Expand understanding beyond marine systems.	Investigate the role of plastic-mediated rafting and aerial dispersal (well-recognised hitchhiker pathways) in freshwater and terrestrial environments; quantify their ecological significance under realistic conditions by testing survival, settlement success and species composition on different plastic substrates; evaluate how wind and animal vectors (e.g. birds) facilitate cross-ecosystem transfers.
3. Trophic transfer and bioaccumulation	Assess the role of non-native species as plastic vectors.	Quantify plastic ingestion and trophic transfer across food webs using isotopic tracers, gut content analysis and contaminant load assessments; evaluate exposure risks to predators and humans; integrate data into ecological risk models.
4. Context dependency	Recognise variability across ecosystems and taxa.	Compare interactions between plastics and biological invasions across terrestrial, freshwater and marine ecosystems using harmonised protocols; assess how environmental variables (temperature, pollution, community composition) modulate outcomes.
5. Taxonomic representativeness	Address biases in studied taxa.	Include under-represented groups, such as vertebrates, plants, fungi and microbes; apply multi-taxa comparative approaches to evaluate physiological and ecological sensitivity to plastic exposure.
6. Methodological innovation	Overcome analytical limitations.	Combine FTIR-ATR with high-resolution techniques, such as Py-GC/MS, Raman spectroscopy and AF4 to detect a wider range of polymer types and size fractions (including nanoplastics); validate methods through inter-laboratory calibration.
7. Ecotoxicology–ecology integration	Link laboratory and field studies.	Develop frameworks that combine laboratory-based toxicological assays with in situ ecological monitoring; use mesocosms and manipulative field experiments to evaluate plastic and biological invasions interactions under realistic environmental conditions.
8. Standardised metrics	Enable cross-study comparability.	Establish unified indicators of invasion success and ecological impact in the context of plastic pollution, such as colonisation rates, physiological stress markers, fitness proxies or community-level changes; promote open data standards.
9. Biomonitoring potential	Use invaders as pollution indicators.	Test the suitability of widespread non-native species as biomonitors of plastic contamination; compare accumulation patterns across taxa and habitats; develop bioindicator indices linking organismal plastic load to environmental concentrations.
10. Global inclusivity	Reduce geographic bias.	Strengthen research capacity and collaborations in under-represented regions (e.g. Africa, Southeast Asia, Central America); invest in local analytical infrastructure and training; promote data sharing and open-access publication.
11. Management and modelling tools	Integrate plastics into risk frameworks.	Apply predictive models (e.g. Species Distribution Models, exposure–response simulations) and AI/GIS-based tools to incorporate plastic pollution variables into non-native species risk assessments; map areas of overlap between invasion pathways and plastic hotspots to provide information for management and conservation prioritisation.
12. Policy and public engagement	Foster awareness and behavioural change.	Incorporate plastics and biological invasions interactions into biodiversity and pollution management plans; promote citizen science and educational campaigns linking plastic mitigation with non-native species awareness; engage stakeholders in co-management strategies.
13. Standardisation and technology	Improve monitoring consistency.	Harmonise sampling and analytical protocols for detecting plastics in association with non-native species; implement advanced tools such as remote sensing, eDNA metabarcoding, machine learning and automated image analysis for large-scale, real-time monitoring.

Conclusions

This review demonstrates that the intersection between plastic pollution and biological invasions remains an emerging, yet critical frontier in global change research. Although scientific attention to this topic has grown in recent years, current knowledge remains taxonomically narrow, geographically biased and methodologically fragmented. Most studies focus on aquatic invertebrates and MPs, limiting our broader ecological understanding.

Moving forward, understanding how synthetic materials and non-native species co-construct ecological change is essential for predicting future ecosystem trajectories.

Addressing these intertwined pressures demands not only methodological innovation and interdisciplinary research, but also a profound reconsideration of how humanity's material footprint becomes biologically active. Recognising this entanglement is crucial to designing management strategies that are as adaptive and persistent as the problems they seek to solve.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

We used AI-assisted tools during the preparation of my manuscript, specifically to revise and optimize R code used for data visualization and figure generation. These tools supported the creation of clear and reproducible graphics, including Sankey diagrams and heatmaps, by helping to debug and improve code structure.

Funding

This study was supported by the Portuguese Foundation for Science and Technology (FCT) through national and European funds under the project "Aqua-Impact: Evaluating Invasive Species Impacts on Trophic Webs within Freshwater Ecosystems under Global Change" (COMPETE2030–FEDER–00730200). Additional support was provided by the FCT through national funds under the project "MULTI-CRASH: Multi-dimensional ecological cascades triggered by an invasive species in pristine habitats" (PTDC/CTA-AMB/0510/2021, https://doi.org/10.54499/PTDC/CTA-AMB/0510/2021). Janeide Padilha was funded by FCT through the Scientific Employment Stimulus programme (CEECIND), under contract number 2023.07078.CEECIND/CP2841/CT0002. Further institutional support was provided by the ARNET (Aquatic Research Network) Associate Laboratory (https://doi.org/10.54499/LA/P/0069/2020).

Author contributions

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Ronaldo Sousa: Supervision, Conceptualization, Investigation, Writing – review & editing, Funding acquisition.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplemenaty data

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Data type: docx

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Link: https://doi.org/10.3897/neobiota.108.163842.suppl1