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Microplastics in South Eastern Australian coastal waters: synthesising current data and identifying key knowledge gaps for the management of plastic pollution

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Executive summary

Managing the presence of microplastics in coastal and marine environments requires a comprehensive approach, underpinned by solid and consistent information on contamination. Because microplastics comprise a broad suite of different contaminants (e.g., plastic types, sizes and chemical additives) management and mitigation are complex. Thus, a key first step is to understand the scale of the problem, and to assess potential impacts and curb contamination. Managers and decision-makers need information on the current status of microplastic contamination, including occurrence, potential sources, pathways and exposure risk (i.e., how much, where, and what types).

Microplastics in coastal and marine environments are a priority issue for multiple stakeholders, including local and state governments, water utilities and the general public. Therefore, engagement is key to understanding shared needs but also barriers and opportunities for the management of microplastics, as well as to develop solutions at a multi-state (national) level.

This project consolidated our understanding of microplastics in coastal marine environments in south-eastern Australia (South Australia, Victoria and New South Wales). The project compiled information from literature, highlighting the main methodological approaches, findings and limitations, including information on potential sources and pathways where available. Multiple stakeholders were engaged, and through the organisation of an online workshop and an anonymous survey, we identified critical gaps in knowledge and future research priorities. These research priorities respond to cross-sector stakeholder needs, and support evidence-based policy, regulation and management.

Overall, there was a low number of studies across water, sediment, and biota matrices in SA, VIC and NSW. But most importantly there was a lack of repeated sampling, and a large disparity and heterogeneity in methodological approaches which leads to results rarely being amenable to direct comparison. The main focus was documenting microplastic occurrence and load in coastal environments. Whilst polymer validation was undertaken, few studies effectively establish a causal link to potential sources and pathways. There was also limited or no assessment of ecological impacts. Nonetheless, microplastics were ubiquitous across the different matrices and locations (estuarine, coastal and deeper offshore areas), with fibres and fragments dominating, and microplastic abundance associated with environmental and urban features (e.g., urban landscapes/population density, stormwater). The importance of wastewater treatments, stormwater and road dust on microplastic occurrence is also highlighted, though there is still a lack of targeted research evidence across the three states, in particular on road dust and microplastics from tyre wear.

Beach surveys were a large source of information but generally focus on debris visible to the naked eye, and often report only larger microplastics (i.e., 1 – 5 mm, with microbeads or fibres likely too small to be sampled effectively). Whilst there are collection or activity-related limitations that apply to smaller microplastics, beach surveys have shown broad-scale and long-term trends in debris abundance.

Engagement with a broad array of experts, stakeholders and end-users (academic research, government, water utilities, NGOs), was pivotal to providing a more in-depth analysis of ongoing research and available information, but most importantly provided a forum for broad discussions and to evaluate perspectives on cross-sector needs. Expert opinion covered a diverse range of topics, from methodological and analytical method development, monitoring, and reconstructing sources and pathways, including modelling, risk assessment or ecotoxicology. Ultimately, it allowed us to identify major priorities to support monitoring and management that can be sought through collaboration and shared understanding, striving towards a national-level application.

The report summarises major knowledge gaps, and cross-sector priority actions, solutions and recommendations that can contribute to supporting meaningful management and policy strategies for microplastics in coastal environments, that are framed under three main overarching research priorities:

- **Need for method harmonisation to increase reproducibility and data comparability** (i.e., there was strong support for refining methodological approaches and establishing standardised guidelines to determine microplastic contamination and combat the lack of comparable data).

- **Need to understand occurrence of microplastics and identify sources and reconstruct possible pathways into the environment** (i.e., promote repeated sampling, document spatiotemporal variation, unravel the environmental and anthropogenic factors driving variations over time and space; allied to source identification and pathway reconstruction, as well as increase the quantification and characterisation of smaller microplastics (<1 mm) for which information is comparatively scarce but likely more relevant regarding ecological impacts).

- **Need to demonstrate the risk of harm to individuals and ecosystems** (i.e., understand the biological and ecological impacts of different microplastics and demonstrate their risk of harm, including as vectors of chemical contamination, to support risk assessments; as well as translating toxicological impacts at sub- or individual levels to higher level population and ecological consequences).

1. Introduction

Over 8.3 billion metric tonnes of plastics have been produced globally since the 1950s, with plastic use continuing to increase sharply (Geyer et al. 2017). From over 380 million tonnes in 2015, current plastic production is estimated at c. 450 million tonnes per year and if present trends continue annual plastic production will reach 1 billion tonnes in 2050. This is the equivalent of all plastic production between 1950 and 1984 (Geyer 2020). This era of increased and widespread plastic use is a result of the unique properties that make plastic a revolutionary product, including its durability, mouldability and low production cost.

Yet, a major issue is plastic disposal, with single-use and low recycling rates contributing to increased waste production. In Australia alone, of the total 3.5 million tonnes of plastics used in 2018-2019, only 13% were recycled (DAWE 2020, 2021). Large proportions of plastic waste are found in coastal and marine environments (Reisser et al. 2013, Eriksen et al. 2014, Hardesty et al. 2017a, Suaria et al. 2020), and poses significant environmental, economic and amenity concerns, as well as contributing to potential human health issues (Browne et al. 2015, GESAMP 2015, 2016, Rochman et al. 2016, Auta et al. 2017, Fossi et al. 2018, Vethaak & Legler 2021).

Of particular concern are microplastics such as clothing fibres, microbeads from domestic and personal care products, or pieces that result from the breakdown and weathering of larger plastics. Microplastics are ubiquitous in marine environments, and have been found from coastal and intertidal habitats to remote and deep oceanic areas (Reisser et al. 2013, Eriksen et al. 2014, Auta et al. 2017, Hardesty et al. 2017a, Suaria et al. 2020, Wootton et al. 2021b). Microplastics are generally defined as particles <5 mm (GESAMP 2015, 2016, Frias & Nash 2019). This definition embraces particles that can be intentionally or inadvertently ingested by biota, and can present different properties or elicit impacts that differ from larger plastic debris. However, there are variations in the literature in both the upper (e.g., <1mm) and lower limits (e.g., 1 to 20 μm) of the term microplastic (Browne et al. 2015, Frias & Nash 2019), and among other issues, this can cause methodological challenges when comparing data (Underwood et al. 2017, Cowger et al. 2020, Wootton et al. 2021b).

Microplastics can also be classified as primary or secondary. If microplastics are manufactured at small sizes (e.g., microbeads, industrial pellets/nurdles) they are primary microplastics but if these small sizes result from degradation or breakup of larger pieces they are known as secondary microplastics. Many sources and pathways drive the occurrence of primary and secondary microplastics in coastal and marine environments, but are overwhelmingly linked to land-based discharges (GESAMP 2015, 2016, Auta et al. 2017, Komyakova et al. 2020). From inappropriate waste management and wastewater treatment plants (WWTP), road dust, and industrial and agricultural uses, microplastics can be transported across ecosystems via river flow, runoff, storm and drain waters, as well as wind, tides and currents (Li et al. 2016, Jensen et al. 2019, Okoffo et al. 2019, Komyakova et al. 2020, Pramanik et al. 2020, Meijer et al. 2021). Ocean-based sources, such as fishing and aquaculture gear are also linked to the presence of microplastics (Cunningham & Wilson 2003, Li et al. 2016, Napper et al. 2022).

Due to their small size, microplastics are readily ingested by marine organisms and have the propensity to accumulate, raising concerns for biota and ecosystem services (Carbery et al. 2018). Microplastics can also act as vectors for chemical contamination, which may exacerbate any potential physical impacts they have, because microplastics can leach plastic additives as well as other chemicals sorbed from the surrounding environment, potentially eliciting a variety of toxicological effects (Brennecke et al. 2016, Li et al. 2018, Carbery et al. 2020, Cousin et al. 2020). While our understanding of the impacts and effects of microplastics are far from well understood, they can reduce growth and feeding rates, or lead to oxidative stress and changed behavioural responses (von Moos et al. 2012, Browne et al. 2015, Rochman et al. 2016, Guzzetti et al. 2018). Overall, because microplastics are widespread, they are regularly found in a variety of food items sold for human consumption (Danopoulos et al. 2020, Wootton et al. 2021a).

Microplastics in coastal and marine environments are a priority issue for multiple stakeholders across Australia, including local and state governments, water utilities and the general public. Engagement with a broad array of stakeholders is important to understand shared needs but also to understand barriers and opportunities for the management of microplastics, as well as to seek solutions at a multi-state (national) and international level. The presence of microplastics in coastal and marine environments is an intricate and multifaceted issue that requires a comprehensive approach, underpinned by solid and consistent information on plastic contamination. Because microplastics enter coastal environments through a wide array of pathways and comprise a broad suite of different contaminants (e.g., plastic types, sizes and chemical additives) management and mitigation are complex. Key first steps for the management of microplastics in Australian coastal waters is understanding the scale of the problem (e.g., how much, where, and what types) and exposure risks.

Ultimately, to curb microplastic pollution and to allow a greater understanding of their impacts, managers and decision-makers first need clear information on the current status of plastic contamination, including microplastic occurrence, and potential sources and pathways. This is essential to define management action strategies, support policy options and inform evaluations of potential trade-offs that effectively reduce the entry and potential impacts of microplastics on coastal and marine environments.

1.1 Project background and aims

Responding to national priorities on the impacts of marine debris (DAWE 2021), this project aimed to consolidate our current understanding of microplastics in coastal marine environments in south-eastern Australia (South Australia, Victoria and New South Wales); then together with multiple stakeholders identify critical gaps in knowledge and future research directions that respond to cross-sector stakeholder needs. Specifically:

1) We undertook a literature review, collating the information on microplastics in coastal marine environments relevant to south-eastern Australia. This review focused primarily on the peer-reviewed published literature but also on documenting, where possible, information from other sources. From the compiled literature, we summarise the main foci

of ongoing research on microplastics in the three states, highlighting the main methodological approaches, findings and limitations, including information on potential sources and pathways where available.

2) We met researchers as well as relevant government and industry bodies involved in microplastic research to supplement information collected in the literature review, and to gather expert opinion on key knowledge gaps and future research needs. This laid the groundwork and identified key topics to address in the subsequent webinar and survey.

3) We organised a webinar bringing together experts from the water services, state and Commonwealth government agencies, non-governmental organisations, and researchers to discuss knowledge gaps and future research priorities. This interactive webinar provided a forum for a comprehensive evaluation of the information needed across sectors for improved assessment, monitoring and management of microplastics. Associated with the webinar we also launched an anonymous survey ranking key threats and research priorities. Ultimately, the goal was to elicit expert opinion across sectors on what gaps and research needs are the most critical to support evidence-based policy, regulation and management.

The webinar and survey were critical components of the project, bringing together stakeholders and end-users interested in microplastics in coastal environments. They provided a clear-sighted focus on research priorities that respond to end-user needs, identifying major foci for improved monitoring and management of plastic pollution in Australian coastal environments.

In this report, we first summarise the information from the literature review (Section 2.1). followed by a summary of information from multiple stakeholders and end-users, collated from reports and meetings (Section 2.2). These also provided a window to the different stakeholders' perspectives on microplastic contamination, including research and development strategies, gaps, and needs. A summary of the webinar and surveys are discussed in Section 2.3. We then synthesise and integrate the outcomes of all the project's engagement and knowledge transfer opportunities, outlining research gaps, future research priorities and cross-sector recommendations and options for enhanced management of microplastics in coastal environments (Section 2.4).

2. Microplastic research in South Eastern Australian coastal environments

2.1 Synthesis of peer-reviewed literature

We used Web of Science and combinations of different keywords relevant to microplastics and coastal areas to characterise the current state of knowledge and to collate the literature published on the occurrence of microplastics in coastal environments in South Australia, Victoria and New South Wales. In *all fields,* we searched for combinations of terms including: *plastic*, Australi*, polymer or polymers (as well as with derivatives of stream or catchment 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). Searches were performed on November 16th, 2021, and the same searches were updated on April 30th, 2022. A total of 42 peer-reviewed studies were found, covering studies on sediments, water and biota, as well as beach surveys with data on microplastics in coastal and marine environments in south-eastern Australia (SA, VIC and NSW) (Figure 1). Whilst not directly in coastal environments, we also extracted information from studies on wastewater, drain water and road/tyre dust, as these sources and their potential pathways to coastal environments were indicated as an area of particular interest in consultation with The Department of Climate Change, Energy, the Environment and Water.

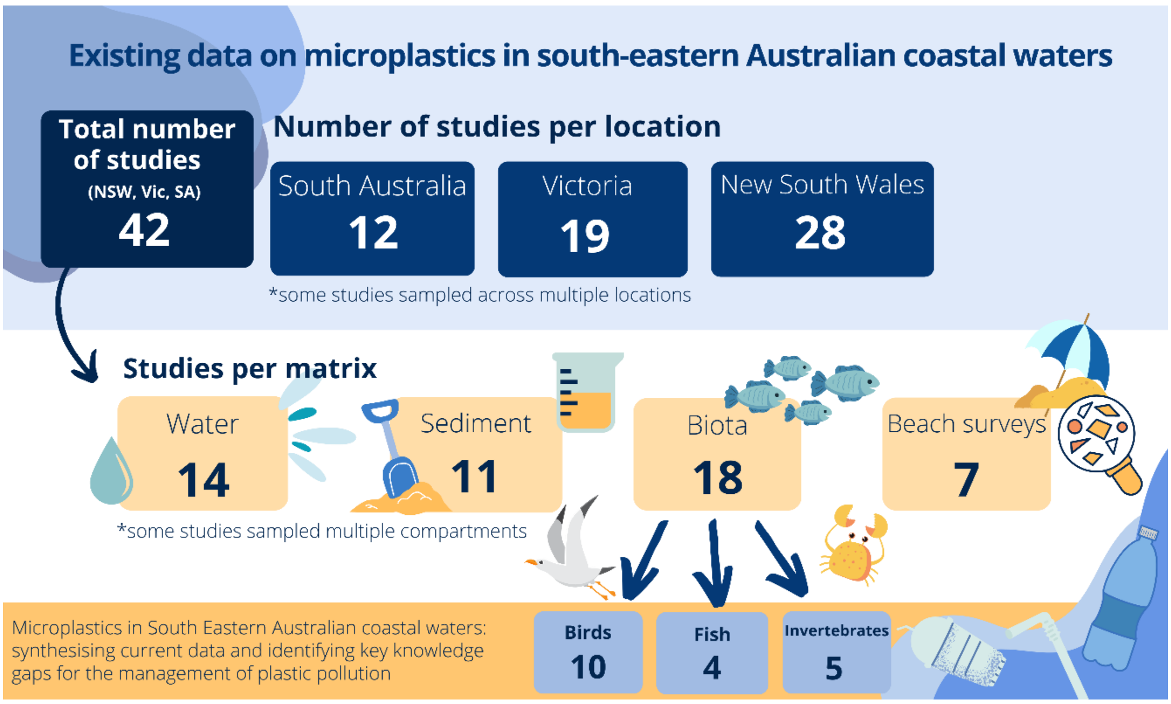

Figure 1: Summary information of the 42 peer-reviewed studies focusing on microplastic contamination in coastal areas of SA, VIC and NSW. Also shown is the partitioning of the number of studies per sample type (sediment, water, biota and beach survey studies). Note several studies focused on multiple locations or environments, and studies per matrix type include waters or sediments from waste water treatment plants or road dust.

For each study, an individual ID was created and data on a large suite of categories were extracted, including location, sample type, processing and quality control methodologies, as well as information on microplastic data (summarised in Table 1, full details in Appendix A).

Table 1: Summary of main categories of information extracted from individual studies (for full details see Appendix A).

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, 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

The motivation to compile information on microplastics in coastal environments stems from a need to synthesise where microplastic assessments are taking place and what are the main research foci. In doing so, we build a broad perspective of the scale of the environmental presence of microplastics (i.e., how much, what and where); as well as a representation of potential sources and pathways; main research areas; and potential hotspots of contamination – but also hotspots for monitoring or gaps in knowledge. This is fundamental to identifying opportunities, barriers, and recognizing priority research needs.

Baseline and long-term evidence are key to monitoring and evaluating how effective different policies may be (Hardesty et al. 2017b, Schuyler et al. 2018, Willis et al. 2022), and allows us to have the best possible information to support future decisions and actions. The sections below synthesise the peer-reviewed literature for microplastics in water, sediments and biota, as well as the outcomes of beach surveys and research on microplastic sources from wastewater, stormwater and road dust in SA, VIC and NSW (Appendix B). This is followed by a summary section with an overview of major findings, opportunities and limitations identified in the literature.

2.1.1 Assessments of microplastics in water

Of the studies assessing microplastics in water, nine focused on marine coastal or estuarine and wetland environments. On a broad scale, Reisser et al. (2013) assessed the concentration of plastics in marine areas across Australia using surface net tows. Microplastics dominated (sizes 333 µm to 5 mm), with the majority of pieces 98% hard polyethylene or polypropylene. They found higher sea surface concentrations (reported as pieces·km^{-2}) near major cities on the east coast but also report increased estimates of occurrence further offshore or in remote areas. Microplastics were associated with ocean currents and tied to potential international and national sources, including inputs from major populated areas on the east coast. However, there were no sampling points in the vicinity of Port Phillip Bay (i.e., Melbourne, VIC) or Gulf St Vincent (i.e., Adelaide, SA).

Focusing on SA, Klein et al. (2022) collected intertidal waters (grab samples – bottles, at <20 cm depth) from ten sites across the state (reported as particles·L^{-1}) with differing oceanographic influence and proximity to urban areas, and suggested a link between neighbouring population size and microplastic concentration. Compared to global studies, concentrations are described as low to moderate, with fibres dominating (c. 89%). In coastal beaches and nearby estuarine areas in the suburbs of Adelaide, microplastics collected in plankton nets (between 1 and 5 mm, reported as items·100,000 L^{-1}) led to similar conclusions regarding lower contamination to other similar studies worldwide (Hayes et al. 2021). These three examples are difficult to compare, due to variations in collection modes or units, among other procedural heterogeneities. For example, Hayes et al. (2021) discarded microplastics below 1mm, which can represent a major proportion of microplastics in coastal waters (e.g., Reisser et al. 2013, Browne et al. 2015, Rudduck et al. 2017, Hitchcock & Mitrovic 2019, Nan et al. 2020, Li et al. 2021). An overview of the research for VIC and NSW, and nationally, suggest an assortment of collection modes and microplastic sizes investigated making broader comparisons challenging.

In VIC, grab samples and manta nets were used to assess microplastics from the water of streams and wetlands in rural and urban areas of Port Phillip and Western Port bays (Nan et al. 2020, Su et al. 2020b). Both studies show a prevalence of fibres (up to 100% of microplastics per site), with polyester the most common polymer, comprising over 30% of analysed samples.

Only in NSW do we find temporal sampling. A year-long study, with monthly sampling, confirmed microplastics were associated with a gradient of anthropogenic presence in three estuaries (Clyde, Bega and Hunter estuaries) (Hitchcock & Mitrovic 2019). Using a plankton net, microplastics across sites and time were dominated by fragment-like pieces, rather than fibres. Size-wise, 66 to 73% of all microplastics were between 45 and 200 µm, with large microplastics (i.e., 1- 5 mm) the least abundant. Increased flows to the estuaries associated with rainfall appeared to amplify microplastic contamination. High frequency, repeated sampling, during and after a storm event demonstrated the influence of rain and storm events as triggers of microplastic contamination, with rainfall and input of stormwater in the Cook's estuary leading to a sharp increase in microplastic abundance (a >43-fold increase, from 400 to 17,383 particles·m^{-3}) (Hitchcock 2020). Inter-annual variation in microplastics (larger than 0.333 µm) in Sydney Harbour and the Tasman Sea off the coast of NSW [following the Reisser et al. (2013) approach and sites] showed that c. 68 % of debris were microplastics (333 µm to 5 mm in size), with greater abundances and polymer diversity found in urban Sydney Harbour versus offshore areas across the years (Rudduck et al. 2017). Surface trawls in marine waters surrounding Lord Howe Island were undertaken to investigate debris available to foraging marine birds (Roman et al. 2016). Little detail was provided on microplastic distribution by sizes (i.e., if >300 µm, >1 mm or 5 mm).

2.1.2 Assessments of microplastics in sediments

Six studies investigated sediment microplastics in coastal areas in south eastern Australia. In two instances, sediment samples were collected at the same time as water samples (in VIC and SA), with trends in abundance of sediment microplastics (items·kg dry sediment^{-1}) very closely related to those in the water, and increasing in abundance and polymer diversity with land use and urbanisation (Su et al. 2020b, Hayes et al. 2021). In 54 sites in the greater Melbourne and Port Phillip Bay areas, sediment showed a higher proportion of fragments than water, with an increased abundance of microplastics in lentic reaches and downstream towards the estuary, as well as with proximity to human activities (Su et al. 2020b). Polyesters and polypropylene dominated (maximum mean per site 173 items·kg dry sediment^{-1}) (Su et al. 2020b), and though near Adelaide Hayes et al. (2021) only investigated microplastics >1mm (maximum mean 2.2 items·kg sediment^{-1}), recyclable polyolefins (e.g., polypropylene and high-density polyethylene) were also the most abundant polymers.

In waterways around Melbourne, Townsend et al. (2019) found microplastics in all sampled sites with human land use again correlated with abundance of microplastics (particularly industrial space compared with residential use). Microplastics (0.063 - 5 mm, items·ml sediment) were similarly ubiquitous in nearshore coastal sediments (5-13 m deep) off NSW (Sydney Harbour, adjacent areas, Jervis Bay, and Eden), VIC (Port Phillip Bay), and SA (Adelaide Metropolitan coast) with fibres comprising 84 % of the total plastic (Ling et al. 2017). However, there were variations in microplastic types among regions, with NSW and Victoria having an increased proportion of fibres compared to SA. Higher abundances were related to finer sediments and were found in urban but also more remote areas, highlighting how local conditions as well as transport pathways influence the occurrence of microplastics. Overall, SA showed the highest nearshore contamination, followed by NSW and Victoria (mean 4.1. 3.4 and 3.2 items·mL sediment, respectively) (Ling et al. 2017).

Further offshore, in sediment cores from the Great Australian Bight (depths 1655 to 3062 m), fragments (50 µm- 5 mm) dominated, with fibres only 10% of the total microplastics (Barrett et al. 2020). Abundance varied from 0 (in 2 out 16 cores) to 13.6 fragments·g^{-1} (mean 1.26 fragments·g^{-1}). Whilst this suggests offshore sediment as a potential sink for microplastics, there is also variation in deposition and retention, as variation in abundance within sampling cores was larger than across cores (Barrett et al. 2020).

In seaports of NSW, both microplastic abundance in sediment and microplastic characteristics were suggested to vary with local industries and uses (Jahan et al. 2019). Mean abundance ranged from 83 to 350 particles·kg^{-1} (dry weight) and was positively associated with finer sediments, demonstrating the importance of local conditions. At the same time, this study compared sediments with contamination in oysters to also evaluate the bioavailability and uptake of microplastics from sediment to local biota.

2.1.3 Assessments of microplastics in biota

A larger number of studies have focused on microplastic occurrence in biota from coastal environments (18), than in water and sediment matrices. Assessments of ingestion in seabirds and shearwaters, in particular, dominate (10 studies). Most took place in Lord Howe Island and Ballina (NSW), focusing on single species, but Gilbert et al. (2016) and Roman et al. (2016) assessed 11 and 61 different bird species, respectively. The majority of studies are based on necropsies (i.e., opportunist collection of dead birds or stranded individuals that died in care), with only three studies undertaking stomach flushing (Lavers et al. 2014, Lavers et al. 2018, Verlis et al. 2018) or collecting boluses when fledglings departed the nests (Bond et al. 2021). Overall, the frequency of occurrence of plastic was high, up to 100% in some cases, as well as the number of plastics found per individual [e.g., >17 items·individual^{-1}, Lavers et al. (2014)]. However, it is not always possible to discern if these were microplastics or larger debris from the information provided. For avifauna, we are lacking information on small microplastics, with studies focusing on pieces >1 mm (generally identified using the naked eye). The exception is Lavers et al. (2019), which demonstrated that neglecting fine plastic pieces (> 0.33 mm <1 mm) underestimates plastic load by >7%. Also, none of the studies undertook a validation or quantification of the polymers collected. This is essential to validate the findings of microplastics and identify potential sources, even if with larger pieces sources could be attributed to materials including balloons, fishing gear, industrial pellets or foam, among others.

Investigating a link between the potential physical and chemical impact of plastic contamination, birds with higher levels of plastic had reduced body condition and increased trace element concentration (Lavers et al. 2014). A causal relationship between the source of chemical contamination and ingested plastic has not been established. Moreover, on other occasions, no clear link between body condition and the amount of ingested plastic was found (Lavers et al. 2018).

Four studies looked at microplastics in the gastrointestinal tracts of fish across the three states. One focused on a non-commercial invasive species in urban wetlands (Su et al. 2019), whilst the others focused on a suite of coastal species that are commercially harvested (Cannon et al. 2016, Halstead et al. 2018, Wootton et al. 2021a). Specimens were either wild caught in estuaries and off the coast, or collected from seafood markets and sold for human consumption. Contrary to bird studies, there has been a focus on smaller microplastics (but across different sizes >20, >38 and >330 μm), except Halstead et al. (2018) who relied on observations with the naked eye. Overall, there is very limited spatial and temporal information, e.g., only one study on fish from SA, but the frequency of occurrence and plastic load was suggested to be generally lower than similar studies globally (Cannon et al. 2016, Wootton et al. 2021a).

Comparisons across regions, species and other locations across the globe are again challenging due to the lack of consistency in microplastic sample preparation (e.g., digestion), identification or even classification. In some instances, sample numbers per species and site are also low, compared with general recommendations (Markic et al. 2020, Miller et al. 2021, Wootton et al. 2021b). Nonetheless, polymer validation was performed in all studies, which is an important advance because it potentially aids in identifying the origin or use of the original product, and therefore can help guide where management action can be most efficacious. Overall, fibres dominated [e.g., c. 82% in Wootton et al. (2021a)] from polyester, rayon and polyolefins but with no further confirmation of the source. However, no study simultaneously assessed fish and environment matrices (water or sediment).

For invertebrates, three of the five studies collected water or sediment adjacent to the organisms (Jahan et al. 2019, Nan et al. 2020, Klein et al. 2022). In six seaports in NSW, oysters and sediments showed similar variations in abundance across sites with increased loads in oysters compared to sediments, and differences in shapes, size and colours between biota and sediments (Jahan et al. 2019). Of note, all oysters had microplastics (100 % frequency of occurrence). Compared with water from wetlands adjacent to Port Phillip Bay (VIC), freshwater shrimp contained a wider variety of microplastic types, though blue fibres were the most abundant in both shrimp and water (Nan et al. 2020). In SA, mussels were collected from six coastal sites, and had the highest reported overall mean of pieces of microplastics per individual (3.6). Prawns and blue swimmer crabs sourced from seafood markets showed variations in microplastic abundance across states with fibres the most common plastic type (Ogunola et al. 2022).

Methodologies across studies on biota also showed variation. Whilst there has been a clear focus on small microplastics, using small sieve sizes (down to 1 µm) and all performing polymer validation, there are discrepancies, with data reported by individual and/or as particles·gram wet weight^{-1}, and limitations associated with reduced sample numbers (e.g., six per site - Klein et al. 2022). The size of an organism is likely an important factor in determining microplastic ingestion – thus information per wet weight is an important aspect to consider.

2.1.4 Assessments of microplastics from beach surveys

Beach surveys include systematic approaches undertaken by researchers (Hardesty et al. 2017b) but also citizen science surveys often associated with beach clean-ups (Cunningham & Wilson 2003). Overall, a characteristic of many beach surveys is the focus on plastics that are visible to the naked eye, and at times that must be detected from standing height (Hardesty et al. 2017b, van der Velde et al. 2017, Olivelli et al. 2020). Necessarily, citizen science surveys utilise accessible, visual methods and may include a minimum size (e.g., 1 mm, 5 mm) but often the data are not presented in a manner that allows easy disentanglement of microplastics (<5 mm) from other smaller debris or macro debris. Moreover, differences in the applied methodologies can limit comparisons across approaches and surveys. Nonetheless, these approaches can illustrate broad scale and long-term trends, and have highlighted factors influencing the abundance of debris, including management changes (e.g., container deposit schemes) (Schuyler et al. 2018, Smith et al. 2018, Willis et al. 2022).

Overall, only four beach surveys covering SA, VIC and NSW include microplastics (*strictu sensu* < 5mm) (Duckett & Repaci 2015, van der Velde et al. 2017, Verlis et al. 2018, Olivelli et al. 2020). However, we also highlight others targeting all visible debris or small fractions starting at 5 mm that have important implications for microplastic assessments (e.g., Smith & Markic 2013, Gacutan et al. 2022).

In beach surveys across Australia (at approx. 100 km intervals) smaller debris, including microplastic (0.2 to 1.2 cm) accounts for 20% of all debris (Olivelli et al. 2020). Their abundance was linked to oceanic and atmospheric processes (wind, drift), as they were more abundant at the shoreline, peaking in the middle reaches and decreasing towards backshore vegetation areas (Olivelli et al. 2020). A similar approach was undertaken by Hardesty et al. (2017b) but no detailed information on microplastics or smaller debris was provided. Nonetheless, the occurrence of miscellaneous debris was also associated with coastline factors (shape, substrate) as well as population density and road proximity. In the greater Sydney area (NSW), a community science project collected plastic debris using a combination of transects and quadrats with a 1mm sieve, with the presence of debris strongly correlated with population density as well as storm-water drains – suggested as the main pathway delivering plastics to the coast (Duckett & Repaci 2015). Data were not broken down by size to unravel proportions and patterns of <5 mm microplastics.

Some studies have focused on debris >5 mm, just above the microplastic threshold. Gacutan et al. (2022) summarised national information from a citizen science approach but highlighted a major and disproportionate gap in assessments in SA. Beach surveys repeated over 20 months in Coffs Harbour (NSW) (debris > 5mm) (Smith & Markic 2013), demonstrate the need for daily assessments or the development of a site-specific accumulation model to accurately estimate marine debris accumulation. Lavers and Bond (2016) undertook beach surveys of debris >5 mm as means to compare the availability and preference of microplastics by shearwaters. These approaches focused on microplastics can improve our understanding of selectivity and potential factors that determine trends in biota contamination, and are likely key to highlighting sources of increased risk.

A key aspect of beach survey data is understanding whether efforts associated with citizen science can enhance research data. van der Velde et al. (2017) discuss multiple caveats but showed that with appropriate controls, protocols and training beach survey efforts can contribute to marine debris data information. Nonetheless, most work only looks at larger debris (e.g., Edyvane et al. 2004, Gacutan et al. 2022) and there are limitations regarding assessments of microplastics (see also Underwood et al. 2017), particularly for the smaller fractions, <1 mm or even <2 mm. For instance, primary microplastics such as microbeads would be too small to detect or quantify accurately relying on visual survey methods. Smaller pieces may also be difficult to accurately identify as plastic, in the absence of polymer validation. Overall, the key issue is whilst the general threshold for visibility may be c. 1-5 mm it is likely there is variation in this limit pending operator or activity-related conditions that are not controlled for (sight acuity, ability to identify plastic, persistence or awareness on sizes to collect) which may compromise the accuracy of the estimates on the quantities of microplastic found. Overall, to increase the sampling power of coastal litter and other survey assessments, tailored approaches are required to enhance sampling and data robustness that allows for consistent spatial and temporal comparisons.

2.1.5 Assessments of microplastics from other key sources

Wastewater treatment plants (WWTP), tyre dust and stormwaters are recognised as key potential sources of microplastics to coastal environments, but targeted research is still nascent in south-eastern Australia (Figure 2).

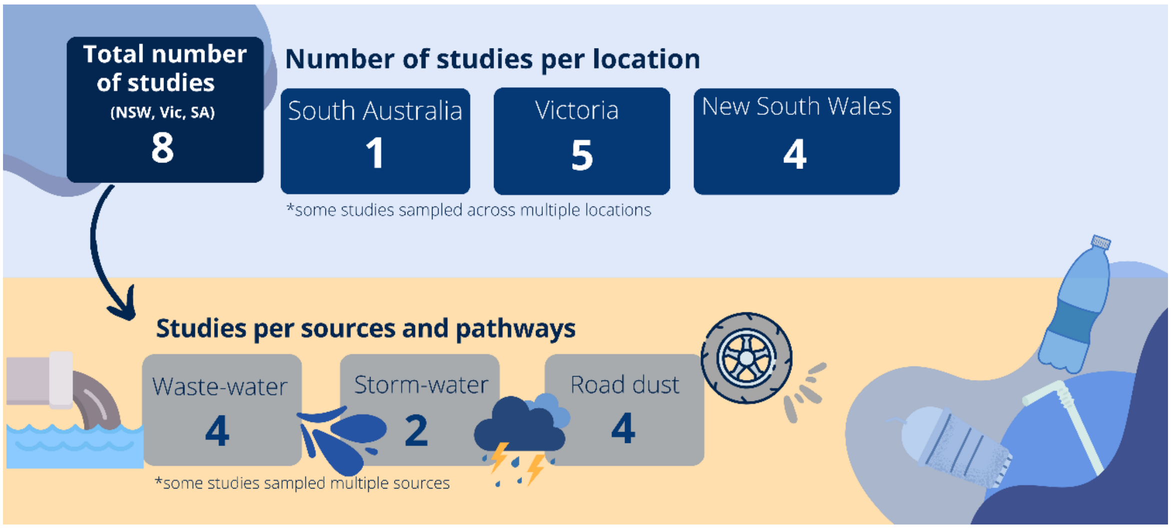

Figure 2: Summary information on peer-reviewed studies in SA, VIC and NSW focusing on wastewater treatment plants, tyre dust and stormwaters as potential sources of microplastics to coastal environments. Note several studies focused on multiple locations.

Overall, to formulate management options and reduce microplastic from these diverse sources, we need to develop reliable methods and background information on the availability and fate of microplastics across the water treatment process, as well as the transport and accumulation of microplastics in road dust and through storm or drain-waters. To date, few studies have quantified microplastics in WWTP across SA, VIC and NSW. Comparing microplastics in tertiary, secondary and primary treated effluent from WWTP in the Sydney region (NSW), Ziajahromi et al. (2017) found an average of 0.28, 0.48 and 1.54 microplastics per litre (sizes >25 µm), similar to the 1 microplastic per litre found by Browne et al. (2011). These estimates increase to 2.8 microplastics when particles >1.5 µm are considered (Raju et al. 2020). Nonetheless, it is important to consider there are methodological variations across studies. Overall, fibres dominated, likely from synthetic clothing, and polyethylene and polypropylene fragments had shapes and sizes associated with microplastic beads from cosmetics. Of note, fibres larger than the filter pore are consistently found, as due to their length to width ratio they can pass (longitudinally) through smaller filter pores (Ziajahromi et al. 2017).

Overall, the efficiency of WWTP in removing microplastics was documented but WWTP effluent is still an important pathway to environmental contamination considering the large volumes of discharge (Ziajahromi et al. 2017, Raju et al. 2020, Ziajahromi et al. 2021). Estimates of three different WWTP loads in Australia indicate that between 22.1 million and 133 million microplastics (>25 µm) are released in effluent per day (Ziajahromi et al. 2021). Moreover, retention of microplastics in treated sewage sludge (across Australia) [e.g., 86 million to 1020 million particles per day (Ziajahromi et al. 2021)] illustrates that biosolids need to be considered as microplastics may be subsequently released from land sources (Okoffo et al. 2020, Okoffo et al. 2021, Ziajahromi et al. 2021) and are a likely source of microplastics back to the environment including aquatic coastal systems (Crossman et al. 2020, Okoffo et al. 2020). A study on biosolids across 20 WWTP in Australia also illustrates the importance of size when addressing microplastics, with the greatest proportion of the total (27%) identified in the smaller fraction (<25 µm) (Okoffo et al. 2022).

Road dust has been an area of growing interest and concern regarding microplastics, including tyre wear, as it is likely a key source of microplastics through runoff and storm or drain-water systems. In stormwaters in Greater Melbourne, all sites contained microplastics, with abundance, predominant shapes of microplastics and polymers (e.g., polyethylene, nylon, polyester) varying among sites, associated with neighbouring land use (e.g., residential vs industrial) (Pramanik et al. 2020, Monira et al. 2022). In industrial areas microplastics in road dust and water from industrial areas (1130 particles·kg^{-1}; 26 particles·L^{-1}) were significantly higher than those in residential areas (520 particles·kg^{-1}; 17 particles·L^{-1}) (Monira et al. 2022). In a spatiotemporal evaluation of microplastics in road dust, microplastic loads were consistently higher in urbanised catchments of Port Phillip and Westernport compared with less urbanised/industrial areas (Su et al. 2020a). Microplastic abundance was also high (up to 530 items·kg^{-1}) but did not vary across seasons (October vs December), also showing similar size, shape and polymer compositions. Microplastics below 1 mm were prevalent (up to 62% of total microplastics per site), further highlighting the importance of robust approaches for smaller sizes. Fibres were also the dominant type (c. 75 % of total and up to 100% per site), with polyester and polypropylene the majority of polymers found. Overall, these recent studies target microplastics down to reduced sizes (e.g., >20 µm), and whilst there is only published literature for VIC, and there are variations in the methodologies used, the result illustrates that microplastics accumulate and are distributed in stormwaters. The presence of tyre wear particles was also demonstrated in road dust in Melbourne suburbs, with collected materials validated against tyre crumb reference materials (Roychand & Pramanik 2020).

2.1.6 Summary, opportunities and gaps in the literature

Across the three states, there is more information for NSW, with data spanning the Sydney region but also across several different coastal and estuarine areas (Rudduck et al. 2017, Hitchcock & Mitrovic 2019, Jahan et al. 2019). In VIC research on microplastics is strongly concentrated in the Port Phillip Bay and greater Melbourne region (e.g., Su et al. 2020b). There are notably fewer publications for SA, though research here focuses on both the Adelaide metro region but also regional SA (Hayes et al. 2021, Klein et al. 2022). Despite attempts to improve sampling design and consolidate guidelines for microplastic assessments (Underwood et al. 2017, Cowger et al. 2020) there is a large disparity and heterogeneity in methodological approaches (Figure 3) which leads to results rarely being amenable to direct comparison.

With this in mind, methods should be chosen based on the scientific question and reported with enough detail to be comparable and reproducible.

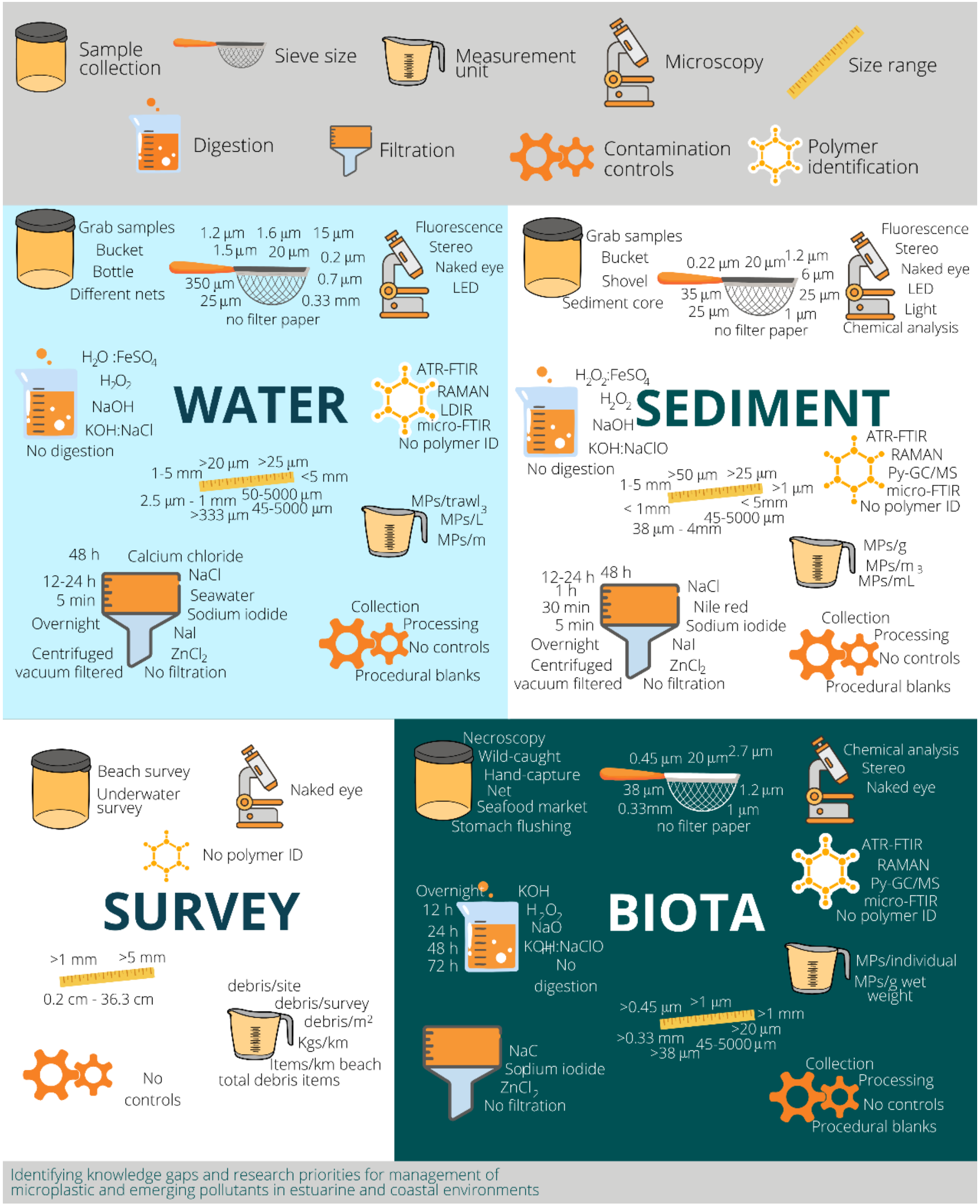

Figure 3: Variability in methods in microplastic research in SA, VIC and NSW (from collection, extraction, analyses, and quality control to reporting) illustrated the need to develop methodological guidelines for the collection and analysis of microplastics across all matrices. It is essential to identify standard, encompassing approaches, chosen based on the scientific question of interest, to promote harmonised approaches that include robust quality controls, accurately quantify all microplastic in a sample and therefore ensure comparability and reproducibility.

Regarding sources, sinks and pathways, research on microplastics collected in coastal environments generally lacked clear identification of the sources of microplastics. This differs from the research on larger debris where this is well established as pieces are generally large enough to identify the source material (e.g., balloon, fishing gear, bottles), but with microplastics, this needs to be supported by polymer identification. In general, potential sources and pathways are mentioned in the compiled literature but few studies effectively establish a causal link. The exceptions are studies collecting information from effluents, linking to storm waters or collecting road dust, where the pathways are evident. In the cases where pathways are evident there is opportunity for management action to institute engineering solutions to mitigate ongoing discharge into the environment. With the exception of clothing fibres or tyre particles, the source consumer product is generally lacking. Nonetheless, available information provides a critical baseline to unravel the factors influencing microplastic contamination, with environmental and urban features at large and local scales linked to plastic contamination (e.g., land use, number of industries, proximity to stormwater drain).

Summary for water and sediment

- Main foci of the published literature is documenting microplastic occurrence and load, with limited identification or information on the source of microplastics.
- Microplastics were ubiquitous in water and sediment samples, and across locations (estuarine, coastal and deeper offshore areas) with fibres and fragments dominating.
- Microplastic abundance increased with proximity to urban landscapes/population density. Variations in microplastic occurrence and type were influenced by urban land use (e.g., residential versus industrial areas). Lower contamination was found offshore compared to estuaries/harbours, which follows global trends.
- Rainfall and stormwater result in transport and increase of microplastics in estuaries. Lack of information on runoff and flow from estuaries and catchments to surrounding coastal areas prevents accurate estimate of inputs.
- Overall, there are a low number of studies and lack of broad spatial and temporal coverage across the land-estuarine and adjacent seascape. This limits our understanding of occurrence but also of accumulation.
- Though current data provide a valuable baseline, there is a general lack of repeated sampling in the literature (e.g., only three studies have repeated water sampling, none for sediment). Long-term and repeat sampling is key to exploring trends and understanding local and regional factors driving microplastic occurrence, as well as how effective different interventions on plastic reduction may be. Moreover, relying on short periods or limited geographic areas can result in misperceptions of microplastic abundance, as order of magnitude variations are associated with spatiotemporal variability (Law et al. 2014).
- Very low number of studies simultaneously analysed microplastics in sediment and water. It is essential to assess the behaviour of different microplastic types and sizes, including how buoyancy and environmental conditions (e.g., current, sediment size) may influence accumulation, sink and dispersal processes.
- Absence of information on coastal habitats of ecological significance (e.g., seagrass, mangrove, saltmarsh) limits the evaluation of impacts on these ecosystems.
- Microplastic contamination is low to moderate in comparison with areas globally, but heterogeneity in approaches significantly limits data comparability nationally and internationally.
- Variation in methodologies encompass multiple processes (e.g., collection, chemical digestion, sample preparation, size of microplastics assessed). More variations

among protocols for sediments than water but with a larger agreement in units used compared with water assessments. Also of concern, are inconsistencies in (reporting of) quality and contamination control across sampling and analyses (Cowger et al. 2020).

- Small microplastics (<1 mm) often dominate. Methodologies need to target these systematically and robustly.
- Percentage of polymer confirmation varies. Polymer validation is critical to confirm plastic identification, ensuring study accuracy, but also to help unravel key upstream sources.

Summary for biota

- Main focus of peer reviewed studies in coastal biota is documenting microplastic occurrence and load, with limited or no assessment or demonstration of ecological impacts. There are more studies on birds than fish and invertebrates.
- Very limited spatial cover per species and environments. Lack of repeated sampling over time. This is key to increasing our understanding of occurrence and contamination trends.
- Increasing sample numbers will boost assessment robustness and is key to allow linking microplastic presence with physical and chemical impacts.
- Comparisons across regional and global assessments undermined by method heterogeneity (including sample preparation, sieve and plastic sizes targeted, among others). Also, discrepancies in quality and contamination control (or in the reporting of these procedures).
- Very few studies link microplastics in organisms with environmental loads (i.e., simultaneous assessments of water and/or sediments). Critical to investigate main source (water vs sediment), and compare availability, environmental sinks, or variations in selectivity/preference.
- For birds – Microplastics found in the majority of specimens. But information on sizes <1 mm is almost absent. All studies, bar one, use the naked eye to identify microplastics. Hard to discern if contamination is strictly microplastics or includes larger debris based on the information provided with polymer validation also lacking.
- Sampling in birds generally based on necropsies leading to a potential bias associated with mortality.
- For fish and invertebrates, sampling often focused on specimens collected from seafood markets. A clear focus on small microplastics (<1 mm) but often limited spatial and temporal information. Fibres are prevalent but no further confirmation of source.

Summary for beach surveys

- Main research of peer reviewed literature on beach surveys is to document the presence of plastic debris in coastal environments.

- Limited information on microplastics. Beach surveys focus mostly on debris visible to the naked eye, and often do not target microplastics or report only larger microplastics (i.e., microbeads or fibres likely too small to be sampled effectively). In beach surveys that integrate larger microplastics (>1 mm), information is often amalgamated with larger debris and not extractable.
- Opportunity for broad sampling, with beach surveys having demonstrated broad scale and long-term trends, including variations in debris abundance linked to policy and management changes (e.g., container deposit schemes, ban on single-use plastics legislation).
- Volunteer collections of debris with adequate training and supervision may not compromise data quality (van der Velde et al. 2017), but there are shortcomings and limitations linked to collection, contamination and other operator or activity-related conditions that will apply for smaller microplastics.
- Citizen science builds awareness. In doing so, engagement may promote caretaking actions (e.g., reduce, reuse, recycle, and other community interventions) that in the long term may reduce the entry of plastics into the environment.

Summary of microplastics from other key sources

- Literature focus on evaluating WWTP, road dust and stormwaters as microplastic sources.
- WWTP treatments are efficient, but they still release significant loads of microplastics due to the large volumes of effluent released.
- Effluent emissions release microplastics directly into aquatic environments. But treated biosolids, when used as fertiliser transfer microplastics to landscapes and/or make them available to enter aquatic environments.
- The presence of tyre wear was confirmed in road dust, but studies only undertaken in VIC. Lack of reliable information across the three states on the occurrence and fate of microplastics in road dust, including tyre wear or rubber crumb.

2.2 Sector-specific synthesis of information on microplastics

Building on the information compiled from the literature review we engaged directly with different stakeholders to synthesise current research interests, actions and data across government agencies, water services and Non-Government Organisations (NGOs).

2.2.1 Government agencies

The Australian Institute of Marine Science (AIMS) through the Australian Ocean Data Portal (AODN) has made available data on micro debris including the characterisation (e.g., size, shape, polymer) and estimated concentration of marine plastics (<5 mm) in waters around Australia from surface net tows. This database includes information from Reisser et al. (2013, see literature review), as well as data collections in 2020/2021, in sites in SA (Gulf St Vincent, Spencer Gulf), VIC (Bonney Coast) and NSW (Port Hacking) (Total 103 microplastics <5 mm) (AIMS 2022).

In NSW, the Marine Estate Management Authority (MEMA) is undertaking a Marine Debris Threat and Risk Assessment (MDTARA) aimed at examining the risk posed by different debris items, including microplastics, and identifying priority threats to the marine estate. The assessment is based on available information and expert elicitation (on potential consequences and likelihood). Work is ongoing but it is recognised that the low coverage and absence of detailed spatio-temporal mapping of microplastics is a key knowledge gap that needs to be addressed and which is being examined. In addition to the collection of surface water microplastics in Port Hacking (AIMS 2022), NSW MEMA has collected >190 samples from 50 different coastal-estuarine areas (using the same methodology) as well as collaborating with AUSMAP (Australian Microplastic Assessment project) (See section 2.2.3, NGOs) for the monitoring and collection of microplastics in beaches (12 sites, with single sampling and multiple sampling times).

The NSW EPA instigated a study with CSIRO and Sydney Water to characterise the presence of microplastics in wastewater influent and effluent samples in two WWTPs (primary and tertiary), as well as optimising an analytical method and evaluating variations over 10 months (Williams et al. 2020). High removal rates were found (e.g., up to 79% primary treatment or 98% tertiary treatment; although occasionally minimal removal was apparent). From influents with up to 14,000 million microplastics per day, wastewater discharges were estimated to contain between 5,400 and 350 million microplastics per day, depending on WWTP and treatment [similar magnitude as Ziajahromi et al. (2021)]. The project also included a chemical hazard assessment of microplastics and associated chemicals in treated wastewater (Williams 2020b, a). This area of research is key to understanding biological impacts and the risk of harm from the chemical compounds present in microplastics. Whilst there were low concentrations of contaminants (ng/L) and low concentrations of microplastics, bisphenol A and triclosan were released from microplastics in conditions simulating the gut environment of marine organisms, suggesting microplastics can act as a potential vector of contamination once ingested.

The State of the Marine and Coastal Environment 2021 (CES 2020), synthesises the latest information available on microplastics for VIC, in particular in Port Phillip Bay. There was no specific or sufficient information for other areas (Western Port, Corner Inlet-Nooramunga, Gippsland Lakes) provided. The status report is based on data from NGOs (see below, section 2.2.3 and peer-reviewed literature) (CES 2020). The report attributes a deteriorating trend for Port Phillip Bay. Despite estimates of the number of microplastics flowing into Port Phillip Bay, the status is ascribed as unknown, as there is an absence of thresholds to guide effective assessment. Developing impact thresholds is critical to improving future reporting.

Overall, government agencies highlighted the importance of comparable methods that enable monitoring and allow clear measurable metrics to be established. The importance of determining how rainfall (run-off, stormwater and river flow) influences the entry of microplastics into coastal environments, and the thresholds that may mobilise particles. As well there is a need to translate the occurrence of microplastics in terms of risk, as information needed to establish environmental and water quality guidelines is still uncertain. For dissolved chemicals we can rely on concentrations, but for microplastics the key metric that relates to environmental and biological threats has not been clearly defined. Microplastics comprise a universe of particles and compounds where volume, size, polymer type, and sorbed chemicals may all play different roles. In particular, government agencies highlighted the importance of evaluating the potential risk and impacts of different polymers, so this can be related to their occurrence in the environment. An understanding of the sources that are releasing particular microplastics (e.g., specific industry or consumer products) may provide the conditions to develop preventive, mitigation or regulatory measures.

Across the three states, there is a large investment in the collection of information together with community groups and NGOs. Many local councils are actively engaged with local communities, promoting citizen science activities related to microplastic contamination with information generally incorporated in citizen science databases (see section 2.2.3).

2.2.2 Water utilities

Many water utilities are involved in research projects, with findings of previous or current research reflected in the synthesis of published literature (e.g., Ziajahromi et al. 2017, Raju et al. 2018, Raju et al. 2020, Ziajahromi et al. 2021). For water utilities, research is primarily directed towards understanding the volumes of microplastics in the wastewater network and either being released to waterways or captured and ending up in landfill or biosolids. In essence, gathering information on the efficacy of WWTP, and collecting long-term trends of microplastic levels in influent, sludge (landfill), biosolids and effluent.

Water services aim at building knowledge that justifies investments, highlighting that quantifying and removal of microplastics is achievable, but to establish water quality guidelines a further understanding of harm and risk thresholds is needed. Methodological refinements and standardising monitoring are also key points that will also contribute to increased shared knowledge and controlling monitoring costs. Current projects are assessing temporal variability in microplastics in WWTP, how different treatments perform, as well as unravelling the major contributing sources or consumer products that generate microplastic loads entering WWTP. For instance, in addition to the collaborations with government agencies mentioned above (section 2.2.1), research from UNSW, together with Melbourne Water and SA Water among others, is investigating methods to avoid, intercept or redesign products and how these alter or reduce fibre emissions, as well as evaluating the ecological impacts of relevant concentrations of microplastics. Other examples include collaborations between South East Water and RMIT University on spatio-temporal variations on microplastics over time at WWTP with different treatment processes, as means to achieve improved microplastic removal. Water utilities across SA and NSW are also measuring microplastics in biosolids and investigating their fate in soil/crop systems. The relevance to the coastal systems of this research is that in addition to impacts on land, these microplastics may then be available to enter the aquatic system through runoff.

2.2.3 Non-Government organisations

As illustrated by the literature review, information on microplastics is spatially and temporally restricted. Documenting the occurrence, sources, and trends of microplastics at large spatial and temporal scales is challenging. There has been a strong focus toward forming systematic robust approaches and datasets on coastal debris that can be applied at a national level. Initiatives such as CSIRO's National Marine Debris program have provided information on long-term variations in beach litter associated with local waste management and the implementation of strategies that boost the stewardship of coastal areas (Hardesty et al. 2017b, Willis et al. 2022). A key aspect of this program is engagement with the community. Many NGOs, beach clean-up and citizen science activities are strongly invested in building awareness of the issue of microplastics, but also document and understand the presence of plastic debris in coastal environments, and are important in the overall assessment of the microplastic issue as they add to the spatial coverage of microplastic studies. In SA, VIC, and NSW, surveys from Keep Australia Beautiful, Adopt-a-Spot, Tangaroa Blue Foundation and the Australian Marine Debris Initiative, or Port Phillip EcoCentre have collected a wealth of information on plastic debris but in many instances the lower limit of collection is >5 mm (e.g., Smith & Markic 2013, Gacutan et al. 2022) – thus missing microplastics which require a different data collection approach.

In this context, NGOs have been developing initiatives to focus specifically on microplastics. AUSMAP (Australian Microplastic Assessment Project) is a citizen science project surveying shorelines nationwide to map hotspots of microplastics (since 2018). AUSMAP applies a consistent method (replicated quadrats along a transect at the high tide or flood line) to collect rigorous data on microplastics between 1 mm and 5 mm in the top 2 cm of surface sediments. Repeated collections also help determine seasonal differences. Samples go through a quality assurance/ quality control vetting process, with subsets tested for polymer and contaminant analysis with project partners. While the project recognises this only provides a snapshot of the full microplastic range that is potentially at a location, it allows managers and the community to be aware if a hotspot of pollution may be occurring.

The AUSMAP interactive hotspot map is available online (https://www.ausmap.org/hotspot-map) and locates where and how much microplastic (average of microplastics$\cdot$m^{-2}) together with a breakdown of colour, shape, size and type. Whilst execution requires training, the AUSMAP approach has been undertaken by different action groups and citizen scientists, with all data acquired with the same protocol and comparable. As of 2022, there have been a total of 32, 16, and 107 different coastal sites monitored in SA, VIC and NSW, respectively. Major hotspots identified include West Lakes in SA and Cook Park in Botany Bay (NSW), with over 1000 microplastics$\cdot$m^{-2}. In addition, regular monitoring across multiple sites allows information on trends in occurrence and variations in types of plastic to be extracted, and AUSMAP data have supported monitoring and management options (e.g., NSW plastics plan). The AUSMAP programme is also investigating the source of microplastics that flow through sub-catchments and drains with arrays of stormwater nets and collectors, aiming to identify locations of origin. This AUSMAP programme is integrated in the Community Litter Program and NSW Plastics plan (NSW EPA) as a tool to build baseline information and monitor microplastic presence, aiming to evaluate if the regulator's actions have been effective.

Tangaroa Blue Foundation and the Australian Marine Debris Initiative (AMDI) use a consistent monitoring methodology to mostly compile information on macro litter and plastic debris >5 mm (AMDI database available at - https://amdi.tangaroablue.org/). They have specific programmes targeting microplastic, and collaborate with AUSMAP to conduct microplastic assessments. This includes microplastic nurdles found in the area surrounding Port Phillip Bay (VIC) (AMDI and AUSMAP databases). Overall, the AUSMAP and AMDI databases are major repositories providing information for broad, long-term assessments (e.g., Gacutan et al. 2022).

Monitoring land-based sources of marine debris (AMDI 2020), project “Let’s Strain the Drains” used litter traps in stormwaters to quantify inputs of debris including microplastics to Port Phillip Bay. In six months, 677,000 pieces of microplastic were collected in 120 traps. Industrial precincts had increased loadings and demonstrated clear source areas for pellets (nurdles). Building on this success, a follow-up project (Operation Clean Sweep) included monitoring of stormwater drains specifically to assess the introduction of plastic pellets (AMDI 2020). This was done in collaboration with EPA VIC, and engagement across land sources (factory, transport and distribution owners and operators) showed the potential of these interception approaches.

Another NGO with a wealth of information on microplastics is the Port Phillip EcoCentre. Projects and data include a study on microplastics (1-5 mm) from 113 monthly manta net (330 µm) surveys conducted in surface waters of the estuaries of the Yarra and Maribyrnong rivers (2015-2020) (Charko et al. 2020). Over 45,000 pieces of microplastics were collected over time, with hard microplastics dominating (>74%), and around half of all microplastics smaller than 2 mm. This established a baseline of microplastic contamination that can be used as a benchmark for litter reduction initiatives. The multiple years of data are a major benchmark, and this project also performed polymer validation, with polyethylene pieces comprising c. 50% of all samples. A clear increase in microplastic loads was found in summer as well as over the years associated with population increase. Port Phillip EcoCentre also conducts beach surveys (12 locations around Port Phillip Bay), where repeat sampling across 3 years illustrated the contamination of the bay by nurdles (Charko et al. 2020). In addition to nurdles, between 16.7 and 123.2 microfibres·kilogram of sand^{-1} were found in the bay (Sustainability Victoria 2019). These data are integrated in the Australian Marine Debris Initiative database.

The geographical and temporal scale of NGO assessments is larger than that obtained from researchers. Nonetheless, there are potential limitations that need to be considered. Namely, validation processes over time are critical to ensure the accuracy of citizen science approaches and that data are comparable, including to those collected by researchers (van der Velde et al. 2017). Interception and clean-up data often lack density or links to environmental data (e.g., stormwater flow), so comparability can be restricted. Another issue is microplastic data not being separated from other larger debris. Approaches such as those undertaken by AUSMAP and Port Phillip EcoCentre for microplastics are designed to be scientifically robust, but that is not always the case, with beach clean-ups lacking clearly defined, systematic and independent/random collection locations and strategies (see Underwood et al. 2017). This is critical for accurate comparisons. Moreover, whilst there is a large amount of information it is spread across diverse platforms, whereby a centralised, systematic collection portal would be beneficial – with the Department of Climate Change Energy, the Environment and Water (DCCEEW) in partnership with CSIRO recently initiating the development of a National Plastic Pollution Portal to centralise data on plastic pollution. Ultimately, one limitation of even these approaches is they still lack information from small microplastics <1 mm, in particular considering that both smaller fractions and fibres are often the most abundant ones (Charko et al. 2020, Roychand & Pramanik 2020).

Citizen science and engagement initiatives do not resolve the issue of microplastic contamination but build awareness and promote custodianship which can aid in abating the use and improper waste of plastics with potentially improved outcomes regarding environmental contamination. One of the overlooked aspects of citizen science and community clean-up programs is that they indicate the public's concerns about primary and secondary microplastics, as well as the uptake of professional science generated information. Whilst concern about ecosystem impacts from microplastics has been raised through media, amenity is also identified as a value threatened by marine plastic pollution. Amenity is identified as a perception of beach users of a location's elements that provide a positive, enjoyable benefit (Frampton 2010) and is listed as an environmental value [e.g., Environment Protection (Water Quality) Policy 2015 (SA)]. People avoid beaches with visible litter, (Krelling et al. 2017) and public awareness about microplastics on beaches in south-eastern Australia shows that the public would be willing to pay a levy to reduce microplastic pollution on beaches (Borriello & Rose 2022). The very existence of citizen science programs focusing on marine plastic pollution strengthens the case for policy change and management action to address the sources of primary and secondary microplastic pollution.

2.2.4 Individual stakeholder engagement and overarching research priorities

Engagement with stakeholders and end-users across the four sectors (academic research, government, water utilities, NGOs) were undertaken at the same time we compiled the literature review. This was pivotal to synthesising information from non-published sources, whilst also providing a forum for broad discussions to evaluate perspectives on the scale of the problem, research priorities, knowledge gaps and solutions for improved management of microplastics. Together with points raised from the literature review, three main overarching gaps and research priorities were evident:

- Method harmonisation to increase reproducibility and comparability *(i.e., establishing standardised guidelines)*
- Mapping occurrence of microplastics and reconstructing sources *(i.e., repeated sampling, spatiotemporal variation, how much and where; allied to source identification and pathway reconstruction)*.
- Risk of harm to individuals and ecosystems *(i.e., quantifying physical and chemical impacts of different microplastic)*

This shared understanding was the groundwork for the subsequent expert elicitation in the organised workshop and surveys.

3. Webinar and survey summary

The management of microplastic pollution in the marine environment is challenging and still nascent enough that engagement with a broad array of stakeholders and researchers is important if management solutions are to be sought at a multi-state (national) level.

Webinar

A workshop was held online (webinar) on July 22nd, 2022, bringing together 84 representatives from state and federal government agencies, academic researchers, water industry, as well as NGOs and other consultants and collaborators. The goal was to elicit expert opinion across sectors on what gaps and research needs are the most critical to supporting evidence-based policy, regulation and management. The workshop provided a cross-sector forum for knowledge transfer to identify solutions, lessen barriers and identify opportunities to ameliorate, mitigate and manage issues related to the presence of microplastics in coastal and marine environments. It provided an opportunity to broaden the discussion of key issues and options for future research and evaluate the cross-sector relevance of issues highlighted by individual stakeholders.

All major comments, identified gaps and cross-sector recommendations raised in the webinar are integrated in the final recommendations section of this report (section 4). Here we outline key points discussed among sectors that highlight areas benefiting from concerted efforts.

- The discussion highlighted examples of ongoing projects showcasing how interactions and synergies among the different sectors can produce collaborative research, innovation and capability building in the environment and water research space to safeguard environmental resources and public health (e.g., water industries and academic research). The webinar hopefully acted as a trigger to expand networks further and develop new collaborations.

- Considering the widespread presence and release of microplastics, engagement across sectors was recognized as essential. There were calls for more centralised and coordinated strategic efforts towards promoting a thorough understanding of exposure risks and consequently identifying opportunities to reduce environmental contamination and promote consistent management of potential source sites/industries/pathways.

- The importance of understanding the interaction between the physical effects of microplastics and their chemical effects (additives or adsorbed contaminants) was discussed. The effects of microplastics carrying contaminants to ecological systems may be distinct from the presence of the toxicant alone in the environment. Microplastics were described as a gateway contaminant where they carry contaminants, and due to their diversity (size, shape, polymer, leachates, weathering) it is important to move away from describing (micro)plastics as a single contaminant and rather see them as a complex gamut of potential contaminants. This is particularly relevant from a risk-based regulatory perspective, and to guarantee resources are directed at key compounds.

- All sectors highlighted the need to develop best practices for sampling and monitoring, as well as understanding microplastic risk and if there are (groups of) species that are more sensitive than others. Current tests and assessments to quantify plastics are expensive. Developing alternatives, and harmonising methods across research and industry can contribute to reducing costs and boosting data integration, including maximising research on environmental loads and release, partition, and removal of microplastics from specific sources.

- Concerns were raised regarding the mere documentation of microplastic occurrence based on inadequate sampling strategies, in particular, assessments that discard smaller microplastics. A need to conform to recognised scientific methods (e.g., structured surveys, randomization) that allow linking occurrence to biological and ecological impacts (i.e., first establish correlations, and then look at what is causing those effects) was identified. There was general agreement that there is a lack of good quality evidence on ecological impacts, and a need to translate sub-organism or individual impacts to higher level effects.

- Opportunities to build on citizen science were highlighted as a means to build awareness and community development beyond potential data collection limitations. An issue raised was how citizen science programmes can safeguard amenity concerns regarding microplastics, and boost calls for management action as they reflect public concerns beyond research and regulatory stakeholders. It was argued that investment and prioritization on a scale required to support large-scale detailed scientific methods may only be forthcoming if the wider community is aware and calling for action on microplastics, as funding priorities will reflect community perspectives.

Online survey

An online survey was distributed to broaden the reach of the project as well as collect anonymous information ranking key threats and research priorities (Appendix D). A total of 54 responses were received. Respondents came from different professional backgrounds (30% from State government agencies, 13% Federal government agencies, 19% Industry, 19% Academic research, 11% NGOs, other 5% and 3% local council representatives and consultants, respectively). Overall, 43 % of respondents identified their primary role as researchers, with respondents generally having a broad range of experience in microplastics related research (from 20% with less than 2 years to 26% with more than 20 years).

The survey had two key parts. In the first, participants were asked to express their expert opinion on *i)* the five main sources/pathways of microplastics to coastal environments, *ii)* the main gaps in our understanding of the impacts of microplastics, and *iii)* the short-term goals and priority research needs. In the second section, participants were asked to rank different potential sources and pathways in terms of importance regarding *iv)* microplastic loads, as well as, v*)* their potential risk or threat to ecological communities. In the following questions, participants ranked *vi)* priority research areas, and critical questions regarding vii*)* methodological procedures and *viii)* the risk of harm of microplastics to biota.

There was general agreement when identifying the main sources and pathways that are contributing to the presence of microplastics in the environment. These generally indicated improperly managed waste and the breakdown of larger debris (including from synthetic clothing, construction, shipping, and fishing), wastewater discharges, stormwater runoff, and accidental or mismanagement of pellets and nurdles. Specific issues such as road dust, tyre wear and potential concerns related to the use of rubber crumb (e.g., sports fields and other applications) were also highlighted.

Gaps in knowledge generally encompassed the need to characterise loads, sources and sinks, as well as the factors governing spatiotemporal variations; the importance of better understanding the tangible impacts (both physical and chemical) on ecosystems; and improve our understanding of microplastics as vectors of contamination through proper experimentation at environmentally relevant concentrations and conditions. Other gaps reflect the lack of comparable data, cost-effective analyses and assessments for <1 mm microplastics. A few examples of responses include:

- "*lack of standardised measurement methods, lack of understanding of loads, sources, sinks and behaviour of microplastics*", or lack of "*quantification of sources and sinks using consistent methods*".
- "*lack of spatial temporal variations in occurrence, repeated sampling, [and] data mismatch resulting from distinct methodological approaches; understanding effects and risk of harm of microplastics including different polymers*"
- *"We lack a standardised set of methodologies, so there are difficulties in comparing microplastics research. Additionally, we need to move onto the effects of microplastics in the environment, and how this might change population structures of species, or the general functioning on the marine environment."*
- "*need [laboratory] studies done with MP forms that are environmentally representative, both in terms of composition (e.g., many studies in polystyrene but this is not common in the environment), but also in terms of properties (e.g., virgin vs aged, [but also] most studies done without biofilm, though biofilm likely plays role in both uptake by organisms and as chemical vector)*" Quote edited for synthesis and clarity.
- On the importance of collaboration among stakeholders, one respondent added: "*sectors bound by different responsibilities tend to focus on different objectives. e.g., water supply and waste water treatment managers are concerned with identifying and quantifying pollutant loads; and not-for-profit community-based organisations tend to focus on identifying and documenting common plastic pollution products and point sources, with a view to advocacy on product stewardship and consumer behaviour change. Both aims are legitimate and important; and both sectors should support each other and look to the possibility of stronger collaborations*."

There was an expected overlap between the main gaps and the key short-term priorities highlighted by participants. Overall, responses outlined the importance of defining sampling, collection and processing standards for multiple matrices, using these to initiate long-term consistent monitoring and promote a better understanding of what are the microplastics of concern in Australia. At the same time participants emphasised the importance of gathering risk information to guarantee research, prevention and remediation funding is prioritised to key areas and potential compounds of concern. Some responses also highlighted the concurrent need to focus upstream and focus on the reduction of use, waste control and management, moving towards a circular economy.

A few representative responses included:

- *"long-term monitoring and setting standard data collection and consistent monitoring program".*
- *"determine 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. Results will inform where new source reduction initiatives are necessary and if existing source reduction plans are working".*
- *"Consolidate data" (e.g., national plastics portal).*
- *"estimate and identify sources upstream (follow drain and stormwaters) for different polymer types and contamination levels".*
- Assess *"removal, remediation options and their effectiveness", as well as "education and mitigation strategies"*
- *"Better understanding of what the microplastics of concern are in Australia. Where are they, what are they and what impact are they having in coastal, marine, riverine and terrestrial environments".*
- *"Demonstrate harm - Volume, size, polymer, which are the environmental metrics that relate to risk of harm."*
- Assess *"toxicity risk at environmentally relevant levels"*, as well as breakup with *"plastics to enter cells, adsorption of chemicals and transfer to biota".*

In the second part of the survey, participants ranked different issues or questions according to the following scale:

1 – Highly important, OR highly important, critical research priority, OR critical need/gap to inform management and policy development.
2 – Important, OR important but not crucial primary research priority, OR important need/gap but not the top priority needed to inform management and policy development
3 – Relevant, OR interesting research foci but not a priority, OR interesting need/gap to address but not key to inform management and policy development
4 – Unimportant, OR trivial and not relevant research foci, OR not an important need/gap to inform management and policy development
5 – Unsure/don't know

Regarding the importance of different sources and pathways and their contributions to plastic loads in coastal environments, participants ranked on average stormwater and other untreated outflows as the most important, followed by fibres from textiles, breakdown of larger pieces and direct entry of pellets/nurdles into the environment (Figure 4, Appendix D). Overall, c. 77% of participants classified stormwater and other untreated outflows as highly important.

On the importance of different sources and pathways and their threat to ecological communities, 64% of participants ranked the breakdown of larger pieces of plastic as highly important. On average, this was the most important threat followed by stormwater and other untreated outflows (Figure 4, Appendix D). However, compared to the previous question on loads and contributions, there was less accord in scoring these sources and pathways regarding their threat, with larger variations in ranking from highly important (score 1) to relevant (score 3) among each category.

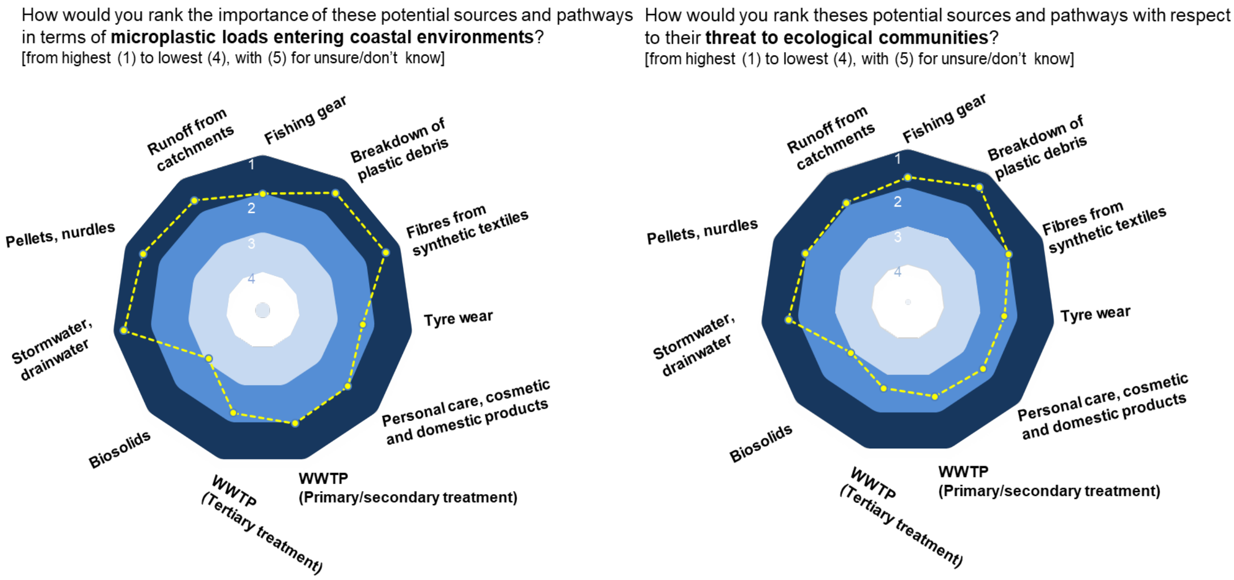

Figure 4: Radar plot of the average ranking score of all participant responses on sources and pathways of microplastics regarding their importance in load contributions (left) and threat to ecological communities (right). Options were ranked from 1 (highest/critical priority – dark blue outer ring) to 4 (unimportant – light blue inner ring), with a score of 5 do not know or unsure. See appendix D for the full questionnaire.

Focusing on critical research areas to support management, on average the highest-ranked priorities were quantifying and understanding the occurrence, sources, and distribution of microplastics in coastal environments; and understanding risks to the environment, impacts and thresholds of harm to biota; with 77% and 68% of respondents ranking them as a high priority (score 1), respectively (Figure 5, Appendix D). This was closely followed by linking contamination to environmental harm and improvements to method standardization. Of all presented options, the lowest average scores were for documenting ingestion of microplastics and modelling the transport and distribution of microplastics, but it is important to note that all the categories had >50% of participants attributing them a score of 1 (top tier), highly important research area, illustrating the combined importance of these research areas.

Regarding methodological procedures, participants identified the need to define standardised and validated methods for microplastic research, with 82% of participants ranking this as a critical/highly important need - the highest across all questions in the survey (Figure 5, Appendix D). The second methodological priority concerned the interconnecting need to identify the best sampling and reporting methods. For the remaining option, the majority of participants ranked them mostly as important (score 2) or relevant (score 3).

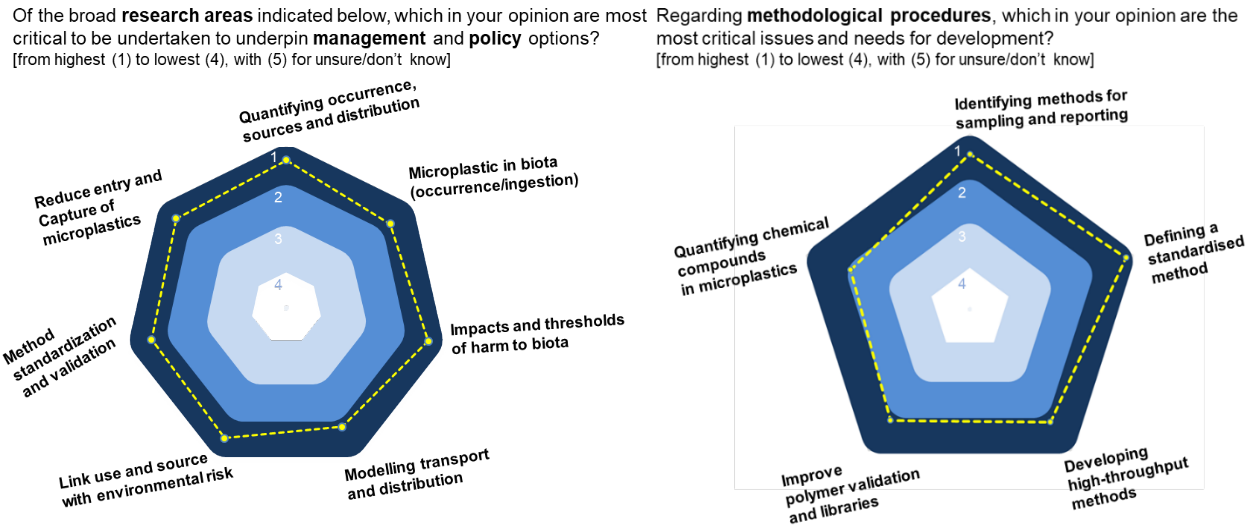

Figure 5: Radar plot of the average ranking score of all participant responses on key research areas to support management (left) and critical issues and needs regarding methodological procedures to support research in microplastics in coastal environments (right). Options were ranked from 1 (highest/critical priority – dark blue outer ring) to 4 (unimportant – light blue inner ring), with a score of 5 do not know or unsure. See appendix D for the full questionnaire.

In the final question, participants were asked to rank, in their opinion, which are the most critical gaps and research needs regarding the risks of harm of microplastics. The top two priorities comprised understanding the thresholds at which a particular type of microplastic elicits negative chemical, and physical effects, with over 71% of respondents ranking these as highly important, critical research needs (score 1) (Figure 6, Appendix D). The third overall ranked priority was the need to define guidelines and information to conduct risk assessments on microplastics (62% of respondents scored this as highly important). Interestingly, the lowest ranked option was related to moving the primary focus from microplastics to nanoplastics.

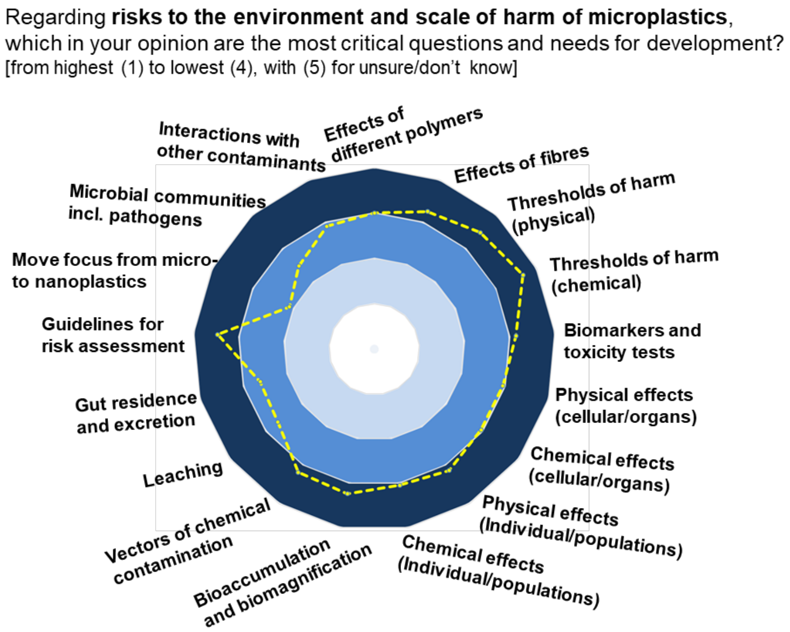

Figure 6: Radar plot of the average ranking score of all participant responses on the critical needs for development to understand risks to the environment and the harm of microplastics to the marine and coastal environments. Options were ranked from 1 (highest/critical priority – dark blue outer ring) to 4 (unimportant – light blue inner ring), with a score of 5 do not know or unsure. See appendix D for the full questionnaire.

Overall, responses to surveys illustrated the need and importance of standardised methodologies, with this particular query achieving the highest agreement among all questions in the survey. The combination of the webinar and survey provided added details on end-users perspectives regarding future directions and incentives for microplastics research, as well as main areas of concern. These include attention to the effects of different microplastics or the need to gather further information on the effects of different polymers to improve risk assessment and allow an understanding of thresholds of harm of microplastics to populations and ecosystems. Whilst individual concerns regarding tyre wear and road dust were highlighted in the webinar as well as in previous engagements with the different stakeholders, this was not so clearly illustrated in the surveys.

4. Knowledge gaps, research priorities and recommendations

This section integrates information from meetings with stakeholders (academic research, government agencies, water utilities and NGOs), as well as the findings and outcomes of the webinar and survey.

As a result of the engagement with a broad array of experts and stakeholders, this scoping project has identified and summarised major key knowledge gaps and cross-sector priority needs and recommendations for improved monitoring and management of plastic pollution in Australian coastal environments. These are summarised below, and framed under the three main overarching themes identified across the project, namely the need to *i)* refine methodological approaches and enhance data comparability, *ii)* understand the source and environmental occurrence of microplastics, and *iii)* demonstrate the risk of harm to individuals and ecosystems. The cross-sector engagement process provided a clear-sighted focus on research priorities that respond to end-user needs. It identified major foci for improved monitoring and management that can be sought through collaboration and shared understanding, striving towards multi-state (national) level application and contributing to actions that can support meaningful policy and management strategies for microplastics in coastal environments. Within the three overarching themes, the following priority scientific information needs and recommendations were identified:

Method harmonisation to increase reproducibility and comparability

- Participants and literature echoed the need for a coordinated effort to harmonise data collection and adopt reliable, reproducible and standardised methods for microplastic quantification and characterization.
  - There was generalised strong support for establishing accurate, comparable, reproducible and transparent guidelines for microplastics assessments. These should cover all aspects from sample collection, extraction/digestion, and microplastic characterisation (i.e., size, shape/type, and polymer composition, as well as terminology and units used).
  - Emphasis was given to the importance of robust quality assurance and quality control procedures (QA/QC) in sampling and analysis. Namely, the use of appropriate contamination (field and lab blanks) and procedural controls; allied to tying experimental design to the specific research question being asked, and conforming to structured replication requirements (i.e., suitable experimental design, and replication to guarantee statistical power). Experts highlighted no single size fits all approach will be readily available, hence the importance of accurately specifying environmental matrices and the research question being investigated.

  Reason for prioritization: Method standardisation in the collection and reporting of microplastics in coastal environments and across the different environmental matrices is fundamental and of paramount importance to combat the lack of comparable data and poor spatio-temporal understanding of microplastic occurrence. It is also key to high-quality outputs that are widely applicable across multiple stakeholders, and in doing so promote better access to robust information. The development of quality assessment procedures can be tied with inter-calibration exercises to maximise comparisons to past data and allow incorporation with ongoing sites/monitoring.

- Strong support to boost quantification and characterisation of smaller microplastics (<1 mm) for which information is comparatively scarce but likely more relevant regarding ecological impacts.

    - Experts emphasised the importance of polymer validation to reduce uncertainty (i.e., under or overestimation) in confirmation of plastic material and to improve the capacity to potentially identify the microplastic source and subsequent links to impacts.

    - Continued technological innovation enabling high throughput approaches for microplastic quantification and identification was also emphasised.

    - Concerns were raised regarding adapting approaches from beach survey plastic debris assessments for this size range, as *in situ* naked eye assessments miss micrometre-sized particles, and lack of polymer validation can bias quantification and limit source identification.

    - Points raised than a further transition to smaller micro and nanoscale (<1 μm) plastics (not the focus of this report) will require different and specific methodological approaches (including strict QA/QC and instrumentation).

    Reason for prioritization: Increased quantification allied to increased efficiency of methods for low levels of small sizes are essential to validate microplastic identification, as well as understanding the occurrence and concentrations of microplastics across all environmental matrices. This is fundamental to establishing present-day baselines for management. Automated or semi-automated high throughput approaches are key for cost-effectiveness and expanded application.

Mapping occurrence of microplastics and reconstructing sources and pathways

- Characterise environmental distribution and abundance of microplastics to define present-day (baseline) environmental levels across multiple matrices and build long-term monitoring programmes.

    - Building on comparable approaches, experts highlighted the need to document how much and where microplastic occurs, and if they are accumulating. Noting that mapping occurrence and determining pathways, sources and accumulation likely require tailored approaches.

    - The need for centralised, easily accessible databases was highlighted as a step towards data consolidation and faster identification of hotspots and changes in microplastics levels over time and space. A National Plastic Pollution portal is currently under development by the DCCEEW and CSIRO.

- Evaluate opportunities to leverage citizen science approaches to gather broad-scale larger microplastic information at broad spatiotemporal scales. Whilst harnessing the large-scale and repeated nature of these actions provides a window to gather broad and long-term data, concerns were raised regarding its applications to smaller microplastics. Recommendations and options focused on the need for method development and harmonisation to guarantee more robust data, ensure structured and randomized sampling, and identify opportunities to calibrate results and polymer validation.

  Reason for prioritization: Knowledge of how much, where and what type of microplastics is essential for management purposes. There is a paucity of routine long-term monitoring as well as studies undertaking repeated sampling and documenting variations in microplastic occurrence over time. Efficient monitoring programmes can be built together with the development of harmonised methodological approaches, as well as integration into widely accessible databases. Moreover, monitoring underpins evaluations of changes in the environment, and is critical to evaluate long-term trends and effects in the environment; as well as to both provide evidence to support policy changes and assess the impact of legislative measures and actions.

- Reconstruct sources and pathways of microplastics, and understand the environmental and anthropogenic factors driving variations over time and space.

  - Investigate spatiotemporal variations in inputs of microplastics (e.g., associated with stormwater, river discharges, currents, anthropogenic activities). And assess how plastic and polymer characteristics (e.g., size, type, buoyancy) influence transport, as well as evaluate the thresholds that govern particle mobilisation.

  - Modelling approaches were identified as a powerful tool to simulate and predict the patterns of microplastic contamination, including their flow from river catchments and via ocean currents. Nonetheless, this must be underpinned by a further understanding (calibration, validation) of how the properties of different plastic properties (e.g., size, type, buoyancy) and degradation influence movement and deposition.

  - The need to further understand the implications of using biosolids (from WWTP) in agriculture and the potential mobilization of microplastics to aquatic environments was also highlighted. This will need to be tied with opportunities to reduce loads as well as evaluations of the benefits of biosolid use.

    Reason for prioritization: To understand potential impacts and avenues for mitigation we need to know where microplastic contamination is coming from and how much. Descriptions of occurrence are the first step but need to be supported by an understanding of the factors governing dispersal, accumulation and deposition. Only by doing so can we put the spotlight on the factors governing contamination hotspots and use that information to assess risk, and support management and mitigation efforts. Knowledge of the importance of sources and pathways [e.g., microbeads or fibres in cosmetics and textiles (sources) from WTTP (pathway); or tyre wear (source) from road dust or stormwater(pathways)] is key in designing management strategies for reducing the generation of microplastics, and preventing or intercepting microplastics from reaching aquatic environments.

Risk of harm to individuals and ecosystems

- Beyond occurrence, there was a strong consensus among researchers on the need to understand and demonstrate the biological and ecological impacts of microplastics, together with how microplastics can act as vectors of biological and chemical contamination.

    - Clarifying the drivers of microplastic toxicity is a key challenge. Emphasis was given to measuring the effects of different microplastics and their risk of harm. A key related issue is determining what is the metric that relates more to threat. Microplastics are a complex array of particles where toxicity and impacts may depend on a combination of volume, size, polymer, and chemicals present (e.g., sorbed from the environment or added as plasticizers).

    - Ecotoxicological and dose-response studies are key to understanding the risks and implications of microplastics, and what are the relevant levels of exposure, as well as if there are (groups of) species that are more sensitive than others. Additionally, there is a need to develop approaches to evaluate ecological impacts, namely assess effects at multiple levels of organisation that allow translating toxicological endpoints in individuals to population-level ecological consequences (e.g., growth, reproduction).

    - Toxicological studies need to be designed to reflect realistic scenarios. This includes concentrations, types of polymers, weathering and chemical contaminants present in microplastics. However, researchers highlighted there is some global inconsistency between the microplastic concentrations, types and sizes used in ecotoxicity evaluations (generally high concentrations, of small-sized microplastics e.g., <100 μm) versus those measured in the environment. Here, guidelines for methodological approaches to boost environmental assessments of smaller microplastics can help reconcile this and underpin environmentally representative trials. Another point that was raised is the need to evaluate if the physical impacts of microplastics are different to that of naturally occurring or other similar-sized particles (e.g., sand, natural fibres)

    - Microplastics can act as vectors of chemical contamination, as they sorb/desorb chemicals from the environment (e.g., per- and poly-fluoroalkyl substances (PFAS), pharmaceuticals) or that are added to the polymer at the time of manufacture (e.g., phthalates and other plasticizers). Leaching and uptake processes in biota are still poorly understood, including processes of translocation. Noting that it will be key to disentangle where chemical contamination is relevant compared with water or sediment exposure.

Reason for prioritization: Identifying the relevant thresholds of microplastic contamination that impact biota will underpin management, regulatory and policy development and the definition of environmental quality standards. In particular, if specific sources and microplastic characteristics can be linked to increased risk of harm and environmental impacts. Microplastic toxicity data are limited and hindered by data comparability. But accurately determining exposure risks relies on understanding toxicity (i.e., responses at different levels of organisation, from sub-organism, to individual and population level) together with high-quality environmental data. Environmental levels also help establish the relevant levels for exposure testing. Understanding impacts will allow understanding of the risks of the presence of microplastics in the environment, and support action to guide environmental quality guidelines as well as support mitigation, removal or interception strategies for particular sources/pathways and microplastics of increased concern.

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Appendix A

Table A1: Categories and description of information extracted from individual studies.

Categories	Description
Study ID	Unique study identifier
Citation Summary	First author, year and journal identifier
Location	
Geographic location	Location of study, landmarks, areas described
State	State where study was undertaken
Latitude	Latitude coordinates
Longitude	Longitude coordinates
Environment	Marine, estuarine or freshwater environments
Other Characteristics	Urban, rural, port areas
Sample type	
Water	Yes or No
Sediment	Yes or No
Biota	Yes or No
Survey	Yes or No
Biota group/species	General biota group (fish, bird) and species info
Collection method	Sample collection gear and methodology
Sample Processing	
Organic material removal	
Manual Removal / Observation / Digestion	Type of organic material removal and separation
Digestion	If used, details on the solution used, and time sample digested for
Filtration	
Membrane pore size	Filter size / pore information
Membrane type	Type of membrane/filter
Microscopy	
Viewing apparatus	Instrument used to separate and identify microplastics, or naked eye
Size range counted	Minimum size of plastic that could be identified

Categories Used (plastic types)	Classification and information on plastic types identified (Types, geometry).
Polymer identification	
Method used	Information on method or instrumentation used for validating plastic identification and polymer type identification
Set-up	Method details
Spectra Interference reduction	Was spectra reduction applied, if Yes - range
Databases used	Database used to match and validate plastic identification
Matching factor threshold	Minimum threshold for polymer validation
Percentage tested	Information on % of plastics validated
Contamination control	
Collection	Were any quality control procedures taken during sample collection
Processing	Were any quality control procedures taken during sample processing, Including airborne contamination control
Procedural blanks	Were procedural blanks used
Microplastic Data	
Frequency of occurrence	% of samples with at least one piece of plastics
Microplastic load	Abundance/number of plastics per sample
Units	Units used to calculate microplastic load
Microplastic / Polymer types (mentioned)	Information on main microplastics and polymer types found
Source or impacts (mentioned)	Author comments on potential sources for identified plastics
Reference DOI	DOI info

Appendix B

Table B1: List of papers with information on microplastics in coastal and marine environments in SA, VIC, NSW. Note references may include information for other locations. For full details see supplementary files.

Reference (9)	Sample type	Location
Barrett et al. (2020)	Sediment	SA
Bond et al. (2021)	Biota (bird)	NSW
Browne et al. (2011)	Water, WWTP	NSW
Cannon et al. (2016)	Biota (fish, invertebrate)	VIC
Carey (2016)	Biota (bird)	VIC
Cunningham and Wilson (2003)	Beach survey	NSW
Duckett and Repaci (2015)	Beach survey	NSW
Gacutan et al. (2022)	Beach survey	SA, VIC, NSW
Gilbert et al. (2016)	Biota (bird)	NSW
Halstead et al. (2018)	Biota (fish)	NSW
Hardesty et al. (2017b)	Beach survey	SA, VIC, NSW
Hayes et al. (2021)	Water, Sediment	SA
Hitchcock and Mitrovic (2019)	Water	NSW
Hitchcock (2020)	Water	NSW
Jahan et al. (2019)	Sediment, Biota (invertebrate)	NSW
Klein et al. (2022)	Water, Biota (invertebrate)	SA
Lavers et al. (2014)	Biota (bird)	NSW
Lavers and Bond (2016),	Biota (bird)	NSW
Lavers et al. (2018),	Biota (bird)	NSW
Lavers et al. (2019)	Biota (bird)	NSW
Ling et al. (2017)	Sediment	SA, VIC, NSW
Monira et al. (2022)	Stormwater, Road dust	VIC
Nan et al. (2020)	Water, Biota (invertebrate)	VIC
Ogunola et al. (2022)	Biota (invertebrate)	SA, NSW
Okoffo et al. (2020)	Sediment, WWTP	SA, VIC, NSW
Olivelli et al. (2020)	Beach survey	SA, VIC, NSW
Pramanik et al. (2020)	Stormwater, Road dust	VIC
Raju et al. (2020)	Water, WWTP	NSW

Reisser et al. (2013)	Water	SA, VIC, NSW
Rodriguez et al. (2018)	Biota (bird)	VIC
Roman et al. (2016)	Water, Biota (bird)	NSW
Roychand and Pramanik (2020)	Road dust	VIC
Rudduck et al. (2017)	Water	NSW
Smith and Markic (2013)	Beach survey	NSW
Su et al. (2019)	Biota (fish)	VIC
Su et al. (2020a)	Road dust	VIC
Su et al. (2020b)	Water, Sediment	VIC
Townsend et al. (2019)	Sediment	VIC
van der Velde et al. (2017),	Beach survey	SA, VIC, NSW
Verlis et al. (2018)	Biota (bird)	NSW
Wootton et al. (2021a)	Biota (fish)	SA, VIC, NSW
Ziajahromi et al. (2017)	Water, WWTP	NSW
Other studies do not clearly mention location e.g.,:		
Okoffo et al. (2021)	Sediment, WWTP	-
Okoffo et al. (2022)	Sediment, WWTP	-
Ribeiro et al. (2020)	Biota (fish, invertebrate)	-
Roman et al. (2020)	Beach survey	-
Ziajahromi et al. (2021)	Water WWTP, Sediment WWTP	-

Appendix C

Engagement with institutions through the project. These represent direct contact and meetings. Both the Webinar and Survey had increased reach and national participation.

Australian Microplastic Assessment Project AUSMAP; Commissioner for Environmental Sustainability Victoria; Commonwealth Scientific and Industrial Research Organisation CSIRO; Cooks River Alliance; Department of Climate Change, Energy, the Environment and Water; Department of Environment and Water South Australia; Department of Planning and Environment New South Wales; Environmental Protection Agency New South Wales; Environmental Protection Agency South Australia; Environmental Protection Agency Victoria; Fisheries Research and Development Corporation; Flinders University; Hills and Fleurieu Landscape Board Landscape Boards South Australia; Melbourne Water; Port Phillip Bay EcoCentre; SA Water; South East Water; Southern Cross University; Sustainable Communities and Waste Hub; Sydney Institute of Marine Science; Sydney Water; Tangaroa Blue Foundation; The University of Melbourne; The University of Newcastle; University of Tasmania; University of Technology Sydney; Water Research Australia;

Appendix D

Survey Questionnaire

- Type of Position [Multiple choice]:Academic; Consultant; Government Agency - Federal; Government Agency - State; Industry, Non-Governmental Organisation, Other
- Primary role [Multiple choice]: Consultant; Environmental Policy; Natural Resource Management; Research; Water Services and Quality; Other
- How many years of experience do you have on microplastics [Multiple choice]: Less than 2 years; 2 to 5 years; 5 to 10 years; 10 to 20 years; more than 20 years
- What geographic regions does your role or research cover [Multiple choice]: ACT; Australia-wide; International; New South Wales; Northern Territory; Queensland; South Australia; Tasmania; Victoria; Western Australia
- Please indicate what best describes your knowledge and experience in microplastics [Multiple choice]: I have extensive work/research experience in microplastics; I have some work/research experience in microplastics; I have a general understanding of the issues surrounding microplastics in the environment, I have little or no knowledge of the issues surrounding microplastics in the environment; Other
- Please indicate up to 5 main sources you think are contributing to the presence of microplastics in coastal environments?
- In your opinion, which are the main gaps/limitations in our understanding of the impacts of microplastics in the environment?
- In your opinion, what are the short-term (next 5 years) scientific information and research priority needs regarding microplastics in coastal environments to inform management and policy development?
- In this section, please rank each of options using the 1 to 4 scale below, where 1 is the highest importance and 4 the lowest importance. Use 5 for unsure/don't know or not applicable.

  RANKING ORDER
  1 – Highly important, OR highly important, critical research priority, OR critical need/gap to inform management and policy development.
  2 – Important, OR important but not crucial primary research priority, OR important need/gap but not the top priority needed to inform management and policy development
  3 – Relevant, OR interesting research foci but not a priority, OR interesting need/gap to address but not key to inform management and policy development
  4 – Unimportant, OR trivial and not relevant research foci, OR not an important need/gap to inform management and policy development
  5 – Unsure/don't know

- How would you rank the importance of these potential sources and pathways in terms of microplastic loads entering coastal environments:
  Derelict fishing gear
  Degradation and breakdown of land based plastic debris
  Microfibres from synthetic textiles

Personal care, cosmetic and domestic products
Tyre wear
Waste water outflows (Primary/secondary treatment)
Waste water outflows (Tertiary treatment)
Biosolids
Stormwater, drainwater and untreated outflows
Industrial primary plastics (e.g., Pellets, nurdles)
Runoff and input from catchments
Others (Please specify) _________

- How would you rank theses potential sources and pathways with respect to their threat to ecological communities?

  Derelict fishing gear
  Degradation and breakdown of land based plastic debris
  Microfibres from synthetic textiles
  Personal care, cosmetic and domestic products
  Tyre wear
  Waste water outflows (Primary/secondary treatment)
  Waste water outflows (Tertiary treatment)
  Biosolids
  Stormwater, Drainwater and untreated outflows
  Industrial primary plastics (e.g., Pellets, nurdles)
  Runoff and input from catchments
  Others (Please specify) _________

- Of the broad research areas indicated below, which in your opinion are most critical to be undertaken to underpin management and policy options?

  Quantifying and understanding the occurrence, sources, and distribution of microplastics in coastal environments
  Assessing the occurrence or ingestion of microplastic in biota, including along trophic webs
  Understanding risks to the environment, impacts and thresholds of harm to biota
  Modelling the entry, transport and distribution of microplastics in the environment
  Linking the use and sources of specific microplastics with potential harm or environmental risk
  Method standardization and validation for microplastic assessments
  Reduce entry and capture of microplastics in potential sources (e.g., catchments, drainwaters, outfalls)

- Regarding methodological procedures, which in your opinion are the most critical issues and needs for development?

  Identifying the best methods for sampling and reporting of microplastics in different environmental compartments and biota?
  Defining a standardised and validated method for the assessment of microplastics in coastal and marine environments, including validation, quality assurance and control?
  Developing high-throughput methods for separation, quantification and characterization of microplastics
  Improve the validation of polymers, and respective microplastic libraries, for the effective characterisation of microplastics and reconstructing contamination sources and pathways
  Harmonising citizen science tools to contribute to broad scale data collection
  Identifying and quantifying chemical compounds in microplastics

- Regarding risks to the environment and scale of harm of microplastics, which in your opinion are the most critical questions and needs for development?

  What are the effects of different polymer types on biota?
  What are the effects of fibres from synthetic textiles to biota?
  What is the level/concentration/threshold at which a particular type of microplastic elicits negative physical (sublethal and lethal) impacts on biota?

What is the level/concentration/threshold at which a particular type of microplastic elicits negative chemical (sublethal and lethal) impacts on biota?
Identifying microplastic contamination biomarkers and specific toxicity tests
What are the physical effects of microplastic on cellular processes?
What are the chemical effects of microplastic on cellular processes?
What are the physical effects of microplastic on individual/populations?
What are the physical effects of microplastic on individual/populations?
Does bioaccumulation and biomagnification occur and potentially exacerbate impacts of microplastics?
Are microplastics key vectors of chemical contamination (e.g., POPs, pharmaceuticals, plasticizers) to tissues/individuals?
Can we disentangle effects of plastic versus secondary effects of chemicals leaching out of them?
How do gut residence/excretion processes influence potential negative impacts on biota?
Are microplastics translocating through physiological barriers?
Define what are the guidelines and information we need to conduct risk assessments on microplastics
Move primary focus from microplastics to nanoplastics.
What are the impacts of microplastics on microbial communities, and are microplastics vectors for the introduction of pathogens or invasive species?
How do microplastics interact with other emerging contaminants in the environment?

Marine and Coastal

National Environmental Science Program

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