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Micro(nano)plastics sources, fate, and effects: What we know after ten years of research

Steve Allen[a], Deonie Allen[b], Samaneh Karbalaei[c], Vittorio Maselli[a], Tony R. Walker[d,*]

[a] Department of Earth and Environmental Sciences, Dalhousie University, Halifax, NS B3H 4R2, Canada
[b] Department of Civil and Environmental Engineering, University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ Scotland United Kingdom
[c] Department of Biotechnology, Faculty of Biological Science, Alzahra University, Tehran, Iran
[d] School for Resource and Environmental Studies, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada

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ABSTRACT

The last decade has been transformative for micro(nano)plastic (MnP) research with recent discoveries revealing the extent and magnitude of MnP pollution, even in the world's most remote places. Historically, while researchers recognized that most plastic pollution was derived from land-based sources, it was generally believed that microplastic particles (i.e., plastic fragments <5 mm) was only a marine pollution issue with effects largely impacting marine biota. However, over the last decade MnP research has progressed rapidly with recent discoveries of MnPs in freshwater, snow, ice, soil, terrestrial biota, air and even found in ocean spray. MnPs have now been found in every environmental compartment on earth, within tissues and gastrointestinal tracts of thousands of species, including humans, resulting in harmful effects. The last 10 years has also seen the development of new techniques for MnP analysis, and re-purposing of old technologies allowing us to determine the extent and magnitude of plastic pollution down to the nano size range (<1 μm). This short review summarizes what key milestones and major advances have been made in microplastic and nanoplastic research in the environment, including their sources, fate, and effects over the last decade.

1. Introduction

The last decade has been transformative for micro(nano)plastic (MnP) research with recent discoveries revealing the extent and magnitude of MnP pollution, even in the world's most remote places (Allen et al., 2019. Materić et al., 2020, 2021; Napper et al., 2020; X Peng et al., 2018. Y. Zhang et al., 2020a). MnP pollution was initially thought of as primarily a marine issue (Barnes et al., 2009) with effects largely impacting marine biota (Gall and Thompson, 2015), and mostly derived from land-based sources (Jambeck et al., 2015). It was assumed that all plastic flowed and became trapped in the oceans, the oceans forming the final sink for plastic pollution (Coleman and Wehle, 1984; Thompson et al., 2004). However, MnP research has progressed rapidly through recent discoveries in freshwater (Wagner et al., 2014; Koelmans et al., 2019), groundwater (Chia et al., 2021; Samandra et al., 2022), snow (Bergmann et al., 2019; Materić et al., 2020; Parolini et al., 2021), ice (Bergmann et al., 2016; Ambrosini et al., 2019; Kelly et al., 2020), soil (D. Allen et al., 2021; Rillig et al., 2017a; Wahl et al., 2021; Wang et al., 2020), sediment (Bergmann et al., 2017; M. Chen et al., 2020; Martin et al., 2021), terrestrial and aquatic biota (Büks et al., 2020; Huerta Lwanga et al., 2017; Krause et al., 2020; Rillig et al., 2019), air (Allen et al., 2019; Brahney et al., 2020; Dris et al., 2017; Klein and Fischer, 2019; Wright et al., 2020) and even re-suspension from the ocean via ocean spray (Allen et al., 2020; Campos da Rocha et al., 2021). It has also seen the development of new techniques for MnP analysis (e.g., NILU MnP deposition collector, TD-PTR-MS (dos Santos Galvão et al., 2022; Materić et al., 2020)), and re-purposing of old technologies (e.g. continuous plankton recorder, FTIR (Ostle et al., 2019; Y. Zhang et al., 2020b)) allowing us to determine the extent and magnitude of plastic pollution down to the microplastic (<5 mm) and nano size (<1 μm or 1000 nm) ranges (Shim et al., 2017; Frias and Nash, 2019; Hartmann et al., 2019; Cowger et al., 2020). Although a clear distinction between microplastic and nanoplastic size definitions have not been agreed upon (Hartmann et al., 2019), this short review seeks to summarize what key milestones and major advances have been made in microplastic and nanoplastic research in the environment, including their sources, fate, and effects, over the last 10 years. Despite the lack of consensus on the size classifications of microplastics and nanoplastics, research in this field is closely related, but they do require different tools and techniques for sampling and analysis. For example, microplastics

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* Corresponding author.
E-mail address: trwalker@dal.ca (T.R. Walker).

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research and methods for analysis or quantification are far more advanced than for nanoplastics. However, for the purposes of this short review, the combined term of MnPs will be used.

The scientific, public, and policy maker interest in microplastics and nanoplastics has been a long process. Plastic pollution such as plastic fragments (mesoplastics, >5 mm to 25 mm) and macroplastics (>25 mm), such as single-use plastics (e.g., plastic bottles, bags and packaging) are highly visible and thus have recently garnered intense public, policy and research interest (Lam et al., 2018; Hartmann et al., 2019; Karasik et al., 2020). However, micro and nano plastic are generally invisible to the naked eye and, in a similar manner to climate change, have been seen as a distal problem by many due to the lack of direct personal impact or visibility. Marine microplastics, specifically the effect of microplastics on marine species, gained momentum in earnest in the early 2000s (Lam et al., 2018; Kasavan et al., 2021), with continued advancement in marine microplastic collection, species and environmental impact assessment in the last decade (Vandermeersch et al., 2015; Tang et al., 2021). Estimates of plastic leakage to the environment identified a 'missing link' in the plastic cycle and environmental loss calculations, driving science to determine where this 'missing plastic' had been lost (Koelmans et al., 2017; Thompson et al., 2004). In response, fluvial water and sediment research accelerated, including the consideration of these environmental compartments as temporary sinks, secondary sources and transport pathways (Ivar Do Sul and Costa, 2014; Harris, 2020; Rozman and Kalčíková, 2022). This was followed by the logical step to investigate terrestrial (soil, agriculture, freshwater, groundwater and wastewater) environmental compartments, almost at the same time as researchers began to look up and consider the atmosphere for MnP (Horton et al., 2017; Y. Zhang et al., 2020b).

In response to this increased interest and focus on MnP in the environment and its consideration on human health, methods of sample collection and analysis have rapidly evolved. Where previously analysis focused on visible plastic particles (generally 500 μm or larger), following visual methods such as hot needle or morphological identification (Hidalgo-Ruz et al., 2012), research focus shifted to smaller particles including nano sized plastics and the particle sizes key to environmental and human health (e.g., PM_{10}, $PM_{2.5}$)(Wright and Kelly, 2017). As a result, the quantity of MnP identified within samples increased significantly, illustrating an exponential to power function increase in particle quantities relative to the decrease in particle size (Caputo et al., 2021; Filella, 2015; Lindeque et al., 2020; Schwaferts et al., 2019). As collection and analysis of smaller particles has become possible, the quantification of MnP in consumables, beyond marine resources (for example water, beer, salt, vegetables, seafood) as well as within waste management processes (for example, waste water treatment plants) has progressed (Corradini et al., 2019; Hanachi et al., 2019; Horton et al., 2020; Karbalaei et al., 2019; Kedzierski et al., 2020;; X Li et al., 2019. Luqman et al., 2021; Peixoto et al., 2019; Talvitie et al., 2015; Q. Zhang et al., 2020).

2. Methodology

A literature search was completed to identify recent trends in relevant publications. Potential papers were searched following the TOPIC search (Title, Abstract and Keyword) in the Web of Science (all databases) and Scopus databases. The search was undertaken focused specifically on six environmental subject areas (marine, freshwater, soils, biota, atmosphere, and human health) and four plastic subject areas specific to plastic pollution size (nanoplastic, microplastic, macro plastic, and plastic pollution) (Fig. 1). The database search allowed all papers over the total database record period to be identified, with papers then sub-categorised by year (see Supplementary materials).

For this review, peer-reviewed journal articles, books, reports, conference abstracts and papers were thoroughly studied. Specific focus was placed on the most recent decade (01/01/2012–31/12/2021) to identify the advancements in plastic pollution research during this period. Two databases (Web of Science and Scopus) were used following the topic key word search (Fig. 1) to ensure results were comprehensive and consistent (see Supplementary Data 1_ Scopus tabulated results and Supplementary Data 2_Web of Science tabulated results). Results were cross referenced to ensure accuracy of publication identification and classification according to the search terms. The literature search was completed at the beginning of January 2022 thus encompasses all work accepted for publishing in 2022.

The data search results were disaggregated to identify research advancements (articles, letters, data studies), review work and other listed works (e.g., conference papers). Results were also disaggregated by publication year (annually back to the 1950′s) for research works. Preeminent papers for each topic search keyword search were identified (the earliest relevant paper published on the general topic), as was the earliest key research paper that occurred or helped instigate the increase in micro and nano plastic research in this past decade. Although some publications included more than one environmental compartment, studies were assigned to specific environmental compartments based on the main focus of the TOPIC search (Title, Abstract and Keyword) of the study.

Database results were similar in total publication number, accuracy in publication identification and classification and identification of key (major advancement) publications (see graphical abstract). Overall, Scopus presented fewer publication numbers (but with comparative overall publication trend) and therefore was used herein to visualise database results.

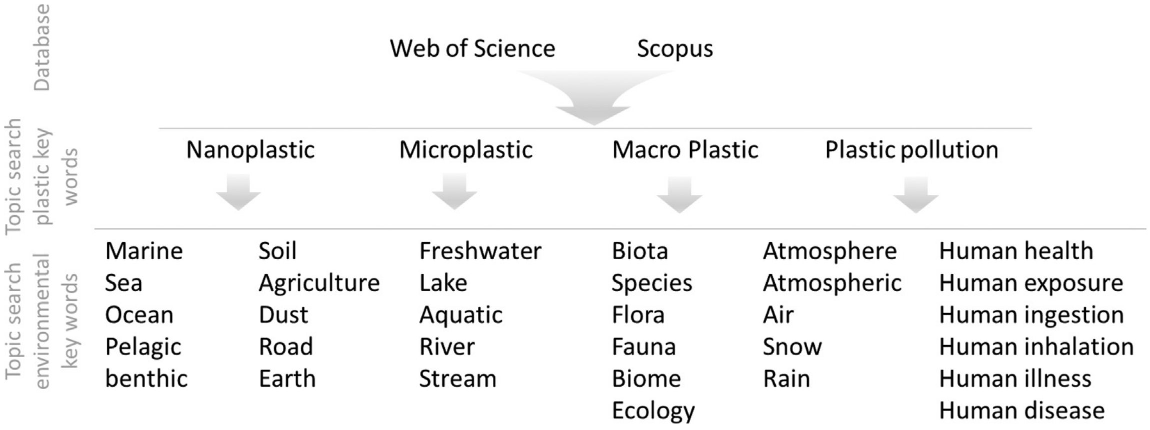

Fig. 1. Literature search methodology and topic (Title, Abstract and Keyword) search words for 6 foci: marine, soils, freshwater, biota, atmosphere and human health.

3. Results and discussion

3.1. Database literature search results and recent publication trends

Database outputs were classified by publication year, plastic size and environmental compartment, creating a dataset that extended back to ~1953 (Goss and Ross, 1953) and disaggregated into 25 classifications (Table S1, Supplementary materials). The preeminent publications for each environmental compartment (marine (Heyerdahl, 1971), freshwater (GESAMP, 1991), biota (Carpenter and Smith, 1972), soils, air (Kaiser and Tolciss, 1963), human health (Pauly et al., 1998)) by reading the oldest recorded published works within each category. These manuscripts and those that followed prior to 2012 help form the bedrock of knowledge for the significant increase in active research advancement in the past decade (Table 1). The key published MnP research for freshwater health (Imhof et al., 2013), atmospheric MnP (Dris et al., 2015a), soil MnP (Huerta Lwanga et al., 2016; Rillig et al., 2017a) and MnP influence on potential human health impacts from MnP exposure studies (Deng et al., 2017a; Schirinzi et al., 2017) were identified by reviewing chronologically published research advances within Scopus and Web of Science works between 2012 and 2021 (see Graphical Abstract).

There is a varying quantity of published work that falls within the classification of plastic pollution rather than a specific plastic particle size (nano, micro or macro plastic) (Fig. 2). This is most noticeable in the soils and air environmental compartments, which corresponds with the more recent research focus in these areas. The quantity of marine plastic published research is greater than any other environmental compartment, as expected due to the extended time this research has been ongoing, and in general the quantity of research follows the duration of time this research has been undertaken (marine>biota>freshwater>air>soils>human health).

Very few studies undertaken on nanoplastic (≤12%). This is still an emergent topic primarily due to the complexity of sampling and analysing environmental nanoplastics. Most studies present microplastic research. The proportion of microplastic studies is an order of magnitude greater than macroplastic studies primarily due to the relatively new introduction of the term macroplastic. Prior to 2017, the term macro plastic was sparsely used (and still is) with studies looking at macroplastic often presenting their findings as plastic pollution of a variation of plastic terminology rather than specifying the results as macroplastic. The terminology (nano, micro, macro plastic) is one of the plastic pollution research achievements in this decade. There is some ongoing debate on the delineation of the upper extent of nanoplastic (<1 µm or <100 nm) and the need for the term mesoplastic (5–25 mm). However, there is a general (if not complete) acceptance in the research community that microplastic are plastic particles <5 mm and nanoplastic are particles <1 µm (Frias and Nash, 2019; Hartmann et al., 2019; Kooi and Koelmans, 2019), with particles morphologically characterised as fragments, films, fibres and foams (GESAMP, 2019; Kooi and Koelmans, 2019; Rochman et al., 2019; Y. Zhang et al., 2020b).

There is a consistent increase in annual plastic pollution research being published since 2011. General plastic pollution publications have increased from ~200 papers per year at the beginning of the decade to >2000 publications per year in 2021 (Fig. 3). Microplastic publications have similarly risen from <50 publications per year in 2013 to >2000 in 2021. Nanoplastic research has been lower in overall publication rate but follows the same increasing publication trend. Interestingly macro plastic specific research has plateaued off, consistently maintaining close to 100 publications per year for the last two years.

The annual publication rate prior to 2012 was low, generally below 10 publications per year in any of the environmental compartments selected in this review. All the environmental plastic research (marine, soils, air, freshwater, biota) and human health impacts of plas-

Table 1
Total number of publications or research articles (excluding review publications) for each environmental compartment returned during this review.

	marine	freshwater/lake	soils	atmosphere/air	biota/flora/fauna	human health
All publications						
macro+micro+nano plastic	3860	3049	1165	673	2379	1390
Plastic pollution	4939	3152	3021	3148	2764	2130
Only research articles*						
macro+micro+nano plastic	3142 (2995)	2391 (2268)	851 (773)	507 (459)	1830 (1730)	889 (820)
Plastic pollution	4067 (3568)	2469 (2127)	2264 (1609)	2264 (1093)	2221 (1883)	1487 (1144)

* Excluding review publicationsValues in (brackets) are publications during the 1/1/2021–31/12/2021 period from the Scopus and Web of Science search.

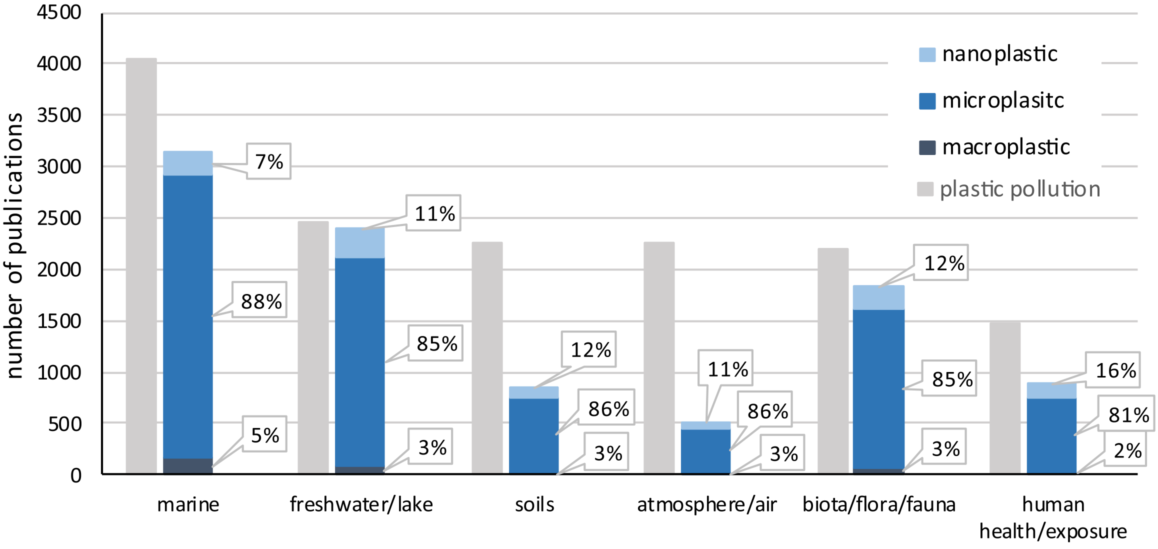

Fig. 2. Total peer-reviewed publications (excluding reviews) relative to the environmental compartment studied.

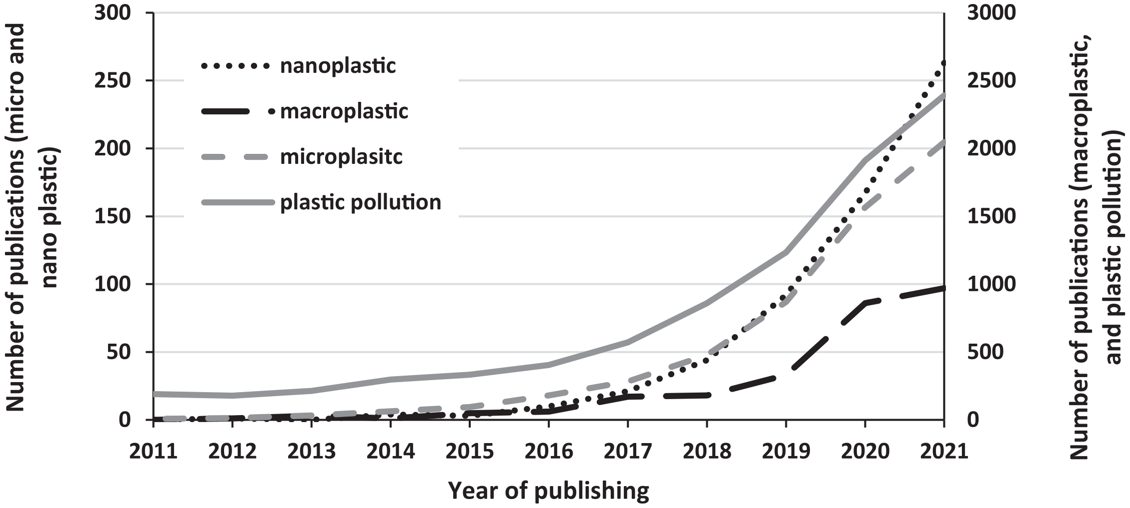

Fig. 3. Annual publications relative to plastic particle size range. Note the scale of the right y-axis for microplastic and plastic pollution research is an order of magnitude higher than for MnPs research on the left y-axis.

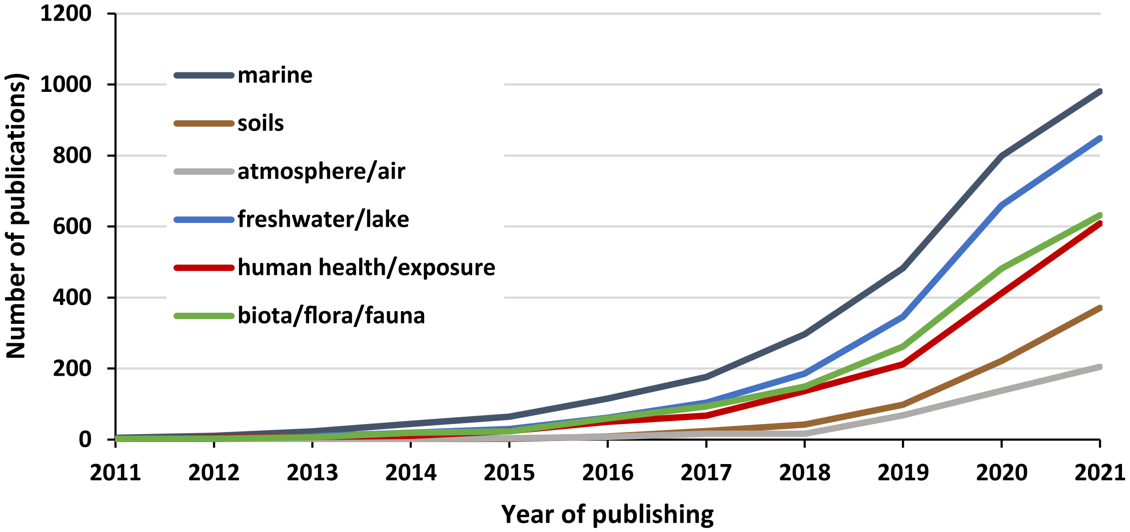

Fig. 4. Trend in publications as an indication of research achievements over in the last decade (2011–2021).

tic have increased dramatically since 2014–2015 (Fig. 4). Atmospheric and soil related research has only really gained significant ground since 2018/2019, after the early remote area and atmospheric transport research was published demonstrating the borderless nature of atmospheric plastic pollution and the ubiquitous (beyond agriculture and roads) pollution of soils (Allen et al., 2019. Bergmann et al., 2019; Deng et al., 2017b; Huerta Lwanga et al., 2016; Klein and Fischer, 2019; Rillig et al., 2017a; Schirinzi et al., 2017). The last decade has seen rapid increases in macro to nano plastic environmental and human pollution research, and that this research is continuing to advance.

3.2. Research trends and key advances in the past decade

3.2.1. Marine

From the coastline to the deep-sea, marine ecosystems have long been considered an important sink for plastic pollution. Based on 2010 data, Jambeck et al. (2015) estimated 4.8 to 12.7 million metric tonnes (MT) of plastic entered the world's oceans, with >10% of the marine plastic budget occurring as microplastics (Koelmans et al., 2017). However, these estimates are now considered conservative, as Borrelle et al. (2020) estimated that 19 to 23 million MT, or 11%, of plastic waste generated globally in 2016 entered aquatic (freshwater and marine) ecosystems.

Approximately 75–90% of marine plastic is terrestrially sourced (Ambrose et al., 2019; Rakib et al., 2022), with 10–25% originating from marine sources (e.g., fishing activities and nautical activities, aquaculture, or oil and gas exploration) (Andrady, 2011; Duis and Coors, 2016; Walker et al., 1997;, 2006). Since 2012, MnP research has advanced understanding of marine plastic pollution source contributions, identifying the role of wastewater treatment plant (WWTP) and current inability to retain MnP from cosmetics, laundry, and domestic uses (Kazour et al., 2019; Magnusson and Norén, 2014; Mintenig et al., 2017). A 2018 study of a WWTP in Vancouver estimated the MnP environmental loss of 1.76 trillion particles per annum, of which 0.3 trillion MnP particles were transported into the marine environment (Gies et al., 2018). This supports an earlier (2015) study suggesting WWTP effluent discharge to act as a marine MnP transport pathway through investigation of effluent release from a Finnish WWTP to the Gulf of Finland (Talvitie et al., 2015). In addition to WWTP influx of MnP to the marine environment, storm sewers transporting urban, industrial and commercial runoff, have been defined as a significant source and transport pathway (Lutz et al., 2021; Mak et al., 2020). Plastics used in agricultural practices are now also recognised as a source of marine MnP via runoff and fluvial transport, wind erosion and atmospheric transport (S. Allen et al., 2021; Evangeliou et al., 2020; Horton and Dixon, 2018). In contrast to the earlier marine sink studies, the seas and oceans have now been identified as a secondary source of MnP to the atmosphere and terrestrial environment, with MnP forming via degradation of larger plastic particles when exposed to solar UV radiation, wind, currents, or other mechanical and biological degradation processes (Allen et al., 2020).

Along global coastlines, plastic accumulation rates vary of orders of magnitude depending on the presence of large cities or busy container ports, shore use, and local hydrodynamics conditions (Walker et al., 1997, 2006; Galgani and Maes, 2015; Ambrose et al., 2019; Rakib et al., 2022). Beach and coastal plastic litter studies and assessment of macroplastics impact of species (entanglement, ingestion (Boren et al., 2006; France, 2016; Mascarenhas et al., 2004)) followed, with a shift in focus from macro towards micro plastic interest in the past decade (Bergmann et al., 2015).

In ocean waters, marine plastic research can be traced back to Thor Heyerdahl's Ra expeditions finding surface plastic in the Atlantic Ocean in 1969–1970 and Carpenter and Smiths quantification of plastic particles in the Sargasso Sea (Carpenter and Smith, 1972; Heyerdahl, 1971). In surface ocean waters, plastic particles of any size float transported by wind and currents, with the first evidence reported almost 50 years ago (Venrick et al., 1973; Wong et al., 1974). Plastic distribution in surface waters is uneven, and the highest concentrations have been detected in ocean gyres (Moore et al., 2001) and named garbage patches. However, it is hypothesised that surface waters only account for a very small fraction, ~1%, of the global marine plastic budget, thus implying that most plastic pollution entering the ocean accumulates at the seafloor (Koelmans et al., 2017; Thompson et al., 2004). Indeed, when covered by biofilm, microplastic particles tend to aggregate more rapidly (Michels et al., 2018): this reduces their buoyant capacity and favour settling and accumulation in seafloor sediment. At the seafloor, micro(nano)plastic particles can either be covered by sediments, and thus sequestered into the sedimentary record, or can be further transported and re-deposited by ocean currents (Kane et al., 2020). In the last 10 years, MnP have been found throughout the marine sediment environment, which has been shown to not act consistently as a static sink but also as a transport pathway with shifting hot spots (Kane et al., 2020). Indeed, increasing evidence of macro and microplastic has been found in active submarine canyons directly fed riverine inputs (Pierdomenico et al., 2019; Zhong and Peng, 2021), with plastic pollution transported by energetic turbidity currents. Marine sediments have also been used to illustrate the historical marine MnP pollution trend. Studies of marine sediment show an increasing quantity of MnP pollution (Bancone et al., 2020; Matsuguma et al., 2017), mirrored in the surface marine MnP records such as plankton trawl records (Ostle et al., 2019).

The marine environment can also act as a source of MnP, as plastic particles can leave ocean waters through bubble burst ejection and spume and become entrained and atmospherically transported (Allen et al., 2020. Lehmann and Gekle, 2020), helping close the global plastic cycle. Marine sea water is also a source of MnP in sea ice: it has been show that sea ice in both the Arctic and Antarctic contain substantive MnP concentrations (Bergmann et al., 2016; Kanhai et al., 2020; Kelly et al., 2020). MnPs in the marine environment has been found to act as a collection and transport vector for pathogens and non-plastic pollutants (Bowley et al., 2021; Radisic et al., 2020), not only transporting these pollutants and pathogens around the marine environment but also into the food chain and potentially to humans. The consideration of MnP particles, pathogens and other MnP transported pollutants into the food chain via the marine environment has helped created a research focus on food safety and human health (Barboza et al., 2018a; Galloway, 2015).

3.2.2. Freshwater

Although freshwater ecosystems can accumulate huge quantities of MnPs, there have been fewer studies of MnPs in freshwater compared to marine ecosystems (J Li et al., 2018.). The first studies in North American rivers (Hays and Cormons, 1974; Moore et al., 2011), a lake (Zbyszewski and Corcoran, 2011), and a European lake (Faure et al., 2012) were published over three decades, from 1974 to 2012. Huge quantities of MnPs can be discharged into natural waters through WWTPs (J Li et al., 2018.). According to Mason et al. (2016), who analysed effluent samples from 17 WWTPs, the average discharge of microbeads from US municipal WWTPs was predicted 13 billion particles per day. Other sources of MnPs to freshwater ecosystems include surface run-off from surrounding urban and rural landscapes, atmospheric deposition, storm water overflow event, incidental release (e.g., during tyre wear), and plastic films used in agricultural lands for crop production (Eerkes-Medrano and Thompson, 2018). Recreation and tourism may also serve as significant sources of MnPs due to fishing activities. For example, fishing nets degrade over time and persist in freshwater ecosystems (Talbot and Chang, 2022).

Early studies focused on the presence of MnPs in freshwater ecosystems were on river beaches, ponds, wetlands, surface waters and sediments of rivers, lakes and reservoirs (Strungaru et al., 2019). It was widely acknowledged that freshwater compartments served as sources and transport pathways for MnPs to the oceans (Dris et al., 2015b), but new research by van Emmerik et al. (2022) suggest that rivers can also act as (long-term) sinks for MnPs. During dry seasons, plastics can have longer residence times in freshwater systems and continue to degrade over time (C. Li et al., 2020). During wet seasons, higher flows can exacerbate MnP pollution in these water bodies and resuspend MnPs previously trapped within sediments (Hurley et al., 2018). Understanding MnP contamination in freshwater ecosystems is critical because these systems support great biodiversity. Furthermore, human populations rely on freshwater systems for a variety of ecosystem services, such as food and drinking water. Therefore, contamination by MnP potentially poses potential ecological and human health risks (H.L. Chen et al., 2021).

3.2.3. Soil

Soils, due to the high organic matter content and complex composition, are one of the most difficult matrices to analyse for MnP. In this past decade major advancements in analytical MnP methodology has enabled soil MnP to be quantitatively characterised (Bläsing and Amelung, 2018; He et al., 2018; Möller et al., 2020). While this is an emergent topic, recent research has established that MnP are present throughout the soil structure, can be seen in the soil archives (soils, sediment and peat), telling a story of plastic pollution through the last 60 years, and form plastiglomerates (Corcoran et al., 2014; D. Allen et al., 2021; Weber and Lechthaler, 2021). Soils are estimated to contain 4 to 23 times the MnP quantity of the oceans, and are one of the direct pathways of MnP into the food web (Horton et al., 2017; Pathan et al., 2020). MnP is a physical soil contaminant which lowers soil bulk density, potentially reduces root penetration resistance, increases soil aeration, soil water movement and water evaporation, modifies soil aggregation and releases (toxic) plastic leachate into soils (Pathan et al., 2020; Rillig et al., 2019).

Soils have been identified as a source of plastic to the atmosphere through wind erosion (wind-erosion MnP from an agricultural surface of 6.91–20.27 mg/kg)(Brahney et al., 2021; Bullard et al., 2021; Rezaei et al., 2019) and to groundwater through infiltration (MnP in karst groundwater showed <15.2 MP/L identified in Illinois (Panno et al., 2019) and 7 MP/m^3 in Germany (Mintenig et al., 2019; Chia et al., 2021). Sources of soil pollution include atmospheric deposition, rainfall runoff and agricultural activities such as compost (2–180 mg/kg), mulch, seed and soil improver coatings, controlled-release fertilisers, greenhouse material, reuse of WWTP sludge (<10 p/g), and irrigation (<320,000 particles/m^3) (Bläsing and Amelung, 2018; Corradini et al., 2019; Nizzetto et al., 2016a). Soils also function as a transport pathway and (temporary) sink for MnP (He and Luo, 2020), with a recent modelling assessment of MnP soil retention suggesting a MnP soil storage capacity of 16–38% (Nizzetto et al., 2016b). Terrestrial worms were one of the earliest identified soil MnP transport vectors due to ingestion and transportation through their activates and excretions (Huerta Lwanga et al., 2017; Rillig et al., 2017b), and MnP terrestrial multicellular soil fauna assessments have since extended to nematodes, springtails, and beetles as well-known model organisms (Büks et al., 2020). MnP exposure assessments of soil fauna illustrate altered biomes, reduced mobility, reduced reproduction, oxidative stress and metabolic malfunction, or increased motility (Büks et al., 2020; Rillig et al., 2017b). The extent of soil MnP pollution, its short- and long-term impact are relatively unknown.

3.2.4. Atmosphere

This decade has seen the creation and flight of atmospheric MnP research. Starting with Dris et al. quantification of atmospheric MnP deposition in Paris (Dris, 2016), atmospheric deposition and air mass concentration studies initiated across European, Middle Eastern and Asian cities (Abbasi et al., 2019; Akhbarizadeh et al., 2020; Cai et al., 2017; Kaya et al., 2018; Klein and Fischer, 2019; Syafei et al., 2019; Wright et al., 2020), identifying atmospheric MnP concentrations of ~1–5700MnP/m^3 (Y. Zhang et al., 2020b) and atmospheric MnP deposition of ~3100 MP/m^2/day outdoors (Soltani et al., 2021) and over 6000 MnP/m^2 indoors (Catarino et al., 2018; Dris et al., 2017). Initially thought to occur as localised contamination surrounding cities and industry, the assessment and modelling of atmospheric transport seriously commenced in 2019 with the quantitative characterisation of atmospheric MnP in remote areas (atmospherically transported to 'pristine' locations) (Allen et al., 2019. Bergmann et al., 2019). Backward air mass and particle history analysis, identifying the 'flight path' of the MnP found in atmospheric samples, providing indications of possible atmospheric source locations and their atmospheric transport duration and elevation (S. Allen et al., 2021; Evangeliou et al., 2020; Wright et al., 2020). MnP can travel thousands of kilometres, between countries and over oceans in a relatively short time (days to weeks) in both the planetary boundary layer and free troposphere (S. Allen et al., 2021; Brahney et al., 2021), illustrating the atmosphere to be a faster transport pathway in comparison to oceanic currents and fluvial transport.

New research identifies MnP water-atmosphere exchange, from rain drop impact and following the bubble burst ejection process found in sea sale aerosol ejection (Allen et al., 2020. Lehmann and Gekle, 2020). This helped close the plastic cycle and demonstrates plastic transport to potentially occur in a never-ending loop (the oceans are no longer only a final sink for MnP but also an atmospheric MnP source). Alongside new understanding of the emission, transport and deposition of these atmospheric MnP, new climate modelling suggests atmospheric MnP particles have an influence on radiative forcing and therefore are an element influencing climate change (Revell et al., 2021).

Atmospheric MnP transport modelling has been extended to start quantification of the atmospheric burden of MnP (Brahney et al., 2021; Liss, 2020). However due to the lack of spatial and temporal datasets (approximately 65 field studies published prior to 2022) and the lack of comparability and reporting uniformity in published studies, these early global atmospheric MnP estimates are highly uncertain (D Allen et al., 2022.). The atmospheric concentration and transport assessments also highlight the knowledge gaps in the particle and transport dynamics (mechanisms and process) for MnP. MnPs are a unique 'species' of particles that are less dense than soil or dust (0.8–1.8 g/cm^3) (Kooi and Koelmans, 2019), have a (predominantly negative, but changeable) charge, function as a vector for bacterial, viruses, elements and contaminants in the environment and occur in a massive range of shapes, sizes, composition and extent of degradation (Imran et al., 2019; Joo et al., 2021; Verla et al., 2019). There is a current focus on expanding the global representation of atmospheric MnP concentrations and deposition knowledge, the marine emission and ocean-atmosphere flux, long-distance transport, global atmospheric MnP burden and definition of atmospheric MnP (primary and secondary) sources.

3.2.5. Biota

Marine biota studies have been going since the early 1960′s with the first seabird plastic ingestion findings (Ryan, 1988; Spear et al., 1995). Biota studies have focused on marine species (mussels to fish, zooplankton, seagrass and coral (Karbalaei et al., 2019; L Peng et al., 2020. Ripken et al., 2020; Seng et al., 2020)) until the shift from macro to micro and nano plastic uptake and impact on biota in the last decade and the resultant increase in biota MnP studies (L Peng et al., 2020. Karbalaei et al., 2021; Ugwu et al., 2021). Pre-2012 marine biota research primarily focused on entanglement and ingestion (gastrointestinal tract, specifically stomach, content investigations), however in recent research has moved beyond this to consider MnP translocation to other organs and circulatory systems. MnP have been found in faeces, gills, skin, muscle, haemolymph and circulatory system (L Peng et al., 2020. Ugwu et al., 2021), and the uptake of these MnP can cause endocrine disruption, tissue inflammation, behavioural changes, reduced grown, reproductive success and survival (Barboza et al., 2018b; Haegerbaeumer et al., 2019; Ribeiro et al., 2017; Sharifinia et al., 2020; Shen et al., 2019). Biota MnP research moved beyond the marine environment in this past decade, extending into the study of freshwater and soil environments fauna and flora (Büks et al., 2020; Haegerbaeumer et al., 2019; Mateos-Cárdenas et al., 2021; Naqash et al., 2020; O'Connor et al., 2020; Yin et al., 2021).

Toxicological assessment of MnP impact on individual species and ecosystems has let to assessment of chronic (rather than just acute) exposure (e.g., *Hyalella azteca* (a freshwater amphipod) PE acute exposure showed 10d mortality rates and chronic exposure to cause detrimental changes to reproduction, growth and egestion) (Au et al., 2015; Pignattelli et al., 2020; Suman et al., 2020). Early exposure studies used very high MnP concentrations (in laboratory controlled experiments) that were not considered representative of the current environmental MnP pollution, resulting in a shift in recent years to environmentally relevant MnP concentrations in biota impact assessments (Bour et al., 2018; El et al., 2020; Koelmans et al., 2020; Sun et al., 2021; Teng et al., 2021). Research has also extended beyond individuals to consider multi-generational impacts, with studies suggesting transference of neurotoxicity from parent to offspring generations (*Caenorhabditis elegans*), multi-generational oxidative stress, trans-generational reproductive toxicity, and multi-generational increased mortality (e.g., *Tigriopus japonicas, Brachionus manjavacas*) (H. Chen et al., 2021; Haegerbaeumer et al., 2019; Jeong et al., 2021; Yu et al., 2021).

Broadening MnP biotic impact assessment from individuals and multi-generational impact, MnP research has recently started to consider trophic transfer and MnP impact within the food web (Chae and An, 2020; Krause et al., 2020). Nanoplastic PS has been seen to transfer from alga, to water flea, to a secondary consumer fish and up to an end consumer fish under controlled laboratory conditions, with noted behavioural and histopathological changes in the secondary and end-consumer fish (Chae et al., 2018). Similarly, behavioural disorders (decreased feeding, foraging and growth were found in terrestrial snails as a result of plant (mung bean, the snails key food source) uptake and accumulation of nanoplastics (Chae and An, 2020). This trophic transfer assessment is just becoming part of the ecosystem service discussion, with early assessment suggesting provisioning, regulation and maintenance services provided by biota (such as insects) to be detrimentally affected by MnP contamination (Oliveira et al., 2019; Sridharan et al., 2021).

3.6. Human health

Prior to 2017, most research considering human health discussed (and to some extent quantified) the MnP in the food chain and therefore potential for human ingestion. The physical impact of MnP within the human system was theorised and discussed but in vivo or in vitro studies did not start in earnest until around 2017. The investigation into human health impacts has grown in the past few years following the government regulatory and funding bodies acknowledgement of the potential issues and risk associated with human MnP uptake (California State Water Resources Control Board, 2020; Grant, 2020; Ong et al., 2020). Research started with assessing the movement and impact of MnP on specific cell lines (e.g., gut and lung epithelial cells) and laboratory uptake and impact experiments on mammals often used as indicators or proxies for human health studies (rats, mice). Semi quantitative assessments of human inhalation and ingestion of MnP suggest inhalation uptake of approximately 48,000 (5000–109,000) MnP/year (Cox et al., 2019; Mohamed Nor et al., 2021; Vianello et al., 2019) and ingestion of 46,000–193,200 MnP/year (Cox et al., 2019; Mohamed Nor et al., 2021; Senathirajah et al., 2021), depending on exposure (location, activities, age, resource access etc.). The last few years has seen significant advancement in the study of MnP transport impact on human cells, with studies identifying inflammatory responses, dysregulation of tight junctions and cytotoxic effects (in the gastrointestinal and lung epithelial membrane)(Deng et al., 2020; Dong et al., 2020; Huang et al., 2020; B. Li et al., 2020; Lim et al., 2019). MnP have been identified in human lung tissue (Amato-Lourenço et al., 2021; Pauly et al., 1998), stool (Braun et al., 2021; Luqman et al., 2021; Schwabl et al., 2019;; J Zhang et al., 2021.), within the circulatory system (Gruber et al., 2020; Liu et al., 2020) and placental (Braun et al., 2021; Gruber et al., 2020), and in multiple organs (hear, spleen, placenta and foetus) of rodents (Fournier et al., 2020). Research to define MnP impacts, both acute and chronic, on human health is accelerating. However, research on the potential human health impacts of MnP uptake are still relatively unknown. Similarly, the cumulative impact of MnP exposure and uptake alongside illness, contaminated water and food and poor air quality (beyond MnP pollution) may have an important role in future human and community health but fall beyond current advancements in MnP research.

3.7. Future directions

Due to the continued and projected increase in plastic and MnPs pollution, it is critical to solve, and better understand the sources, fate, and effects (i.e., toxicity) of these particles in the environment. In the past decade, there has been a dramatic increase in MnPs studies. While most studies focus on reporting the presence of MnPs in environmental compartments or in individual biota species, few studies have examined MnPs toxicity effects on organisms beyond controlled laboratory studies or considered multi-generational or multi-species (food web) toxicity. Most laboratory studies have used high concentrations of virgin MnPs, which may not reflect environmentally relevant concentrations. In the natural environment, MnP concentrations vary widely and occur in different size combinations, degraded primary or secondary MnP characteristics. Therefore, more studies on environmentally relevant concentrations, are required to better understand their potential toxicity effects on organisms and humans. MnPs are also known to sorb contaminants from the environment at concentrations many orders of magnitude higher than ambient concentrations. Therefore, more studies are required to better understand the toxic impacts of contaminants associated with MnPs on biota. Additionally, MnPs comprise a complex suite of polymer types and each polymer type comprises hundreds or even thousands of plastic additives (chemicals added to plastic polymers to alter their physical properties). However, many of these plastic additives are known to be toxic to humans and biota and many more remain unknown, resulting in a huge knowledge gap that need to be addressed in future studies.

4. Conclusions

This decade has seen the initiation and growth of MnP research beyond the marine environment. MnPs have been found in every environmental compartment investigated, from the upper atmosphere to the deepest depths of the oceans, and within thousands of marine and terrestrial species. Recent advances in MnP analysis has allowed for more precise quantitative characterisation of even smaller microplastics compared to a decade ago and even down to the nanoplastics size range in the environment. Consequently, these recent advances in MnPs analytical and sampling techniques has opened the door to the environmental and human health assessment. Early studies suggest MnP to be detrimental to ecosystems and species health, modifying mobility, fecundity and mortality. The explosion of MnP knowledge in recent years has not yet been fully understood, and future research will need to focus of impact assessments, identification of acute and chronic exposure thresholds, and advancing the quantitative understanding of the global MnP burden and plastic life cycle. Given the toxic nature of many plastic additives and sorbed contaminants, environmentally relevant toxicology studies that consider multi-generational effects are needed, including bioaccumulation studies across Multiple species and environmental compartments. Plastic production and the creation and mismanagement of plastic waste show no signs of slowing, so the need to understand the impact of this anthropic persistent pollutant remains of vital importance.

Declaration of Competing Interest

None.

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

CRediT authorship contribution statement

Steve Allen: Conceptualization, Resources, Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Deonie Allen:** Conceptualization, Resources, Methodology, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Samaneh Karbalaei:** Writing – original draft, Writing – review & editing. **Vittorio Maselli:** Resources, Project administration, Funding acquisition, Writing – review & editing. **Tony R. Walker:** Conceptualization, Resources, Project administration, Funding acquisition, Methodology, Data curation, Investigation, Writing – review & editing.

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Supplementary materials

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