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Research priorities on microplastics in marine and coastal environments: An Australian perspective to advance global action

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ABSTRACT

Plastic and microplastic contamination in the environment receive global attention, with calls for the synthesis of scientific evidence to inform actionable strategies and policy-relevant practices. We provide a systematic literature review on microplastic research across Australian coastal environments in water, sediment and biota, highlighting the main research foci and gaps in information. At the same time, we conducted surveys and workshops to gather expert opinions from multiple stakeholders (including researchers, industry, and government) to identify critical research directions to meet stakeholder needs across sectors. Through this consultation and engagement process, we created a platform for knowledge exchange and identified three major priorities to support evidence-based policy, regulation, and management. These include a need for (i) method harmonisation in microplastic assessments, (ii) information on the presence, sources, and pathways of plastic pollution, and (iii) advancing our understanding of the risk of harm to individuals and ecosystems.

1. Introduction

Plastic contamination and the presence of microplastics (particles <5 mm in size) in the environment are increasingly receiving global attention (Bailey, 2022; Qin et al., 2020). This is spurred by an awakening in public opinion and media responses to issues surrounding plastics, alongside an upsurge in the reports of microplastics across land- and seascapes (Petersen and Hubbart, 2021; Wootton et al., 2021c). Overall, there is increasing public awareness of plastic pollution, and its perceived or actual impacts, with calls for global action, management and mitigation (Catarino et al., 2021; Wootton et al., 2022). This will require effective solutions to limit the potential threats that microplastics place on our environments at regional, national, and international levels.

The input of plastic to the environment is unlikely to abate soon, and as plastic degrades and fragments, it contributes to the increasing abundance of microplastics in coastal and marine ecosystems (Borrelle et al., 2020; GESAMP, 2015). It is now well-accepted that microplastics, and their even smaller derivatives, nanoplastics (1 nm – 1 μm), are spread so far and wide they are ubiquitous (Ling et al., 2017; Yang et al., 2021). Plastic contamination is now recorded throughout a plethora of environments and organisms, including in the most remote of environments; for example, Mariana Trench (e.g. Chiba et al., 2018) or ice shelves of Antarctica (e.g. Waller et al., 2017). Due to their small size, microplastics are readily ingested, both intentionally and unintentionally, by terrestrial and marine organisms. The potential for microplastics to bioaccumulate, transfer across trophic webs or biomagnify raises concerns for biota and ecosystem services (Carbery et al., 2018; Chagnon et al., 2018). Moreover, plastic additives and chemical contaminants sorbed from the surrounding environment have the potential to cause a variety of toxicological effects (Carbery et al., 2018; Cousin et al., 2020; Li et al., 2018; Tuuri and Leterme, 2023).

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Despite the growing volume of work documenting the presence of microplastics in the environment, our understanding of long-term impacts, effects and risks is often in initial stages, particularly at local management scales. In part, this is because data collection, dissemination and methodological trials use a myriad of poorly compatible approaches that often lack validation. These issues make it difficult to accurately demonstrate the physiological, environmental, and societal impacts of microplastics (Hartmann et al., 2019; Lusher et al., 2020). Decisions for evidence-based management, to support policy-relevant and action-oriented strategies of microplastics, require a synthesis of the available scientific information, to underpin practices, and inform research and priorities (de Ruijter et al., 2020; Omeyer et al., 2022; Provencher et al., 2020a).

As microplastics enter coastal environments through a range of pathways and comprise a broad suite of different contaminants (e.g., polymers, sizes and chemical additives) management and mitigation are complex. Plastic debris and microplastics in coastal and marine environments are now a priority issue for multiple stakeholders, including different levels of government, regulatory bodies, water utilities and the general public.

To aid in tackling these issues, we reviewed the state of knowledge of microplastics in coastal and marine environments in Australia through a scientific literature review, and then facilitated engagement with experts and stakeholders from various sectors to identify research priorities and optimum pathways to address and manage microplastic contamination. First, a systematic literature review was undertaken to collate all information on microplastics in Australian coastal environments. Then, a series of surveys and workshops were conducted, to gather expert elicitation from multiple stakeholders including, researchers, industry representatives, government officials, and non-government organisations. Combined, the objectives of the review, surveys and workshops was to identify critical gaps in knowledge and research directions based on the specific needs of stakeholders. In Australia, like in many countries, microplastics are a priority issue for multiple stakeholders, with growing interest from government allied to raising public awareness. Increasing research efforts are evident but we still lack a comprehensive understanding of microplastic occurrence at relevant scales and its implications to inform future risk analysis. This collaborative approach, and the insights gained from cross-sector engagement, will contribute to advancing the understanding and management of microplastic contamination worldwide.

2. Methodology

2.1. Systematic literature review

A systematic literature search was undertaken to investigate research on the presence of microplastics in Australian coastal environments. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed to ensure replicability and robustness (Moher et al., 2010). The literature was searched using the Web of Science database (January 5th 2023). In *all fields*, we searched for all combinations of the terms: *plastic*, Australi*, polymer or polymers (as well as with derivatives of: river or lake, stream or catchment or freshwater or stormwater or lagoon or estuary or coast or marine) – where the asterisk acts as a wildcard allowing all derivatives of the words to be identified (e.g., *plastic* allows microplastic, microplastics, or plastics among others).

Eligibility criteria and screening were used to assess and ensure the suitability of individual studies for inclusion, as per PRISMA guidelines (Moher et al., 2010). First, the title, abstract and keywords of the 3043 identified documents were scanned, with 243 peer-reviewed studies viewed as potentially relevant (Fig. S1). The full text of these were then assessed with 93 studies identified as passing the selection criteria. Selection criteria were studies with empirical data from published works that sampled for microplastics (<5 mm); in either sediment, water, or biota in marine and coastal environments (including, estuarine and transition ecosystems) in Australia (including offshore island territories). Collections made as part of beach surveys or that reported microplastics from outflows (e.g., wastewater, stormwaters) entering coastal environments were included.

For each study, an individual ID was created, and data was collected from a suite of variables (e.g., location, sample type, methods). Microplastic data, including levels of contamination (summarised in Table 1, for full details see Table S1) were also collected. Data were obtained directly from the text and tables. Where necessary, data were extracted from published figures using the desktop version of WebPlotDigitizer (Rohatgi, 2022).

Information from citizen science initiatives that were not published in peer-reviewed outputs were not included in the review of information though they are represented in the survey and workshop participants (see below). Citizen scientists have often acquired considerable knowledge (e.g., Adopt-A-Spot, AUSMAP, Tangaroa Blue), however access to reports and details of studies are not always readily available.

2.2. Cross-stakeholder engagement, online survey, and workshop

A broad range of experts and stakeholders with expertise and work on the topic of microplastics in coastal environments were identified through the literature, via an open call, and through word of mouth. To identify authors of microplastic studies, a list of all Australian authors was compiled during the literature review. Commonwealth and state government agencies and departments, as well as multiple peak bodies were also contacted to request relevant contacts. Research institutions, industries, environmental agencies, and non-government organisations (NGOs) across south-eastern Australia (New South Wales, Victoria, Tasmania and South Australia) who were actively involved or leading efforts in addressing plastic contamination were contacted. An open call was also disseminated through various channels such as email lists, newsletters, and government agencies, to ensure inclusivity and maximise our outreach. We reached out to 113 stakeholders during June and July 2022 from these groups. In total, 80 respondents representing 37 organisations replied. These collaborative efforts allowed the identification of major thematic areas and issues that required attention and would be the focus of subsequent surveys and workshop (Fig. 1). The results from the systematic literature view were not provided to the experts and stakeholders.

2.2.1. Online survey

An anonymous survey was implemented to seek input from the recruited stakeholders across different groups to guide future research priorities. The survey was reviewed and tested by five users, across

Table 1
Summary of main categories of information extracted from individual studies (see full details in Supplementary information, Table S1).

Categories	Description
Study ID	Unique study identifier
Citation summary	First author, year and journal identifier
Location	Location and environment (e.g., marine, estuarine, freshwater)
Sample type	Water, sediment, biota, beach survey
Biota group/ species	General biota group (fish, bird) and species info
Collection method	Sample collection gear and methodology
Sample processing	Materials and methods for sample processing, including specifications on removal of organic material, density separation, filtration, microscopy, polymer identification, and quality/contamination control
Microplastic data	Frequency of occurrence, microplastic load, units, polymer types, and potential sources or impacts, when available
Reference DOI	DOI

Fig. 1. Summary of the undertaken approach, starting with consolidating available information via a systematic review, followed by consultation and engagement with multiple stakeholders, anonymous surveys, and expert workshops. This framework provided a gateway to summarise information, confirm need and scope, broaden recruitment, identify major thematic groups, laying the groundwork for eliciting expert opinion through surveys and collaborative multistakeholder workshops.

different levels of expertise in the topic of microplastics, to ensure user readability and limit obscurity in the questions. Survey Monkey, an online survey tool, was used to collect information from 17 questions (see Table S2 for survey questions), that included a mix of short-answer, multiple-choice and ranking questions (Fig. 1).

The survey was anonymous (did not collect identifying data) and had three parts. The first part solicited participant background information, including geographic region, position (e.g., government, consultant, academic), years of experience and self-assessed level of knowledge in the microplastic field. In the second part, based on their expert opinion, participants specified (i) main sources and pathways for microplastics in coastal environments; (ii) main gaps in understanding the impacts of microplastics, as well as (iii) priority research needs. All questions in this section were open-box, short answers. The third part of the survey comprised participants ranking, according to their opinion, given sources and pathways of microplastic contamination regarding their potential loads, as well as threats to ecological communities. Participants were also asked to prioritise research areas and what future directions (including e.g., options on sources, occurrence, transport, methodologies, risk, impacts and others) they regard as more important or critically needed (see Table S3 for ranking categories).

Survey responses were exported from SurveyMonkey, and analysed using Microsoft Excel, to assess broad-level trends across survey respondents, and among different stakeholder groups.

2.2.2. Expert workshop

An online workshop (interactive webinar) was held to bring together representatives from a range of stakeholders (Fig. 1). There were 84 attendees at the workshop, and it was held online on the 22/07/2022. The goal of this workshop was to elicit expert opinion across stakeholder groups and different sectors on what research needs are critical to support the future of evidence-based policy and regulation regarding microplastic mitigation. The workshop was a forum for open discussion, structured around the summary of review results, survey questions, and included short presentations by the different stakeholder groups that presented on key research priorities, gaps, unknowns, and needs. These acted as a roadmap for the open discussion, helping guide and structure the exchanges among participants sharing perspectives towards a collaborative goal to further outline the key research priorities and barriers to meeting critical cross-stakeholder needs. The workshop strengthened the results from the survey while also providing extra layers of detail. Such workshops act as a platform for stakeholders to actively rank and discuss research directions, encouraging collaboration and co-learning, and providing a bottom-up/top-down communication gateway to support cross-sector actions (Lusher et al., 2020).

Human ethics approval was obtained from the Human Research Ethics Committee (The University of Adelaide, approval number: H-2022-079) for the survey and workshop.

3. Results and discussion

3.1. Systematic review of microplastics in Australian coastal areas

Ninety-three studies have investigated microplastics in coastal environments in Australia (Fig. 2). These studies encompassed all states and territories, including some offshore remote territories [e.g., Cocos (Keeling) Islands (Lavers et al., 2019)]. However, there was a clear focus on the eastern coast, which is home to the majority of the Australian population. Queensland and New South Wales had the highest number of studies (36 and 30, respectively), and South Australia and the Northern Territory the lowest (13 and 8 studies, respectively) (Fig. 3, Table S4). The geographic distribution aligns with global trends where microplastic research tends to be centred around urban and populated areas (Lusher et al., 2021) due to anticipated contamination and ease of access. Overall, the frequency of microplastic occurrence observed in Australian studies was lower compared to global contamination levels (Hayes et al., 2021; Klein et al., 2022; Wootton et al., 2021b). For most studies, microplastic fibres were the predominant plastic shape (e.g., Ling et al., 2017; Wootton et al., 2021a), as seen elsewhere, including a global review (Gago et al., 2018; Yu et al., 2018).

Sediment sampling had the highest number of studies, locations and greatest spatial coverage (Figs. 2, 3). This was driven by beach surveys and monitoring often linked to citizen science actions (N studies = 17) (Fig. 3), some of which collect at regular intervals, providing a broad-scale dataset for Australian beaches and adjacent habitats (Hardesty et al., 2017). However, despite the larger dataset, beach surveys can have methodological limitations, in particular for smaller microplastics (e.g., due to size restraints during collection) as surveys often involve observations with the naked eye, with 40 studies across all matrices only recording pieces >1 mm (e.g., Edyvane et al., 2004; Gacutan et al., 2022). Sediment collections analysed for microplastics in the laboratory (n = 24), covered marine, coastal and beach sediments, as well as estuarine and associated ecosystems. Few studies sampled across multiple states but Ling et al. (2017) provided unique broad-scale information, showing that South Australia had higher microplastic loads than sites in more populous New South Wales and Victoria. Overall, there is still limited information available on microplastic in both water and sediment collected from deep waters. In Australia, only four studies sampled sediments offshore, and only one those in deep sea environments (Barrett et al., 2020). In addition to further offshore sampling, future studies should leverage grab or core sampling in sediments to also investigate accumulation patterns of microplastic in sediment profiles.

Investigations of microplastics in water were the least common (28 studies), and whilst sampling occurred around Australia (Fig. 3), there was a clear imbalance between the east coast and the rest of the country. Few studies have quantified microplastics in water at multiple sites using the same methodology (e.g., Reisser et al., 2013). Twelve studies analysed estuarine and coastal waters but were limited to a few states and locations (SA, VIC and NSW) and generally system or state-focused, without extensive or repeated sampling. Key outcomes show storm events increase microplastic contamination, leading to higher microplastic abundance (>43-fold increase, Hitchcock, 2020), and that microplastic contamination in stormwaters from industrial areas is greater than from residential areas (Monira et al., 2022). Storm and drain waters, together with runoff and transport through rivers and estuaries are a major avenue linking land sources to coastal and marine

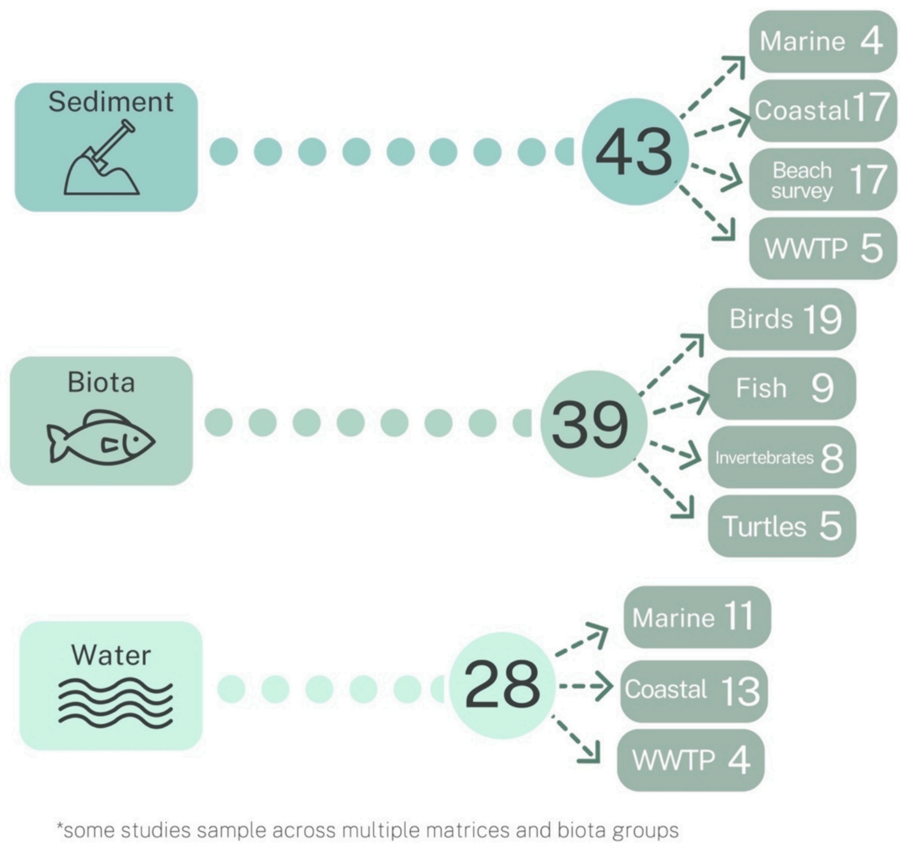

Fig. 2. Summary of available literature on microplastics in coastal environments in Australia ($N = 93$ studies), outlining the number of studies in sediment, water and biota, including per animal groups. Note, some individual studies investigate more than one matrice or biota groups.

environments (Meijer et al., 2021), but there was a lack of assessments on runoff, flow, and export of microplastics from estuaries and catchments to characterise and estimate inputs to coastal and marine sources.

Globally, biota samples are one of the most investigated matrices (Lusher et al., 2021), likely propelled by an increase in public interest. In Australia, biota studies addressing microplastics have sampled over 120 species including turtles, birds, fish and invertebrates (e.g., crustaceans, bivalves) (Fig. 3). Noticeably, 19 (out of 39) studies focus on seabirds, seven of which were in the remote Lord Howe Island region (Fig. 2). The key focus is on the ingestion of microplastics (i.e., occurrence in gastrointestinal tracts), with few links to potential effects. Furthermore, there is a lack of interdisciplinary research, where scientist from different research fields work together to help inform policy decisions. Nonetheless, Lavers et al. (2014) documented reduced body condition in birds with increased plastic and heavy metal load but no clear link to effects was found in others (Lavers et al., 2018), with no causal relationship established between ingested plastic and chemical load. Overall, there is a lack of repeated sampling over time, with most studies focusing on single sites/areas [but see e.g., Jahan et al., 2019, Klein et al., 2022, or Wootton et al., 2021b comparing biota across multiple sites or states].

Additional matrices monitored for microplastics included samples released to the environment from wastewater treatment plants (WWTP – biosolids, sludge, effluent) and road dust (e.g., Su et al., 2020; Ziajahromi et al., 2021). Four studies estimated microplastics in water from coastal outflow/effluent of WWTP (e.g., Raju et al., 2020; Sucharitakul et al., 2021; Ziajahromi et al., 2017, 2021) but there was no information on untreated wastewater, another recognised pathway for microplastic and other debris (Woodward et al., 2021). Though these point sources or diffuse pathways are not the origin, they warrant particular attention as they link the sources (e.g., household and washing of synthetic textiles; tyre particles) and the environment. Overall, understanding the occurrence, source and release pathways are key metrics for measures to reduce plastic contamination (Allen et al., 2022; Lusher et al., 2020), including WWTP, as they represent release points for continuous loads of microplastics to adjacent environments (coastal areas and waterways) as well as transport from land-based sources further upstream (Browne et al., 2011; Ziajahromi et al., 2017).

Whilst scientific literature relating to microplastic occurrence and presence throughout Australian coastal environments is diverse, there are evident gaps, limited interdisciplinary research, and a lack of harmony across data sets, associated with discrepancies in experimental design and methodologies that we need to tackle as research focus continues to grow. The lack of repeated temporal and spatial sampling is a clear limitation. Many studies sampled only a single time point, for each location (e.g., Wootton et al., 2021a), making it difficult to evaluate the effect of weather events, seasonal patterns, and other drivers of variations on microplastic contamination levels. Although some studies sampled across multiple locations (e.g., Wootton et al., 2021b; Reisser et al., 2013; Ling et al., 2017), they generally did so within a limited area and with no temporal resolution. Others sampled environmental matrices and biota from the same area; for example, Roman et al. (2016) sampled birds and water in an effort to associate potential sources of microplastic ingestion, and Jahan et al. (2019) assessed oysters and sediment to investigate similar relationships. Despite this, no study sampled the three biological matrices, an important piece of evidence to characterise contamination within an ecosystem and apportion contamination pathways to biota.

Despite achieving an Australia-wide coverage, comparable data are scarce due to differences in methodological approaches both among and within assessments of water, sediment or biota (Fig. 4). These differences encompass aspects such as sampling design, collection methods, extraction techniques, analysis procedures, and quality controls. Significant issues arise from inconsistent or ambiguous determination of

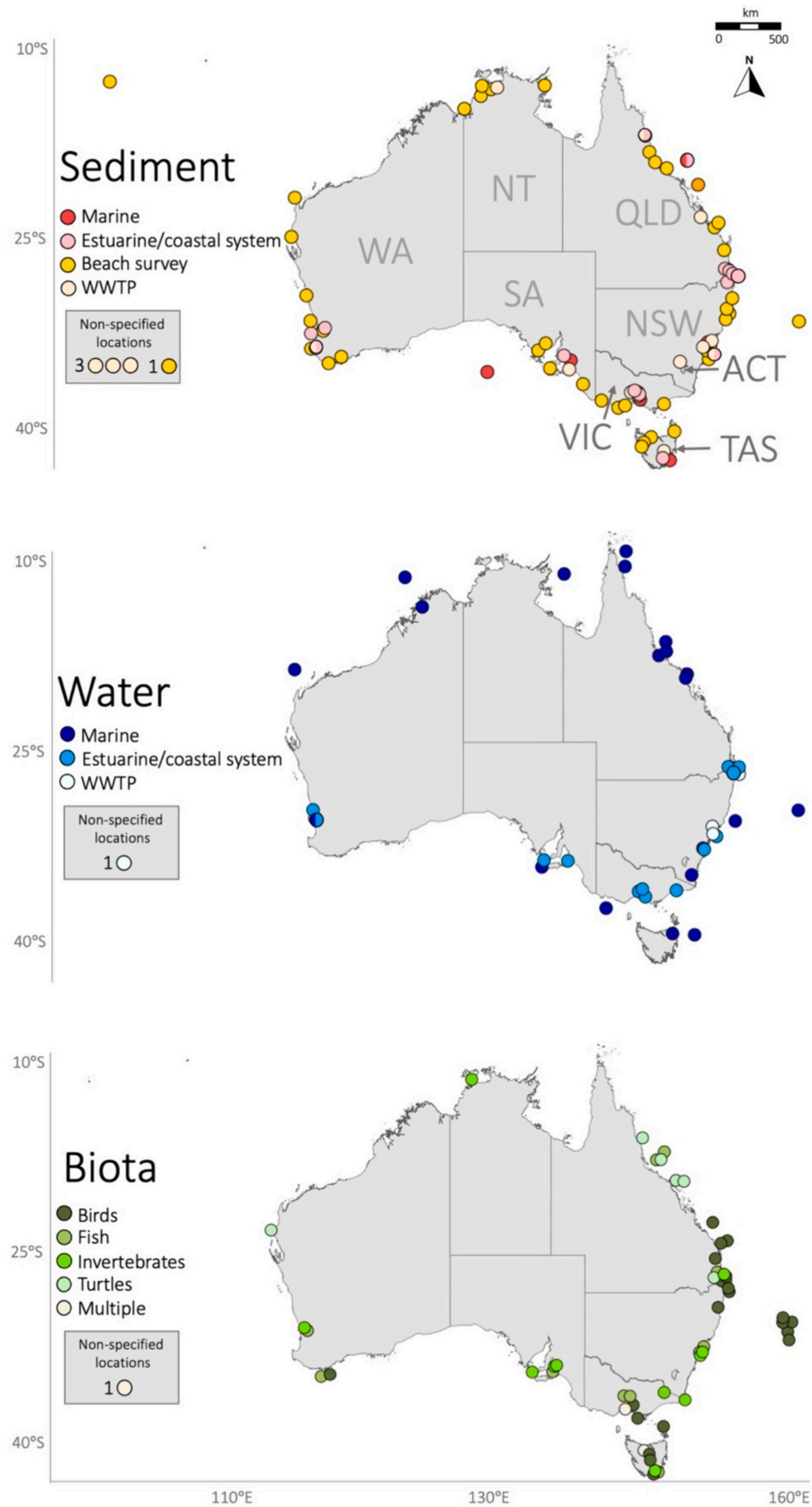

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Fig. 3. Locations where microplastic presence has been examined in sediment, water and biota across Australian marine and coastal systems. Each location is represented as one point, with additional points for studies that sampled across multiple states or matrices. Note, site location is jittered (i.e., random variation to avoid overlap, for accurate coordinates refer to Table S4); multiple refers to studies that sampled multiple species per location; and non-specified location refers to studies that did not report the state or location where sampling occurred. Number of locations does not match the number of studies as a study can sample multiple locations. WA – Western Australia, NT – Northern Territory, SA – South Australia, QLD – Queensland, NSW – New South Wales, ACT – Australian Capital Territory, VIC – Victoria, TAS – Tasmania.

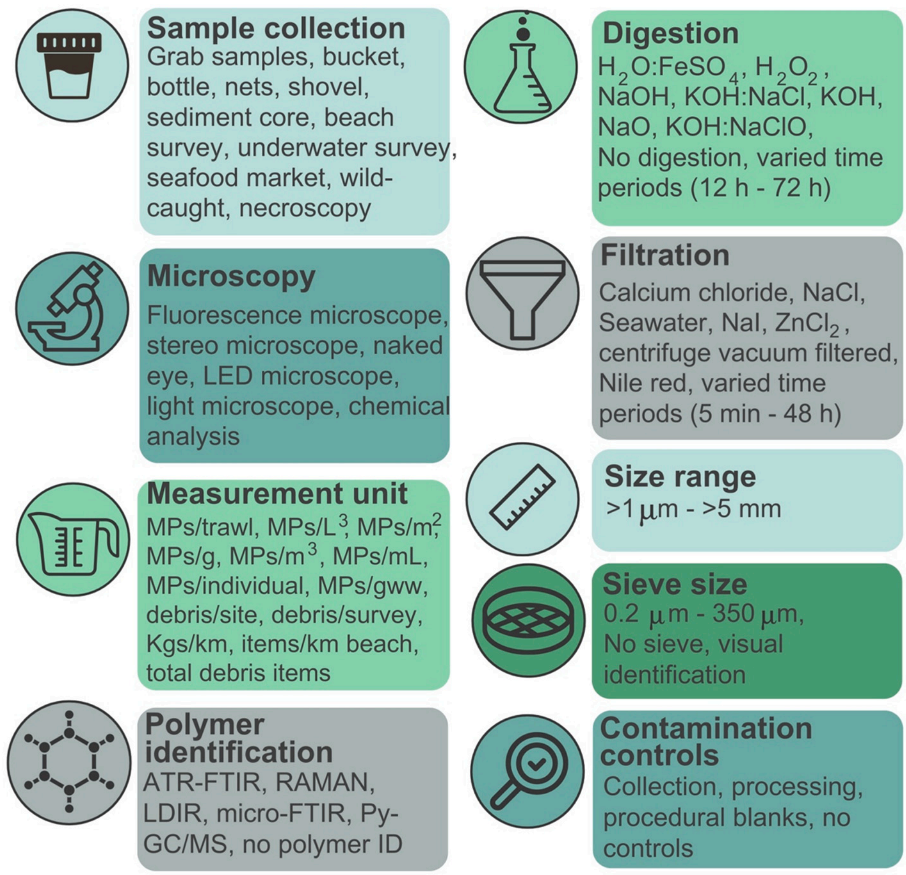

Fig. 4. Graphical representation of the variety of methodological approaches used in microplastic studies in Australia.

the minimum size of targeted plastics, and discrepancies in the utilisation and reporting of contamination controls (Fig. 4). These factors can introduce potential biases when comparing contamination levels between studies. The divergence in methods and reporting makes comparisons arduous or unachievable, and even unattainable to make broad interpretations or conclusions on large-scale variations, beyond the context of the individual studies. Therefore, there is a clear need for consistent, preferred practices and data harmonisation, to reduce ambiguity and enhance the coherence and compatibility of data (see research priorities below for more details) (Aliani et al., 2023). Our review strongly supports the call for consolidating guidelines for microplastic assessments, including developing robust and standardised procedures for collection and sample preparation (Provencher et al., 2017; Underwood et al., 2017).

3.2. Research priorities

While the review of literature synthesised what is known about microplastics in coastal regions of Australia, we still lacked information on the key priorities and research questions from industry, government, and academia stakeholders. Engaging with stakeholder groups is pivotal to incorporating diverse perspectives and fostering meaningful discussions to broaden the appeal of research that can support policy. The online survey was widely distributed to the stakeholders, with a total of 54 responses received from a broad spectrum of professional backgrounds (43 % from state and federal government agencies, 19 % from industry and academic research, 11 % from NGOs, and the remaining 8 % from local authorities and consultants). This diversity of backgrounds, combined with the high levels of experience of the stakeholders (80 % of respondents working with plastics >2 years), resulted in comprehensive feedback. Eighty-four representatives took part in the workshop, including government agencies, water industries, NGOs, consultants, and researchers. Combined, the survey and the expert workshop served as inclusive platforms to identify and elevate the discussion on research priorities and aimed at supporting policy prioritisation. The workshop provided an open space for the examination and assessment of the cross-sector significance of issues raised by individual stakeholders, while providing further support for the survey results. Incorporating diverse perspectives and fostering discussion was essential. If workshops and discussions were made with only individual stakeholder groups, there could be a possibility bias may arise towards certain research focuses. However, the surveys showed a high agreement across major prioritisation themes, regardless of stakeholder sector (e.g., 100 % importance for method harmonisation). Moreover, the triangulation of results from the workshop, survey and review limited any potential bias, providing a strong platform to understand consensus and cross sector priorities.

Together the systematic review of the literature, and the consultation process via the online survey and workshop, highlighted three major areas for future microplastic research. Namely, (i) method harmonisation (including, collection, processing, and reporting), (ii) understanding the presence, sources, and pathways of plastic contamination, and (iii) increasing knowledge of the risk of harm to individuals and ecosystems (Fig. 5). Specific recommendations, priorities and actions are framed under these three broad thematic groups and discussed below. While the Australian microplastic community identified these priorities, outcomes align with the views of experts and other stakeholders worldwide, where similar approaches exploring perceptions or horizon scanning have been carried out (Clausen et al., 2020; Grünzner et al., 2023; Jones et al., 2024; Omeyer et al., 2022; Provencher et al., 2020b).

3.2.1. Method harmonisation

Issues regarding method disparities found during the systematic review were echoed in the consultation process with stakeholders. In the survey, the need for validated and standardised methods was ranked as critical/highly important by 82 % of participants - the most unanimous of survey responses (Fig. S2). Respondents further supported this by stating for example, "*lack of standardised measurement methods*" and "*data mismatch resulting from distinct methodological approaches* [lead to] *difficulties in comparing microplastic research*". The harmonisation of methods and reporting guidelines is a crucial step in obtaining valid, reproducible, and comparable data to inform benefit policy makers, researchers, and the global community alike (Cowger et al., 2020). Stakeholder feedback resonated with global literature indicating a need to prioritise harmonising data collection and research outputs (Hermsen et al., 2018; Lusher et al., 2020; Primpke et al., 2020; Provencher et al., 2017). These suggestions for standardisation and cost-efficient microplastic assessments are reflected both in reviews (GESAMP, 2019; Markic et al., 2019; Wootton et al., 2021c) and similar stakeholder research priority studies (Grünzner et al., 2023; Jones et al., 2024; Lusher et al., 2021; Omeyer et al., 2022) demonstrating there is a global consensus to tackle this issue.

Participants at the workshop voiced strong support for sets of reproducible practices and guidelines for microplastic assessments, covering all steps from sample collection and design, laboratory procedures for extraction, and plastic characterisation (i.e., size, shape, polymer composition and terminology). In particular, confirmation of polymer types was defined as an essential validation step to reduce uncertainty, which also provides important information on potential sources and pathways of contamination (Brandt et al., 2020; Löder and Gerdts, 2015). Overall, consistent terminology, definitions and data reporting parameters, together with appropriate sampling design are critical to maximising future data re-analysis and statistical integration (Provencher et al., 2020a; Underwood et al., 2017).

High standard quality assurance and quality control procedures (QAQC) were also highlighted as essential to ensure data integrity and elevate data accuracy and comparisons (Fig. 5). This includes environmental contamination and procedural controls during laboratory procedures, as the small size of microplastics and their ubiquity create challenges when controlling for background contamination (Brander et al., 2020; Wesch et al., 2017). Sampling design should be dictated by the matrix (e.g., water, sediment, biota), likely sources (e.g., litter, influent) and pathways of contamination (e.g., WWTP, wind, run-off), following guidelines that enable widespread comparison across time and space (Brander et al., 2020). While different research questions, environments or species may call for some flexibility, guidelines on experimental designs and methodologies (including, fundamental considerations on replication, randomisation and sample independence) will amplify data comparison and ensure sampling matches aims and needs (Brander et al., 2020; Underwood et al., 2017).

Both survey and workshop participants indicated that advancing the quantification and characterisation of small microplastics (<1 mm) is key, as the likelihood of ecological impacts in this size category of plastics may be increased. In parallel, technological innovations to assist in the identification of smaller microplastics (and nanoplastics) is a crucial next step (Keys et al., 2023). As the size of particles decrease and their physical properties become invisible or undiscernible, validating plastic identification and characterising polymer type is paramount.

It is clear from the systematic review that there is a spectrum of methods and collection procedures (Fig. 4) and whilst many groups, researchers and institutions may fear losing data continuity when new guidelines are adopted, the development of quality assessment procedures and inter-calibration exercises can allow transitions from previously collected data. Overall, a clear-sighted focus on method harmonisation and development of best practices, decision trees or operational procedures will elevate monitoring capacity, accelerate data integration, and invigorate our understanding of global patterns in plastic contamination (Fig. 5).

3.2.2. Presence, sources, and pathways

Environmental assessments reveal base levels of contamination, with long-term monitoring key to elucidating trends across time and space, and insight into the impact of mitigation and legislative measures. Furthermore, only by resolving sources and reconstructing transport

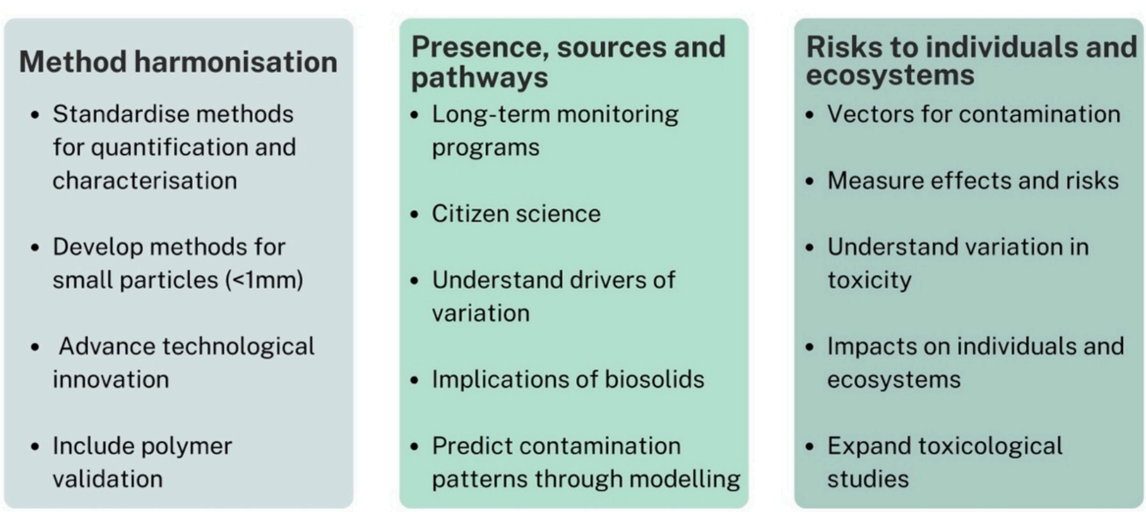

Fig. 5. Summary of research priorities identified during cross-sector stakeholder engagement and workshop.

pathways can we identify the environmental and anthropogenic drivers of microplastic contamination. Combined, these datasets can empower policy makers to create legislation to assist in reducing plastic releases into the environment. Open responses in the survey championed these issues, reinforcing the need to "*determin[ing] the most scientifically robust methods in order to regularly monitor a suite of coastal reference sites to track types and quantities of microplastics over time*" and "*estimat[ing] and identify[ing] sources upstream (follow drain and stormwaters) for different polymer types and contamination levels*".

Many data on microplastics in Australia reflect a single matrix, time point and restricted spatial distribution (e.g., Carey, 2011; Halstead et al., 2018; Kroon et al., 2018). This mimics global information, with opportunistic collections often limiting future replication over time and space (Lusher et al., 2021). This knowledge gap was emphasised by experts in both the surveys and workshops, with 90 % of survey participants ranking it as an important or highly important research priority. Emphasis was given to the implementation of long-term, systematic monitoring programs, utilising standardised methods to trace long-term trends and support policy and mitigation action as needed (Fig. 5). In addition, the potential to enhance long-term data collection through citizen science initiatives and taking advantage of their repeated and broad-scale actions was also discussed. Internationally efforts in this space are already occurring, with guidelines for sampling approaches across Europe (European Commission, 2023) and globally (GESAMP, 2019).

Land-based sources (e.g., sewage, farmland, and roads) and associated pathways (e.g., WWTP, rivers) play a major role in microplastic emissions (Duis and Coors, 2016; Jambeck et al., 2015). Contributions of terrestrial sources, including freshwater systems, are priority pathways to consider regarding monitoring and legislation (Bellasi et al., 2020; Leterme et al., 2023; Meijer et al., 2021). Because source (e.g., synthetic textiles) and release pathways (e.g., WWTP effluent) are intrinsically linked, they should be discussed in unison when identifying measures to reduce microplastic contamination. In line with this, it is crucial to quantify the source and transfer of microplastics from biosolids (organic sludge obtained from wastewater and frequently used as a fertilizer). A majority of stakeholders ranked storm-, drain and other untreated waters (95 %), and catchment runoff (85 %), as highly important or important priorities to resolve spatiotemporal variation in microplastic inputs and abundance (Fig. S3). Other top-ranked issues included microfibres from synthetic clothing (90 %), and the degradation of land-based plastic debris (90 %). Understanding how the characteristics of common polymers (e.g., buoyancy, size, type) and their degradation influence transport and accumulation, including conditions governing particle mobilisation, is an important extension (Hardesty et al., 2017). Validating this information and capitalising on the power of model simulations to track and predict patterns in microplastic contamination was also encouraged by multiple stakeholders (e.g., flow from river catchments and with ocean currents) as means to direct legislation and mitigation strategies towards specific microplastic types or sources.

With method harmonisation come increased opportunities for consolidated, centralised databases that can facilitate the identification of hotspots and changes in microplastic contamination. Overall, to identify avenues to intercept, prevent or mitigate microplastics from reaching coastal and marine environments we need to know where microplastic contamination is coming from and how much. This is a global need, with experts and stakeholders in Australia but also elsewhere (e.g., UK, Norway, Southeast Asia, worldwide) calling for further focus on the sources and pathways of contamination assessments (Grünzner et al., 2023; Jones et al., 2024; Lusher et al., 2021; Omeyer et al., 2022). Characterising occurrence is the first step but information on the factors governing dispersal, accumulation and deposition is essential. By doing so we can direct the spotlight to the factors triggering contamination hotspots, and then use that information to evaluate risk, and support management and mitigation efforts.

3.2.3. Risks to individuals and ecosystems

Risks associated with plastic contamination for biota, ecosystems, and even human health, remain relatively unmapped (Enyoh et al., 2020; Provencher et al., 2019). There was a strong consensus among the plastic experts in the workshop and survey that we need to understand and adequately demonstrate the biological and ecological impacts of microplastics, and how they may act as vectors of biological and chemical contamination (Fig. S4). Comments from the survey supported this, namely regarding the need to demonstrate the "*effects of microplastics in the environment, and how this might change population structures of species, or the general functioning on the marine environment*".

Whilst challenging, clarifying microplastic toxicity, and measuring the effects of different microplastics and their risk of harm was emphasised (Campanale et al., 2020; Verla et al., 2019). It was recognised that microplastics comprise an array of particles and chemicals, and toxicity is likely intertwined with their physical and chemical characteristics (e.g., particle size, polymer, chemicals added as plasticizers at the time of manufacture or sorbed from the environment) (Rochman, 2015). Microplastics can become a 'chemical cocktail' where chemicals from the environment (e.g., pharmaceuticals, PFAS, phthalates) can adsorb to the exterior surface of the plastic particle (Rochman, 2015; Rochman et al., 2019). It is well understood that many of these chemicals can have negative biological effects on organisms (e.g., Mathieu-Denoncourt et al., 2016; Sinclair et al., 2020; Tuuri and Leterme, 2023), however, the effects of leaching and chemical uptake from microplastics, including the associated to translocation processes, is still poorly understood (Campanale et al., 2020; Prata et al., 2020; Rahman et al., 2021).

There are an increasing number of studies investigating the effects of microplastics on marine organisms (Guzzetti et al., 2018; Palmer and Herat, 2021; Vázquez and Rahman, 2021). Yet, the concentrations, polymer types, chemical additives and levels of weathering are often not reflective of what occurs naturally or is anticipated to realistically occur in the marine environment. Comments from survey respondents called for research with "*microplastic forms that are environmentally representative, both in terms of composition [and] properties*", and "*toxicity risk at environmentally relevant levels*". Moreover, there is a need to evaluate if the impacts of microplastics differ from those of other similar-sized debris. Ecotoxicological and dose-response assays are key to defining thresholds of risk, and if there are groups of species more sensitive or at risk (Koelmans et al., 2016; Lithner et al., 2011). Moreover, stakeholders emphasised the importance of developing methods that can evaluate the ecological impacts of microplastic contamination across multiple levels of organisation (Fig. 5), therefore indicating toxicological endpoints in an individual (e.g., oxidative stress, hormone changes, reproductive issues) to ecological consequences at a population level (e.g., population decline).

Determining exposure risks relies on knowledge of toxicity and an abundance of high-quality comparable environmental data. Globally, there are risk assessments that highlight the chemical toxicity of a number of pollutants associated with microplastics under different scenarios (Gouin et al., 2019). Ultimately, to develop management, regulatory and policy guidelines for microplastic contamination it is important to go beyond this and identify the relevant thresholds that impact biota (Anbumani and Kakkar, 2018; Wang et al., 2019). This information helps to establish relevant levels for exposure testing and guide environmental quality guidelines, mitigation, removal, or interception strategies for microplastics of concern.

4. Moving forwards and conclusions

Only through broad data integration will we be able to understand the drivers of variability in microplastic contamination, demonstrate changes in contamination and potential impacts, and gauge how effective are different reduction or mitigation measures over time and space. Most research is fragmented, with limited overarching coordination regarding effort and focus, and derived from small, standalone research questions that lack broad, integrated spatiotemporal sampling, likely associated with constrained funding opportunities. To gain a more comprehensive view of microplastic contamination, multidisciplinary action on both national and international platforms is essential (Mofokeng et al., 2023). Despite positive steps for collaborative approaches across stakeholder groups to combat plastic contamination this is still in its infancy. Pressing for funding that focuses on collaborative projects, embraces multiple stakeholders' needs, and connects international experts is key to tackling global issues related to microplastic occurrence. Further, leaders in the microplastic space should strive to collaborate on international agreements, cross-border partnerships, and knowledge-sharing platforms. In particular, the resolution to end plastic pollution (United Nations Environment Programme, 2022) provides a clear platform for change, with specific provisions encouraging collaboration and multi-stakeholder agendas as groundwork for policy change and impetus for actions at local level. This legally binding approach may also create the momentum needed for the microplastic community to define best practices, harmonising data collection, processing and reporting guidelines. This is being assisted by The Scientists' Coalition for an Effective Plastic Treaty, where scientific and technical experts translate knowledge to decision makers and the public. By pooling resources and expertise, we are most likely to succeed in implementing effective strategies that address microplastic occurrence, sources, pathways, and associated risks.

The lack of global coordination in research effort and broad cooperation is mirrored when it comes to policy and legislative action, though the United Nations Environment Assembly has recently passed a resolution aiming to have a legally binding Global Plastic Treaty to tackle plastic pollution by 2024 (United Nations Environment Programme, 2022). The nature of ocean currents means that plastic does not conform to geographical boundaries, with plastic waste appearing from both international and local sources (Barnes et al., 2009; Duncan et al., 2020). The international connectivity of plastic contamination drives the need for similar connectivity in global legislation and cooperation for mitigation strategies (Wang et al., 2021). There have been several attempts globally to advance the harmonisation of research priorities across different regions (Provencher et al., 2022, 2020b; Savoca et al., 2022; Vegter et al., 2014). Despite this, there are likely tensions between the priorities of local and/or regional governments compared to those focused on a wider global picture. We need to ensure that communication between these differing governing bodies is clear, so research efforts, mitigation strategies and funding can be utilised efficiently and proactively. It is critical that funding is directed to answering the research gaps that are pertinent both regionally and globally, and across multiple stakeholders.

Scientific research and public awareness should not operate in silos, but rather be synergistic parts of a management process (Jones et al., 2024). The public can play a vital role in the global effort to reduce microplastics by advocating for evidence-based policies and participating in mitigation actions. Awareness and engagement help shape effective solutions as well as implement policy interventions, while involvement in citizen science initiatives can provide valuable data to the science community. Importantly, public awareness can play a key role in implementing localised policies, connecting a global problem with local action. Ultimately, empowering the public with science-based knowledge fosters informed decision-making and collective responsibility for environmental preservation. As an extension to public involvement, engagement with both stakeholders and the public needs to be prioritised to provide science-based knowledge on the risks and sources of microplastics. The media attention given to reports of varying quality on predicted, perceived or potential impacts of microplastics can lead to a mismatch to the scientific literature where the risk of harm is yet not fully clear, resulting in a distortion of expectations between public awareness of the issue and scientific knowledge (Catarino et al., 2021; Völker et al., 2020). In turn, this may influence or even initiate policy action unnecessarily, with focus shifted towards specific types of plastic rather than more beneficial solutions that target the crux of the problem (Kramm et al., 2018). Whilst an abundance of caution is the best precautionary measure, haphazard or over-detailed policies in the absence of clear evidence risk loss of perspective; in contrast, loss of contextualisation, failure to communicate and failure to take action can lead to loss of motivation from the community (Soares et al., 2021).

Overall, creating a multidisciplinary forum for discussion and knowledge transfer across stakeholders stimulated engagement and lowered barriers for collaboration on improving monitoring and management of plastic pollution. Stakeholders outlined research foci and priorities that are relevant and applicable globally. A critical part of the process is providing information back to stakeholders. Positively, this study has demonstrated the commitment and interest of government agencies and industry in Australia to work together to combat plastic pollution, which can be utilised as a roadmap for global mitigation. Publications such as this one and keeping engagement momentum and communication gateways are essential to disseminate lessons learnt, galvanise application, and amplify outcomes. By inspiring effective research and communication, we can respond to public concerns about microplastics, support regulators' and policy makers' aspirations, and proactively create beneficial mitigation strategies.

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CRediT authorship contribution statement

Nina Wootton: Writing – review & editing, Writing – original draft, Project administration, Investigation, Formal analysis, Data curation. **Bronwyn M. Gillanders:** Writing – review & editing, Funding acquisition, Conceptualization. **Sophie Leterme:** Writing – review & editing, Conceptualization. **Warwick Noble:** Writing – review & editing, Conceptualization. **Scott P. Wilson:** Writing – review & editing, Conceptualization. **Michelle Blewitt:** Writing – review & editing, Conceptualization. **Stephen E. Swearer:** Writing – review & editing, Conceptualization. **Patrick Reis-Santos:** Writing – review & editing, Writing – original draft, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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