Birds as bioindicators of plastic pollution in terrestrial and freshwater environments

Mansfield, Imogen; Reynolds, Jim; Lynch, Iseult; Matthews, Tom; Sadler, Jon

DOI:
10.1016/j.envpol.2024.123790

Environmental Pollution 348 (2024) 123790

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Birds as bioindicators of plastic pollution in terrestrial and freshwater environments: A 30-year review☆

I. Mansfield [a,*], S.J. Reynolds [b,c], I. Lynch [a], T.J. Matthews [a], J.P. Sadler [a]

[a] *School of Geography, Earth and Environmental Sciences, Birmingham B15 2TT, UK*
[b] *School of Biosciences, College of Life & Environmental Sciences, University of Birmingham, Birmingham B15 2TT, UK*
[c] *The Army Ornithological Society (AOS), c/o Prince Consort Library, Knollys Road, Aldershot, Hampshire GU11 1PS, UK*

A R T I C L E I N F O

Keywords:
Avian
Ecotoxicology
Emerging pollutants
Pollution sinks

A B S T R A C T

Plastic pollution is a global concern that has grown ever more acute in recent years. Most research has focused on the impact of plastic pollution in marine environments. However, plastic is increasingly being detected in terrestrial and freshwater environments with key inland sources including landfills, where it is accessible to a wide range of organisms. Birds are effective bioindicators of pollutants for many reasons, including their high mobility and high intra- and interspecific variation in trophic levels. Freshwater and terrestrial bird species are under-represented in plastic pollution research compared to marine species. We reviewed 106 studies (spanning from 1994 onwards) that have detected plastics in bird species dwelling in freshwater and/or terrestrial habitats, identifying knowledge gaps. Seventy-two studies focused solely on macroplastics (fragments >5 mm), compared to 22 microplastic (fragments <5 mm) studies. A further 12 studies identified plastics as both microplastics and macroplastics. No study investigated nanoplastic (particles <100 nm) exposure. Research to date has geographical and species' biases while ignoring nanoplastic sequestration in free-living freshwater, terrestrial and marine bird species. Building on the baseline search presented here, we urge researchers to develop and validate standardised field sampling techniques and laboratory analytical protocols such as Raman spectroscopy to allow for the quantification and identification of micro- and nanoplastics in terrestrial and freshwater environments and the species therein. Future studies should consistently report the internalised and background concentrations, types, sizes and forms of plastics. This will enable a better understanding of the sources of plastic pollution and their routes of exposure to birds of terrestrial and freshwater environments, providing a more comprehensive insight into the potential impacts on birds.

1. Introduction

The global human population, presently at 7.7 billion, is estimated to increase to 9.7 billion (United Nations, 2019) by 2050. Such growth is associated with intensifying anthropogenic activity including the production of household waste, with related environmental impacts such as plastic pollution (Avio et al., 2017). Plastic production has increased from approximately two million metric tonnes in 1950 to 368 million metric tonnes in 2019 (OFCOM, 2019). The rising demand for plastic and limited options currently available for its safe disposal and recycling, have resulted in plastic being one of the most significant pollutants worldwide (Zalasiewicz et al., 2016). Recognition of the impacts of plastics on the environment has subsequently increased in recent years (e.g., Eriksen et al., 2014; Allen et al., 2019; Borrelle et al., 2020).

1.1. Environmental degradation of plastics

Plastics are predominantly categorised by size, typically, from macro- (e.g., bottles) down to micron-sized (e.g., microbeads previously used in toothpaste). Intentionally produced plastics at the micron scale are termed primary microplastics. Secondary (or incidental) microplastics originate from larger plastic fragmenting due to degradation through chemical, mechanical and biological processes such as UV irradiation and enzymatic action (Zhang et al., 2021). Microplastic are particles <5 mm and typical environmental samples can range in size, shape, colour and polymer type (Cole et al., 2011; Duis and Coors, 2016;

☆ This paper has been recommended for acceptance by Eddy Y. Zeng.

* Corresponding author.
E-mail address: ILM851@student.bham.ac.uk (I. Mansfield).

https://doi.org/10.1016/j.envpol.2024.123790
Received 11 October 2023; Received in revised form 11 March 2024; Accepted 12 March 2024
Available online 25 March 2024

Martí et al., 2020). Due to the stochastic nature of their degradation and durability, plastic particle size distributions are broad and likely contain many secondary nanoplastics.

1.2. Plastic occurrence in the environment

Most existing research has focused on the fate of plastic in marine as opposed to freshwater (Blettler et al., 2018) and terrestrial environments (Hurley et al., 2020). This bias may reflect prominent adverse interactions between plastic and marine wildlife which have received much recent media coverage (e.g., BBC, 2020; The Guardian, 2020) and have been the subject of public awareness campaigns highlighting the burgeoning accumulation of marine plastic (e.g., Bravo Rebolledo et al., 2013; Schuyler et al., 2013; Acampora et al., 2016; Markic et al., 2018; Nelms et al., 2019). Terrestrial and freshwater environments warrant much closer examination as they may also host significant plastic pollution hotspots. Plastic pollution predominantly originates through on-land production, therefore most sea plastic litter can be traced back to terrestrial sources (Jambeck et al., 2015; Hurley et al., 2020). Before reaching the marine environment, plastic pollutants move from the terrestrial environment through freshwater water courses and bodies (Galafassi et al., 2019). Thus, there is an urgent need to assess the impacts of plastic and plastic pollution pathways in freshwater environments (Krause et al., 2021).

1.3. Pathways of plastics within terrestrial and freshwater environments

Approximately 79% of all plastic produced globally (mass based) is not recycled; instead, it is deposited in landfill or released into the wider environment (Geyer et al., 2017). Plastic can degrade into smaller pieces while in landfill, dispersing via mechanisms such as wind deflation, where lighter particles lift from a dry surface (Wright et al., 2020) into surrounding environments (Barnes et al., 2009). Sewage treatment plants which deal with domestic waste (e.g., discarded cosmetic products) are also a source of terrestrial and freshwater microplastics that evade collection on filters designed for larger plastic fragments due to the filter size. Even after sewage treatment (e.g., the removal of solids from the wastewater, and purification of remaining wastewater using biological processes such as anaerobic digestion), sludge (organic and inorganic solids in water) may remain contaminated with plastic which can then transfer to agricultural soils when applied as nutrient-rich fertilisers (Corradini et al., 2019). Plastic is also released into terrestrial and freshwater environments during product use, making urban settlements major hotspots for plastic littering. For example, thread-like secondary microplastics (microfibres) are expelled into the atmosphere by friction between vehicle tyres and roads (Carr, 2017). Micro- and nanoplastics can be further transferred through terrestrial and freshwater ecosystems (Beraldi-Campesi, 2013) from soil (Huerta Lwanga et al., 2017), water (Silva-Cavalcanti et al., 2017) and air (Amato-Lourenço et al., 2020), eventually being ingested and inhaled by organisms during feeding and respiration. Humans can ingest environmental plastic through consumption of agriculturally sourced foodstuffs such as honey and salt (Liebezeit and Liebezeit, 2013; reviewed in Walker et al., 2022) and foods from higher trophic levels such as fish, where plastic bioaccumulates (e.g., Rochman et al., 2015; Bessa et al., 2018; Akhbarizadeh et al., 2020). Microplastics (Dris et al., 2017) and nanoplastics (Lim et al., 2019), particularly from indoor air, can be directly inhaled.

1.4. Toxicological impacts of plastic pollution

During plastic production, chemicals such as plasticisers are used to enhance physical properties such as their resistance to fire (e.g., brominated flame retardants [BFRs]; Pivnenko et al., 2017). Chemicals such as polybrominated diphenyl ethers (PBDEs) can cause health problems including kidney damage and thyroid cancer in various animal species (Gorini et al., 2018; Sepp et al., 2019; Baines et al., 2021). Consequently, plastics containing certain PBDE compounds such as Penta-BDE will be banned from recycled plastics after 2030 (Sharkey et al., 2020). Moreover, plastic is an effective transport medium for toxic chemicals such as persistent organic pollutants (POPs) (Hirai et al., 2011) and heavy metals (Ashton et al., 2010), and for pathogenic microorganisms (Yang et al., 2020). Nanoplastics have a greater surface area than microplastics so are more able to absorb, and adsorb onto, toxic chemicals (Rist and Hartmann, 2018). Their small size enables them to be internalised in animals via processes such as inhalation and ingestion (Lehner et al., 2019). Once inside organisms, they are transported around somatic compartments, sometimes being internalised by cells such as epithelia (von Moos et al., 2012). Their internalisation can result in the bioaccumulation of harmful chemicals such as plastic additives (Browne et al., 2013; Kühn et al., 2020). Due to size-derived difficulties with the detection and quantification of nanoplastics (Nguyen et al., 2019), less is currently understood about their interactions with chemicals, and subsequent adverse impacts on organisms compared to microplastics (Lehner et al., 2019; MacLeod et al., 2021).

1.5. Birds as bioindicators of plastic pollution

Bioindicators are organisms which are used to highlight the quality of an environment (e.g., air quality), and to detect environmental changes (e.g., biodiversity loss) (Parmar et al., 2016). Birds are effective bioindicators (Furness and Greenwood, 1993) because they are far ranging, and are part of many trophic levels and complex food webs that often contain bioaccumulated pollutants (Egwumah et al., 2017). Birds have been used as bioindicators of a number of key pollutants such as heavy metals (e.g., Turzańska-Pietras et al., 2018; Aziz et al., 2021; Rashid et al., 2021), flame retardants (reviewed in Tongue et al., 2019) and plastics (Provencher et al., 2019). Most plastic pollution studies using birds as bioindicators have been focused on birds of marine environments (e.g., Pierce et al., 2004; Avery-Gomm et al., 2018; Le Guen et al., 2020; De Pascalis et al., 2022). However, as interest in plastic as a pollutant and understanding its myriad entry points into the terrestrial environment, such as through agriculture has grown, so has the extent of research addressing terrestrial and freshwater plastic pollution and birds. A recent UN Food and Agriculture Organization report (FAO, 2021) estimated that agricultural value chains used 12.5 million metric tonnes of plastic products during plant and animal production in 2019.

The limited existing research on terrestrial and freshwater birds has focused on impacts from macroplastics (e.g., American crows [*Corvus brachyrhynchos*]—Townsend and Barker, 2014; Chinese bulbuls [*Pycnonotus sinensis*]—Wang et al., 2009; common blackbirds [*Turdus merula*] —Møller, 2017), including a systematic review of the use of anthropogenic materials in nests (see Jagiello et al., 2023), but not their internalisation and toxicity. A fuller appraisal of birds as bioindicators of terrestrial and freshwater plastic pollution must consider all contamination pathways, including: inhalation of plastic aerosols (Gasperi et al., 2018; Tokunaga et al., 2023); ingestion of plastic and associated chemicals in food and water, from feathers during moulting (Avery-Gomm et al., 2013; Lavers et al., 2014) and preen oil during feather preening (Provencher et al., 2020); transfer of plastic fragments between adults and their offspring during food regurgitation and provisioning (Carey, 2011; D'Souza et al., 2020); and exposure to nestlings from plastic in nest materials (Votier et al., 2011; Townsend and Barker, 2014; Jagiello et al., 2023). Future studies should compare plastic pollutant loads in birds at different life stages (Acampora et al., 2014), feeding guilds (Poon et al., 2017), life-history (Moser and Lee, 1992) and migratory strategies (van Franeker and Lavender, 2015). Highlighting the characteristics of (micro)plastics that are more commonly ingested by terrestrial and freshwater bird species is also key in this review.

In this review, we explore the interactions of avian terrestrial and freshwater bioindicator species with environmental plastics of all sizes.

We consider four themes that are fundamental in understanding the negative impacts of environmental plastic pollution on birds: (1) routes of plastic exposure; (2) types of plastic and their characteristics (e.g., sizes, colours); (3) field and laboratory plastic sampling methods; and (4) the impacts (negative and positive) of plastic exposure. We also discuss the limitations of current methodologies and reporting practices in relation to environmental plastic sampling, and propose directions for future research and minimum adequate reporting guidelines. Our goal is to further our understanding of the extent and impact of extrinsic plastics on terrestrial and freshwater birds.

2. Methods

2.1. Systematic literature search

We conducted a systematic search of the scientific literature for studies that have analysed plastic pollution in freshwater and terrestrial bird species, using the online database Web of Science (Web of Science, 2021). The search (Fig. 1) was divided into four separate topics: (1) focal avian taxa; (2) plastic material; (3) sample type; and (4) sampled environment. All topics were included within the same search, joined by "AND" as a Boolean operator. Asterisks allowed terms to be used as stems of words in searches. The Boolean search command "OR" was used between words. The search was not restricted by date of publication or by language of publication. Book chapters and reviews were not included.

We complemented the search for literature with an additional systematic search on the online database Scopus (using the same terms as for the Web of Science search – Fig. 1). The first 10 pages (1000 papers), ordered by relevance, were assessed. In order to capture as many relevant studies as possible, a tertiary search was conducted, using Google Scholar, with the following search terms "bird and plastic and (terrestrial or freshwater)". We assessed the first 10 pages of paper returned from this search also.

2.2. Criteria for study inclusion

Research had to have been conducted in a terrestrial or freshwater environment, including focal bird taxa that are routinely associated with marine environments such as gull (Laridae) species but that roost and/or feed close to terrestrial landfills at the time of sampling. We discounted coastal studies with littoral species unless birds were shown definitively to be spending most of their time, such as during nesting and/or feeding, in terrestrial as opposed to marine environments.

The returned papers were then screened against the inclusion and exclusion criteria (Fig. S1), and categorised according to: species studied, environment type, description of plastics observed or characterised in terms of size, form (shape/morphology) and composition, end-points evaluated (e.g., location of plastics/microplastics, uptake etc.) and geographic location of the study. In some cases, studies spanned more than one category (e.g. focal species, plastic type), resulting in the number of studies presented within a category differing from the total number of studies listed in this review. For example, studies which measured micro- and macroplastics were assigned to both categories. If the plastic size was not documented in a study, we followed the steps outlined in Fig. S1 to assign the study to the most appropriate size category. For example, if no methods of magnification (e.g. a binocular microscope) were used to identify the plastics, we assumed that plastics found were not micro- or nanoplastics. Fig. S1 also describes the steps taken to categorise studies based on form and colour.

3. Results and synthesis

From the 1442 papers identified in the Web of Science literature search, 95 studies of plastic pollution in terrestrial and freshwater bird species met our inclusion criteria. Another nine papers were added using Scopus, and two with Google Scholar.

3.1. Type of environment

Out of 106 papers, 83 studies included terrestrial bird species and 38 included freshwater species. Fourteen studies included coastal species (only studies where sampling was predominantly linked to freshwater and/or terrestrial rather than marine environments were included for this category). Fifteen studies monitored plastic pollution across more than one environment type (i.e., a mix of terrestrial and freshwater species across a range of orders; Fig. 2).

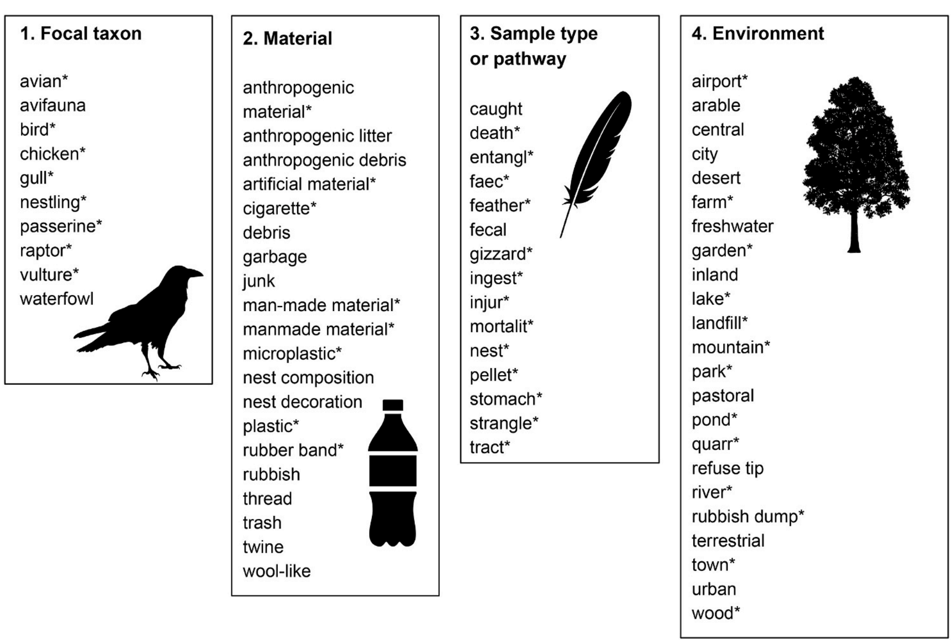

Fig. 1. A four-stage diagram highlighting the structure and individual terms deployed within the Boolean search for this review. The asterisk (*) represents any group of specific characters, along with additional characters. For example, searching quarr* will return studies which include the terms "quarry" and "quarries".

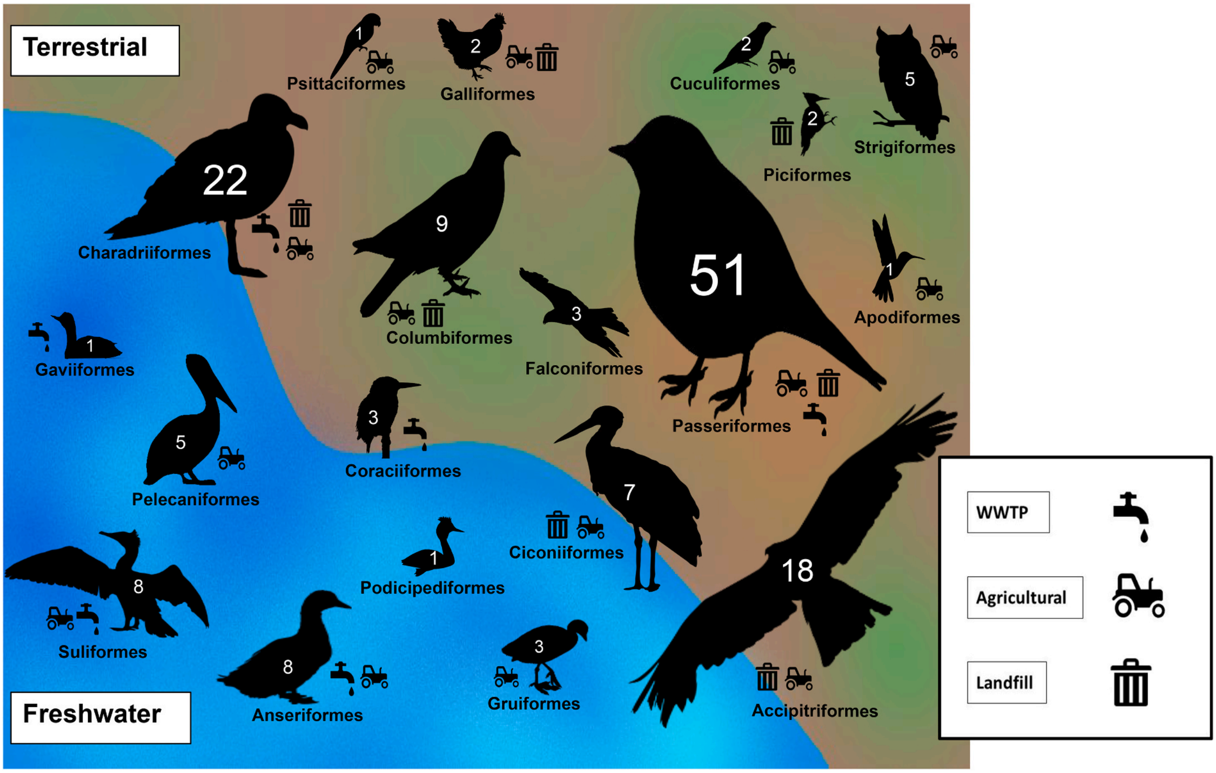

Fig. 2. A schematic diagram displaying a representation of avian orders in published studies of interactions between birds and freshwater/terrestrial plastics. The number inside each silhouette represents the number of studies per order. Avian orders at the boundary of the two environments are associated with both. Distance from the boundary of the two environment types does not reflect the degree of specialisation to that environment (e.g., owls are not more terrestrial than woodpeckers). The size of the silhouette is not proportional to the number of studies. Also displayed in the legend are the associated land use types (i.e., WWTP: wastewater treatment plant, agricultural land and landfill) for each order.

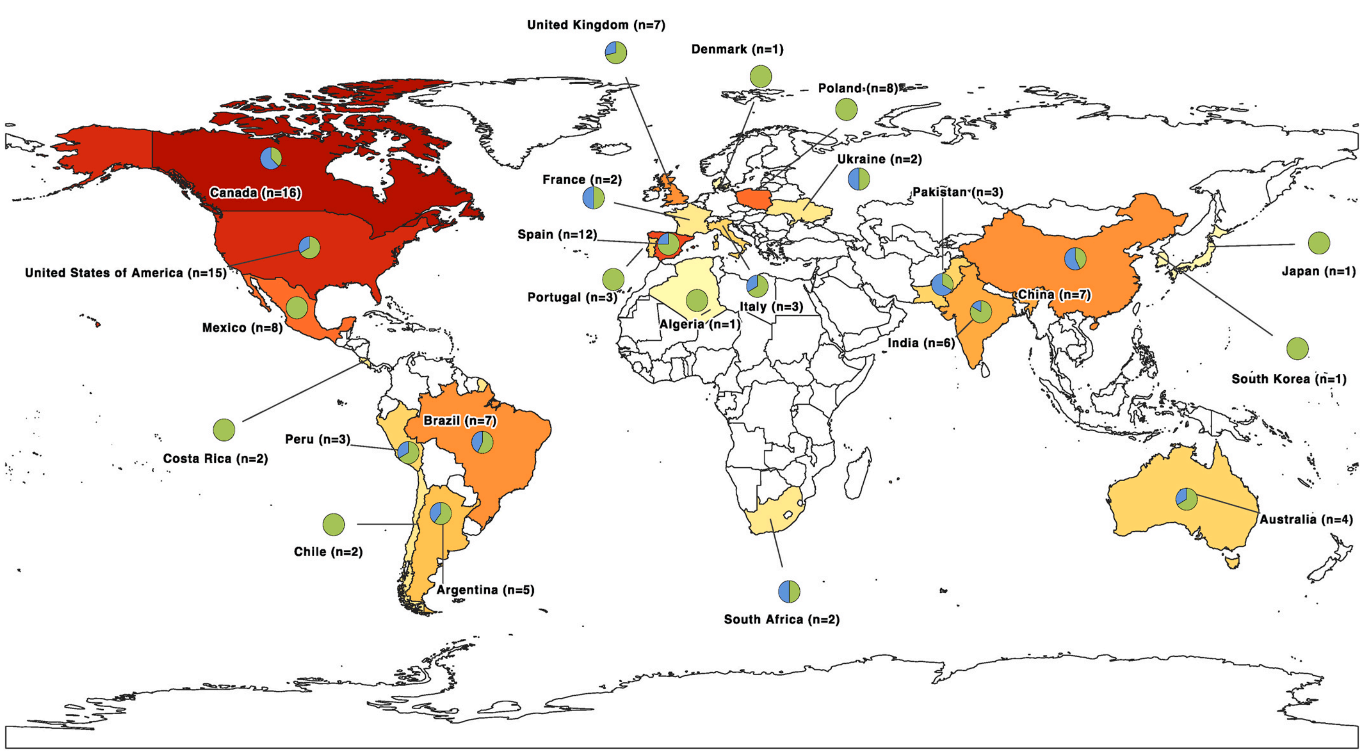

Fig. 3. Geographical distribution of studies of interactions between environmental plastic, and freshwater and terrestrial bird species. The pie charts show the proportion of terrestrial (green) and freshwater (blue) studies. Some studies include both environment types. The n refers to the number of studies found. A colour gradient on each country is used to indicate the number of studies (from n = 1 [yellow] to n = 16 [dark red]).

3.1.1. Global distribution of studies

Many studies were based in North America (n = 41), followed by Europe (n = 36) and South America (n = 19) and Asia (n = 18). Least represented by continent were those in Oceania (n = 4), and Africa (n = 3) (Fig. 3). In South America, Brazil (n = 6), which has the third highest number of bird species globally, and Argentina (n = 4) (BirdLife International, 2021a), which has the fifteenth highest number of bird species (BirdLife International, 2021b) have limited coverage, even though Jambeck et al. (2015) estimated Brazil and Argentina to be the fourth and fifth greatest producers of plastic waste in the world (11.85 and 2.75 million tonnes of plastic waste per year, respectively). Five of the Asian studies were conducted in India (e.g., Katlam et al., 2018; Francis et al., 2020; Francila et al., 2023), which is ranked ninth for global bird species (BirdLife International, 2021c). India is projected to become the fifth highest global producer of plastic waste by 2025 (Jambeck et al., 2015). The spatial bias in the studies sourced in this review is also seen in marine-based plastic bird studies, as recently discussed by Puskic et al. (2020).

3.2. Inter-specific trends in plastic exposure

3.2.1. Taxonomy

Nineteen orders of birds have been investigated (Fig. 2), the most represented being Passeriformes (songbirds) (n = 51 studies in this review). We anticipated an even greater representation of passerines because they belong to the largest order (i.e., 60% of extant bird species) (IUCN, 2021). They are also the principal order containing terrestrial species. This suggests a research bias towards non-passerine species, including gulls (i.e., Charadriiformes), many species of which occupy hotspots of plastic pollution such as landfill and wastewater treatment plants (WWTPs). Gulls were the second most represented order (n = 22 studies or 14%). Depending on the country of the study, many gull species can legally be ‘collected’ for research in part because of their ‘Least Concern’ conservation status. Vultures and other birds of prey (Accipitriformes) were moderately represented in studies (n = 18 studies). Birds of prey belong to high trophic levels, biomagnifying food chain plastics from lower trophic levels (Egwumah et al., 2017). Like gulls, they often roost and feed at landfills (Tongue et al., 2019) where they are more exposed to environmental plastics than other taxa. Birds of prey and gulls both regurgitate pellets of indigestible material including plastic, making them potent focal bioindicator species (Provencher et al., 2019).

Thirty-six studies reported plastic pollution across a range of species from the same order (e.g., Anseriformes – English et al., 2015; Charadriifomes – Seif et al., 2018; Passeriformes – Jagiello et al., 2023). Reynolds and Ryan (2018) found marked variation in microplastic contents in the faecal samples from seven duck species in South Africa. Interspecific differences may reflect contrasting foraging ecologies. For example, cape shovelers (*Spatula smithii*) primarily forage in lake water, whereas Egyptian geese (*Alopochen aegyptiaca*) forage on land. Out of 35 cape shoveler faecal samples, 17% contained plastic, compared to 1% of 60 Egyptian geese faecal samples.

3.2.2. Feeding guilds of birds

Omnivorous bird species (e.g., kelp gull [*Larus dominicanus*] – Witteveen et al., 2017; Eurasian dippers [*Cinclus cinclus*] – D’Souza et al., 2020) were the most frequently sampled group of birds (n = 64 studies), followed by carnivores (e.g., turkey vulture [*Cathartes aura*] – Torres-Mura et al., 2015; Andean condor [*Vultur gryphus*] – Gamarra-Toledo et al., 2023) (n = 30). Despite being biomagnifiers by feeding at high trophic levels on plastic-biaccumulating prey, fish-eating (piscivorous) bird species (e.g., common kingfisher [*Alcedo atthis*] – Winkler et al., 2020; double-crested cormorant [*Phalacrocorax auritus*] – Laurich et al., 2019) were only monitored in 15 studies. Insectivorous species (e.g., tree swallow [*Tachycineta bicolor*] – Sherlock et al., 2022; barn swallow [*Hirundo rustica*]- Tokunaga et al., 2023) were the subjects of 15 studies. Only eight studies monitored granivorous bird species (e.g., Gutiérrez-Galán and Alonso, 2016 – turtle dove [*Streptopelia turtur*]; Zheng et al., 2022 – spotted dove [*Spilopelia chinensis*]).

3.3. Plastic characterisation

3.3.1. Plastic size

Most studies in this review focused only on macroplastics (n = 72), followed by microplastics (n = 22), whilst 12 studies measured a mix of micro- and macroplastics. The first macroplastics study identified in this review was Ewins et al. (1994), whilst the first microplastics paper was English et al. (2015). The 21 years between them may be attributed to delays in developing repeatable analytical protocols and, indeed, laboratory equipment of sufficiently high resolution to detect microplastics. No study to date has identified nanoplastics in terrestrial or freshwater bird species possibly because of limited discriminatory capabilities of current analytical protocols for plastic recovery from complex biological matrices (Jakubowicz et al., 2021).

3.3.2. Plastic colour

The colour of plastic ingested by birds is informative in identifying foraging behaviours related to the dietary uptake of plastics (Provencher et al., 2017). Plastic colour was listed in 35 of the papers reviewed, white being the most commonly reported (n = 23 studies), followed by blue (n = 7) and red (n = 5) (Fig. S2). Zhao et al. (2016) reported mid-tone coloured plastics (e.g., pink, red) in 81.6% of gastro-intestinal (G-I) tract samples of 17 individual terrestrial birds in Shanghai, China. This bias may reflect foraging colour preferences for prey or ease of detection and ubiquity of such plastic in the environment (Sergio et al., 2011; Zhao et al., 2014). It is important to consider species-specific tetrachromatic colour vision systems, and subsequent differences in colour discrimination abilities in relation to plastic ingestion (Kelber, 2019; Martin, 2022).

3.3.3. Plastic type

Plastic type was only confidently identified in 19 studies using techniques such as Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy (i.e., Brookson et al., 2019; Carlin et al., 2020; D’Souza et al., 2020; Thaysen et al., 2020; Winkler et al., 2020; Borges-Ramírez et al., 2021; Cunha et al., 2021; Hoang and Mitten, 2022; Nessi et al., 2022 ; Sherlock et al., 2022; Zheng et al., 2022;Partridge et al., 2023 Kang et al., 2023; Tokunaga et al., 2023). Using FTIR, D’Souza et al. (2020) identified polyester, polyvinyl alcohol mixtures and vinyl chloride/vinyl acetate copolymers in adult and nestling Eurasian dipper regurgitates and faecal samples in South Wales, UK. Common sources of these polymers include textile coatings and concrete layers. Dippers likely frequently come into contact with these polymers as they are prevalent in urban areas. They are also present around, and on the surfaces of river sediments, making it possible for benthic prey of the dippers to transfer them through the riverine food chain. Polyethylene, another ubiquitous polymer in packaging material, was reported in many other studies (e.g., Brookson et al., 2019 – double-crested cormorant – Winkler et al., 2020 – common kingfisher).

Plastics were identified in a further 18 studies based only on visual techniques such as light microscopy. The most prevalent polymer in all studies was polyethylene (n = 11), followed by anthropogenic cellulose (n = 7).

3.3.4. Plastic form

The form of plastic was only reported in 58 papers and a lack of standardisation across studies resulted in the inconsistent use of terminology in published reports. Thread-like plastics and fibres were the most common plastic reported (n = 40), followed by sheet plastic (n = 14). Morphology or form was more frequently reported in microplastic studies (89% – 21 out of 22 studies which focused solely on microplastics) than macroplastic studies (38% – 27 out of 72). Fibres were the most abundant form of microplastic reported in papers (n = 17), followed by fragments (n = 9).

3.4. Plastic sampling methods

Birds can be used as bioindicators of pollutants through necropsy (e.g., Holland et al., 2016; Coughlan et al., 2021b) and gavage (i.e., flushing with water by insertion of a tube into the upper digestive tract) (e.g., Lavers et al., 2014), as well as via non-invasive sampling techniques such as feather clipping and plucking (e.g., Espín et al., 2014; Copat et al., 2020), egg sampling (e.g., Tongue et al., 2021), pellet collection (e.g. Winkler et al., 2020; Borges-Ramírez et al., 2021; Nessi et al., 2022) and faecal collection (e.g., Costa et al., 2014; Berglund et al., 2015) (Table S1).

3.4.1. Ingestion of plastic by birds

Fifty-seven of the studies in this review examined plastic ingestion by birds, with 23 using necropsy (Fig. 4). Necropsies allow for assessment of plastic loads, including sizes, colours and shapes/forms, in isolated sections of the G-I tract (e.g., Provencher et al., 2019). Internal injuries and/or death from plastic ingestion can be investigated, along with secondary impacts of plastic ingestion, such as chemical toxicity from plastic-associated chemicals (Thaysen et al., 2020).

Alternatively, plastic ingestion can be investigated non-destructively by collection of faeces, regurgitates or pellets (Provencher et al., 2019; Winkler et al., 2020), the latter being the most frequently described in literature (n = 24) (e.g., Torres-Mura et al., 2015; Francis et al., 2020; Ballejo et al., 2021). A drawback of pellet dissection is that pellets are not produced by all bird species so it can only be used on a subset of species. Gastro-intestinal tract contents can also be obtained from carrying out gavage, a procedure which, although invasive, rarely causes lasting harm to birds (Goldsworthy et al., 2016). We found one such study (kelp gull – Yorio et al., 2020).

Faecal samples have been examined for plastic in nine studies (i.e., Ewins et al., 1994; Gil-Delgado et al., 2017; Huerta Lwanga et al., 2017; Reynolds and Ryan, 2018; D'Souza et al., 2020; Coughlan et al., 2021a; Sherlock et al., 2022; Cano-Povedano et al., 2023; Charles et al., 2023). One limitation of faecal analysis is that faeces contain only plastic that has been excreted, not material that has been retained in the G-I tract or sequestered into other tissue compartments (Gil-Delgado et al., 2017).

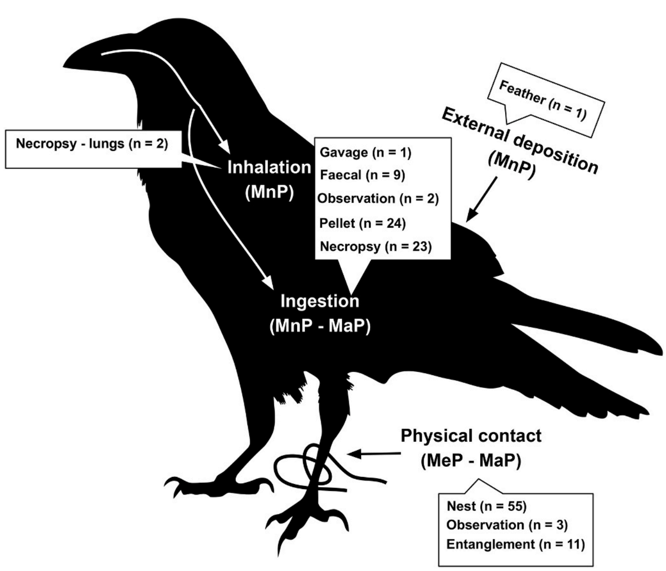

Fig. 4. The number of studies (n) of birds interacting with environmental plastic pollution according to the plastic sampling method. The number of published studies sum to more than 89 because some studies investigate more than one avian sample type. Plastic size ranges from micro-nanoplastics (MnP) to macroplastics (MaP) and megaplastics (MeP).

Both microplastic and macroplastic ingestion were measured in 35 different studies, respectively. Macroplastics were more abundant than microplastics in gavage samples (n = 1 and 0, respectively), and pellets (n = 21 and 8, respectively). In contrast, studies based on faecal samples more frequently reported microplastics than macroplastics (n = 8 and 3, respectively). Gastro-intestinal tracts also contained more microplastics than macroplastics (n = 19 and 10, respectively). Huerta Lwanga et al. (2017) found that microplastics accumulated most in faecal samples taken from domestic chickens (*Gallus domesticus*) (129.8 ± 82.3 particles g^{-1} of faeces) followed by gizzards (10.2 ± 13.8 g^{-1}), while the crop (an expandable pouch-like section of the oesophagus, which stores food prior to ingestion) contained no microplastics. Faecal samples are likely to contain more microplastics because macroplastics are degraded into microplastics at earlier stages of digestion such as when transferred from the crop where ingesta is stored to the gizzard where mechanical digestion takes place (Duke, 1997; Klasing, 1999). In contrast, macroplastics were present in both gizzards (45.8 ± 42.6 g^{-1}) and crops (11.0 ± 15.3 g^{-1}) of the same birds. The prevalence of macroplastics in the gizzard and crop may reflect the retention of larger plastic fragments at early stages of digestion that are not then excreted (Ryan and Jackson, 1987). This may also be explained by their higher detectability compared to microplastics (Nguyen et al., 2019).

3.4.2. Inhalation of plastic by birds

Two studies measured microplastics in lung samples from free-living terrestrial and freshwater bird species (Qaiser et al., 2023; Tokunaga et al., 2023). Qaiser et al. (2023) measured microplastic load in 10 free-living necropsied white-breasted kingfishers (*Halcyon smyrnensis*), using a stereomicroscope. Microplastics were found in lung samples from five of these birds whilst all samples from their G-I tracts contained microplastics, potentially indicating that ingestion was the main route for microplastic internalisation in birds, rather than inhalation. Using micro-Fourier transform infrared (μFTIR) spectroscopy, Tokunaga et al. (2023) measured microplastics in the lungs of free-living rock doves (*Columba livia*), black kites (*Milvus migrans*), and barn swallows in Japan, all hunted for pest control. Of the 22 lung samples analysed, three polymers were identified (polypropylene, polyethylene, and ethylene vinyl acetate). Unlike Qaiser et al. (2023), Tokunaga et al. (2023) did not measure microplastic ingestion in parallel with inhalation.

3.4.3. Monitoring of environmental plastic load

Feathers could be used to measure background plastic load in freshwater and terrestrial environments, as they may trap microplastics on their surface. Reynolds and Ryan (2018) is the only study to measure plastics (microplastics) on the feathers of waterbirds but no such study has been carried out on terrestrial species. In particular, the presence of microplastics on the feathers of aquatic bird species may increase oil pollution adsorption rates onto the feathers, and subsequently lead to feather damage and reduced water resistance (Jeong et al., 2023).

Birds can also interact with environmental plastic during nesting. Jagiello et al. (2019) reviewed the literature and found that nests of terrestrial species were more likely to contain anthropogenic debris (including plastic) than those of marine species. We found 55 studies that reported plastic in nests, revealing the potential to use nest deconstruction to monitor plastic pollution within the immediate nest vicinity of species (O'Hanlon et al., 2021). Lato et al. (2021) and Escalona-Segura et al. (2022) were the only studies in this review which quantified microplastics in nests. Lato et al. (2021) measured plastics in the nests of American herring gulls (*Larus smithsonianus*) and great black-backed gulls (*Larus marinus*) in northeastern USA. Plastics were isolated using mesh sieves (1.0 and 5.0 mm) and identified with a 3-inch diameter 5 diopter magnifying lamp (a light and magnifying glass) and dissection microscope (only plastics 1–5 mm in diameter were analysed using the microscope). The authors suggested that spectroscopy would improve plastic identification and description.

Eleven studies out of 106 provided accounts of bird entanglement with plastic both in, and outside of, nests. They are informative as snapshots of plastic load in terrestrial and freshwater environments and of plastic-related injuries to birds (Townsend and Barker, 2014) by highlighting the adverse effects of environmental plastics. As in the case of data from birds examined by necropsy, reports of plastic entanglement are of limited worth because they commonly lack associated life-history data from the individual birds involved (Kelly and Kelly, 2004). If a bird is found dead in the field it is not possible to attribute with confidence the cause of death as plastic, rather than another causal agent.

3.4.4. Inter-sample comparisons of plastic load

Twenty-four studies used more than one type of sampling method to compare plastic loads. Reynolds and Ryan (2018) measured microplastic ingestion in ducks (Anatidae) in the Western Cape, South Africa and found that 5% of faecal samples (n = 283 samples) and 10% of feather samples (n = 408 samples) contained microplastic fibres. These studies indicated that because many ingested plastic pieces are likely to be regurgitated as pellets (Winkler et al., 2020), faecal samples containing low plastic loads likely under-estimate plastic ingestion (Bond et al., 2021).

3.4.5. Life stage of birds

Life stage of organisms at the time of monitoring may determine important variation in plastic exposure. An advantage of monitoring plastic load of nestlings is that in altricial and semi-altricial species they are often either nidicolous for a large proportion of the nestling stage or move short distances from the nest before fledging compared with adult birds. Exposure to plastic of nestlings therefore reflects local environmental plastic pollution, including the foraging area of nestling-provisioning parents. Eight studies investigated plastic ingested by nestlings, including analyses of faeces (D'Souza et al., 2020; Sherlock et al., 2022), observations of nestling-provisioning by adults (Brown and Ewins, 1996), gavage of G-I tracts (Yorio et al., 2020), and necropsy (Brookson et al., 2019; Méndez et al., 2020; Sherlock et al., 2022; Bilal et al., 2023; Leviner and Perrine, 2023). Yorio et al. (2020) randomly collected pellet samples (n = 2355 samples) of breeding adult kelp gulls in Chubut, Argentina. Plastic was present in pellets at all nine breeding colonies of birds under investigation. Gastro-intestinal tract samples (n = 588 samples) of nestlings from five of six colonies sampled also contained plastic, which implies that contamination occurs during feeding around breeding sites, as young in the nest cannot feed independently.

3.5. Analytical techniques and plastic characterisation

3.5.1. Pre-processing of avian samples in the laboratory

In order to identify and quantify plastics in biological samples, plastic must be isolated from the organic matrix in which it is held, through digestion, suspension, sieving, filtration etc. This is important in staining techniques such as Nile Red (Nel et al., 2021) because organic material in the matrix can also fluoresce, thereby resulting in false-positives. Ten studies used digestion methods in the form of potassium hydroxide (KOH)-based solutions to digest organic matrices in samples collected from avian G-I tracts before identification of plastics (i.e., Zhao et al., 2016; Brookson et al., 2019; Carlin et al., 2020; Deoniziak et al., 2022; Qaiser et al., 2023 Sherlock et al., 2022; Zheng et al., 2022; Bilal et al., 2023; Charles et al., 2023; Leviner and Perrine, 2023). Another three studies used hydrogen peroxide (H_2O_2) (Coughlan et al., 2021a,b; Nessi et al., 2022) and iron (Fe) in the form of Fenton's Reagent (containing H_2O_2 and Fe) to isolate plastic from its organic matrix. Overall, KOH is considered more effective for digesting animal-derived matrices such as feathers, whilst Fenton's Reagent is effective in digesting woody organic matter such as driftwood (Prata et al., 2019) and so might hold promise in isolating plastic from nest samples. This review found no articles using such digestion methods to isolate plastic in feather or nest samples, but this has been achieved in egg matrices (e.g., Kirkwood, 2020; Liu et al., 2022). Liu et al. (2022) used KOH to digest the egg white and yolk, and isolate potential plastic contamination which may be passed from parent into the egg. Density separation is also used to distinguish plastic from organic and inorganic (non-plastic) matter. This involves suspending the sample in a liquid of intermediate density such as sodium chloride (NaCl) or zinc chloride ($ZnCl_2$), and materials passively separate based on their weights, and the floating plastics can then be retrieved via filtration. Huerta Lwanga et al. (2017) added demineralised water to samples from avian gizzards, faeces and crops, and recovered floating micro- and macroplastics after 24 h. This latter approach has significant limitations, as smaller pieces (i.e., micro- and nanoplastics), denser plastics and dirty plastics made heavier by fouling may not be detected.

Whilst some studies used microscopy (e.g. binocular) to aid plastic identification (e.g., D'Souza et al., 2020; Nessi et al., 2022), use of visual identification alone should be avoided where possible as it lacks accuracy (Kalaronis et al., 2022). Potential plastics can also be identified using the melting test (De Witte et al., 2014), where a hot needle is applied to an unidentified fragment, and if the fragment melts, it is likely to be plastic. This review only found four studies using this technique (Zhao et al., 2016; Deoniziak et al., 2022; Charles et al., 2023; Qaiser et al., 2023). Although this method is quick and cost-effective, it is susceptible to generating false negatives because some materials containing plastic do not respond predictably to a hot needle (Minor et al., 2020). One study used a scanning electron microscope (SEM) (Winkler et al., 2020).

3.5.2. Polymer identification in avian samples

Polymer identification can link pollutants to their original source (Löder and Gerdts, 2015). The majority of studies (i.e., 87 of 106) identified material as plastic without confirming its polymer composition using identification methods such as Raman spectroscopy. For example, Brookson et al. (2019), Thaysen et al. (2020), Sherlock et al. (2022) and Cunha et al. (2021) identified plastic composition with Raman spectroscopy, which involves firing a laser at a sample of the plastic. The vibrations exerted from the sample are then converted into visual spectra. Different wave peaks are associated with different chemical groups and can be identified with reference to existing spectral libraries (e.g., Butler et al., 2016; Germond et al., 2017; Ntziouni et al., 2022). Three of these four studies (except Cunha et al., 2021) also used FTIR to identify the main polymers of the plastic fragments identified. A further 11 studies (e.g., Carlin et al., 2020; D'Souza et al., 2020; Winkler et al., 2020; Borges-Ramírez et al., 2021; Escalona-Segura et al., 2022; Bilal et al., 2023; Cano-Povedano et al., 2023; Tokunaga et al., 2023; Girão et al., 2024) relied solely on FTIR to identify the plastics. Like Raman spectroscopy, FTIR also identifies molecules using a spectral library, based on vibrations of the molecules when irradiated with infrared light (Hidalgo-Ruiz et al., 2012; Mecozzi et al., 2016; Xu et al., 2019). Zheng et al. (2022) used an alternative polymer identification method called laser infrared imaging spectrometry, where the size and abundance of plastics were measured and then formally identified using a spectral library.

3.5.3. Characterisation of plastic-associated chemicals

The efficacy of laboratory-based procedures for analysing plastic-associated chemicals (e.g., phthalates, bisphenols and flame retardants – UNEP and BRS, 2023) in biological samples, in the form of either intentional additives or environmentally acquired sorbed co-pollutants, vary depending upon sample type and target chemicals. Thaysen et al. (2020) was the only study to analyse avian samples for plastic-associated chemicals. Gastro-intestinal tracts were removed in the field before analysis for a range of flame retardants. Thaysen et al. (2020) used pyrolysis gas chromatography mass spectrometry (pyGC-MS), a process where samples are volatised and separated into compounds, and a retention time is recorded (the time taken for each compound to travel through the column to the detector) (Shellie, 2013). The mass spectrum for each compound is then compared to known mass spectra.

3.5.4. Quality control and standardisation of avian samples

Quality assurance and quality control (QA/QC) is important when measuring the plastic load in biological samples (particularly when the plastics in question are micro- and nanoplastics). When collecting samples in the field, air blanks should be taken in order to account for environmental contamination of samples from plastic aerosols. The containers used to hold the samples should also be accompanied by blank containers for QA/QC purposes. To reduce accidental contamination of samples, strict anti-contamination measures should be in place, both in the field and in the laboratory. Equipment such as glassware and tweezers should be washed free of plastics (e.g., with deionised water) to remove plastic residues before their use in the field and laboratory. Samples should be handled by experimenters wearing plastic-free gloves and cotton clothing.

3.6. Land use associated with birds and plastic exposure

3.6.1. Agricultural land

Agriculture is a key land use associated with plastic pollution, primarily due to the application of contaminated sewage sludge as fertiliser on soil (Corradini et al., 2019) and the use of plastic in agriculture (e.g., mulching, polytunnels). We identified 17 studies of birds exposed to agricultural sources of plastic that referred to macroplastics used in agricultural cultivation. For example, baling twine sourced from agricultural practices was commonly reported in birds' nests (e.g., Antczak et al., 2010; Townsend and Barker, 2014; Potvin et al., 2021; Jagiello et al., 2023 and references therein). Whilst research has shown that microplastics are being ingested by livestock (Beriot et al., 2021), few studies have investigated agriculture-derived microplastics in free-living birds (e.g., Gil-Delgado et al., 2017; Thaysen et al., 2020; Ballejo et al., 2021; Nessi et al., 2022; Charles et al., 2023).

3.6.2. Landfills and wastewater treatment plants

Twenty-three studies (22%) proposed landfill as a main source of plastic pollution (e.g., Henry et al., 2014; Lopes et al., 2021), with plastic products such as rubber bands tracked to landfills.

We found no studies that directly investigated plastic loads of passerines in relation to landfill, despite the fact that passerines such as common starlings (*Sturnus vulgaris*) and carrion crows (*Corvus corone*) are frequently observed on landfill (Arnold et al., 2021). Wastewater treatment plants were referenced as sources of environmental plastic in seven studies (i.e., Sazima and D'Angelo, 2015; da Silva et al., 2018; Reynolds and Ryan, 2018; Brookson et al., 2019; Thaysen et al., 2020; Winkler et al., 2020; Sherlock et al., 2022). Although acknowledged as major sources of plastic pollution (Mahon et al., 2017), WWTPs have not been frequently considered in such studies of birds. Winkler et al. (2020) measured microplastic load in 133 pellets collected from common kingfishers along the Ticino River, North Italy. Microfibres were the most common form of plastic detected in the samples (11 out of 12 of them found microplastics). The authors suggest that the nearby WWTP, which releases its effluent into the river, may be a dominant source of the microfibres, with many of the fibres likely to have originated from textiles.

3.6.3. Urban environments

Several previous studies have related the degree of urbanisation to microplastic pollution (e.g., Reynolds et al., 2016; Hanmer et al., 2017; Jagiello et al., 2020, 2023; Lato et al., 2021; Deoniziak et al., 2022; Vasquez et al., 2022; Partridge et al., 2023). Jagiello et al. (2020) monitored plastic loads in 49 nests of white storks (*Ciconia ciconia*) in Madrid, Spain. A Human Footprint Index (HFI) based on human activity ratios (i.e., a proxy for human population impacts) was calculated for each nest location, with a 1 km^2 accuracy. Fifty-seven percent of nests contained anthropogenic debris, the weight of which was positively related to the HFI. In contrast, Reynolds et al. (2016) found no significant effect of position along an urban gradient in Birmingham, UK on anthropogenic material content (including plastic) of nests of urban blue tits (*Cyanistes caeruleus*). These inconsistent findings may be explained by, *inter alia*, differences between species in nest-building behaviour (Jagiello et al., 2023), the different distances travelled between nests and plastic hotspots such as landfill sites (Jagiello et al., 2020), and even the ways that urbanisation is described and quantified between studies. In the latter case, Reynolds et al. (2016) established an urban gradient by percentage of connected tree cover and built cover whereas Jagiello et al. (2020) did so using the HFI.

Land-use comparisons can be made by monitoring birds which forage across several habitat types. Méndez et al. (2020) and Thaysen et al. (2020) used Global Positioning System (GPS) tracking to study foraging activity and habitat use by ring-billed gulls (*Larus delawarensis*) in multiple environments. Méndez et al. (2020) found that in seven adult GPS-tagged yellow-legged gulls (*Larus michahellis*) in Barcelona, Spain, 52% of all GPS locations were in urban areas. Fifty percent of G-I tract samples taken from 101 nestlings contained plastic.

3.7. Impacts of environmental plastics on birds

3.7.1. Entanglement

Birds can interact directly with plastic in the environment and become entangled in it. Injury and death occurred in all 15 studies that reported incidences of plastic entanglement. Townsend and Barker (2014) found that 11 of 195 American crow nestlings were entangled with anthropogenic material, including plastic in the nests. Nestlings that were entangled had significantly lower fledging success rates. Reported associated impacts of entanglement included bone malformation, and one individual was found deceased, with its legs bound together with synthetic string.

3.7.2. Nest detection and predation rates

Plastic may make nests more susceptible to nest detection by predators. Møller (2017) monitored nest predation rates in relation to plastic load in nests of common blackbirds in Denmark. Predation (nests that were destroyed, or nests where nestlings did not develop into fledglings) was significantly higher in nests containing plastic (49.4%: 42 of 86 nests) than those that were plastic-free (29.1%: 162 of 556 nests). However, this trend only applied to outdoor nests, as indoor nests (i.e. inside stables and barns) in this study had the same predation rates regardless of plastic presence/absence. In contrast to the correlative nature of the study by Møller (2017), Canal et al., 2016 experimentally altered plastic content in the nests of black kites, by adding white plastic bags to some of the nests. Using Unmanned Aircraft Systems to simulate black kite visual perception, human participants of the study recorded nest detection rates. The nests with added plastic were more easily detected, compared to undecorated nests, which may leave the nests more susceptible to predation. However, plastic nest decorations may signal high fitness, with decorated nests leading to less challenges over territory for the adult birds occupying the nest (Sergio et al., 2011).

3.7.3. Ectoparasite load

Six studies reported changes in ectoparasite load of nests in relation to plastic nest constituents (i.e., Suárez-Rodríguez et al., 2013; Suárez-Rodríguez and Garcia, 2014, 2017; Reynolds et al., 2016; Hanmer et al., 2017; Potvin et al., 2021). Suárez-Rodríguez and Garcia (2017) manipulated the plastic load in nests of house finches (*Carpodacus mexicanus*) in Mexico by relining them with brown felt (a substitute for natural nest lining materials) to test the impact of cigarette butts on ectoparasites. Ectoparasites (live, dead or a mimicked control) were then incorporated into the artificially-lined nests. Birds brought significantly more cigarette butt fibres to nests containing more ectoparasites compared to control (unmanipulated) nests. Nests with higher proportions of cigarette butts in the nests pre-manipulation had higher fibre content following manipulation. This may reflect a self-medicative behavioural response to reduce nest infestation rates, as the chemicals (e.g., nicotine) in cigarettes have anti-parasitic properties (Schorderet Weber et al., 2019).

Neither Reynolds et al. (2016) nor Potvin et al. (2021) found statistically significant relationships between anthropogenic material (including plastic) content of nests and ectoparasite load. Nests across both studies may contain fewer anthropogenic materials with anti-parasitic properties (e.g., cigarette butts – Suárez-Rodríguez and Garcia, 2014) and have lower ectoparasite loads. Storage and preparation processes (e.g., museum samples treated by removing parasites) may further lower ectoparasite loads.

3.7.4. *Impacts of plastic ingestion on avian health*

One study recorded mortality due to physical complications from plastic ingestion. Henry et al. (2014) found that 26% (15 of 57) of white storks necropsied in Alsace, France had G-I tracts containing rubber bands, and five individuals were reported to have died from gut obstruction and subsequent starvation.

Thaysen et al. (2020) reported likely bi-directional transfer of halogenated flame retardants (HFRs) on plastics ingested by ring-billed gulls on landfill on Deslauriers Island, Montreal, Canada, by comparing HFR concentrations found on ingested plastic (isolated from G-I tracts), and in plasma samples taken from the same individuals (n = 25 birds). Halogenated flame retardant concentrations were mostly higher on ingested plastic than in the plasma. Ingested plastic might therefore act as a vehicle for 'cleaning up' HFRs, with chemical transfer predominantly taking place from bird to plastic.

Finally, Cunha et al. (2021) measured biomarkers of toxicity in adult black vultures (*Coragyps atratus*) collected from landfill in Goiás, Brazil, to examine the physiological consequences of plastic ingestion. Although only correlative, results suggested that birds that had consumed plastic had higher concentrations of biomarkers of toxicity, including reactive oxygen species (ROS) such as H_2O_2 and malondialdehyde, when compared with control birds found with no plastic in their G-I tracts.

4. Summary and recommendations for further research

4.1. *Research gaps*

This review has identified a key research gap: no study to date has attempted to investigate the smallest of environmental plastics (i.e., nanoplastics) in freshwater or terrestrial bird species. Only one study (Potvin et al., 2021) used nest specimens in a museum collection to examine temporal trends in environmental plastic pollution but, to the best of our knowledge, no study has measured plastic pollution in the biological samples (e.g., feathers, lungs) from avian museum specimens of any terrestrial, freshwater or marine environment. Existing studies of other pollutants that have investigated avian museum specimens (e.g., DuBay and Fuldner, 2017; Movalli et al., 2017) should be consulted when developing protocols to study environmental plastic pollution when using such museum sources. Furthermore, this review found no study that has attempted to bridge the gap between plastic and associated chemicals in a terrestrial or freshwater songbird species; this is particularly concerning given that such species make up more than 50% of the world's avifauna.

4.2. *Further research*

This review has revealed significant knowledge gaps in the study of pathways of transfer of environmental plastic into, and impacts on, terrestrial and freshwater birds. We suggest the following as potentially important directions for future research in this regard:

4.2.1. *The setup of robust analytical methods to enable detection, identification and quantification of micro- and nanoplastic exposure of terrestrial and freshwater birds*

Our current understanding of the relationships between biota and airborne micro- and nanoplastics is particularly limited; methods to track such particles' movement in terrestrial and freshwater environments are lacking. Researchers should ideally design studies that collect at least two different sample types (e.g., faecal and pellets) per exposure route, and analyse background environmental samples (Table 1). Studies that include both macro- and microplastics are most informative as they provide empirical data for one of the principal sources of microplastics. On a wider scale, birds should be a key focal taxon for the study of airborne nanoplastic pollution, as they are likely to be the most vulnerable animal class to airborne plastics by virtue of their high breathing rates and exposure to atmospheric sources during flight. Although Raman spectroscopy and FTIR can both effectively reveal the polymer composition of micro- and macroplastics, misidentification is more likely for nanoplastics as they are logistically challenging to detect and quantify because of their small size and the current resolution limits of analytical approaches (Löder and Gerdts, 2015; Cai et al., 2021). Development of suitable nanoplastic separation and detection methods for biological samples is needed to enable reliable detection of nanoplastics in terrestrial and freshwater bird species. It will be beneficial to refer to comparable studies assessing other micron-sized materials, where bird samples have been analysed using techniques such as spectroscopy. For example, Shim and Lee (2020) analysed nests of cave swiftlets (*Aerodramus fuciphagus*) for micron and sub-micron calcite particles using SEM, FTIR and Raman spectroscopy.

4.2.2. *Adopt standardised protocols for sampling plastics (including QA/QC) and for characterising (describing) and identifying (naming) plastics (and their additives where possible)*

Researchers should report their findings in as much detail as possible – including plastic forms, colours, sizes, and confirmatory techniques such as hot needle, Nile Red staining, or chemical identification including FTIR. To measure the behavioural and toxicological impacts of exposure to plastics on terrestrial and freshwater birds, and further our understanding of impacts of micro- and nanoplastics, protocols need to be standardised. Prioritising QA/QC will aid the testing of feather and nest samples as plastic indicators, as both materials are readily subject to contamination and provide important insights into background levels and sources of exposure.

4.2.3. *Track the transfer of plastics along food chains of birds and within a broader taxonomic base*

To date, studies have partially examined omnivores' and carnivores' food chains but piscivores remain under-represented. Species at higher trophic levels are more susceptible to plastic ingestion due to biomagnification. Insectivores and granivores are under-studied and so future studies should examine plastic loads of birds and their food at each trophic level as potential ways to characterise patterns of plastic transfer and biomagnification. Only 19 orders were investigated for plastic exposure, out of a total of 44 orders that currently exist globally (Gill, et al., 2023). Investigating plastic pollution across all orders will further our understanding of how different bird species are differentially affected, along with accessing information about plastic pollution in a broader variety of environments. Additionally, food chain analysis will further our understanding of the transfer of plastics within and between compartments in terrestrial and freshwater environments.

4.2.4. *Monitor birds for sub-lethal impacts from plastic ingestion*

We are only aware of one existing study which has controlled plastic ingestion and measured health impacts in a passerine bird, but this was under captive conditions (de Souza et al., 2022). Experimentation on either captive or free-living individuals to measure sub-lethal impacts of plastic ingestion is rightly precluded by ethical concerns and wider issues of animal welfare, and we therefore do not support this type of research. There are further potential limitations of controlled trials, including higher costs, more set up time required (e.g., creating the correct laboratory conditions, and obtaining licences to work with captive animals), and under- or over-estimations of the impacts of plastic pollution on free-living birds, as plastic loads used in controlled settings may not represent true environmental loads. We instead recommend that studies focus on pre-existing sub-lethal effects (i.e., physiological changes) in free-living birds already known to be exposed to high environmental plastic loads. Research should explore the bio-analysis of non-destructive avian samples such as faeces and pellets to screen for changes in the gut microbiome, particularly, to detect changes in intestinal gene expression in response to plastic exposure (Lear et al., 2021). Sub-lethal behavioural changes such as modification of foraging distances should be closely studied in free-living birds (e.g., passerines).

4.2.5. Investigate susceptibility of species (especially passerine species) to microplastics sourced from agricultural sludge, WWTPs and landfills

Passerines generally do not produce pellets so non-invasive methods for plastic monitoring might involve analysis of nests, feathers, faeces and tissues from opportunistic necropsies. Stable isotope analysis of avian tissue samples is useful in dietary analyses (Inger and Bearhop, 2008; Bond and Hobson, 2012), and could be an informative tool to identify potential plastic hotspots. Isotope ratios enable researchers to build a temporal and spatial profile of the dietary niche, by matching the consumer's (i.e., terrestrial and freshwater bird's) isotope ratios in the consumer samples (e.g., pellets) with ratios of food sources (Perkins et al., 2014).

4.2.6. Increased ornithological research investigating birds as plastic bioindicators in countries where forecasts suggest that environmental plastic is to become a pollution crisis

Future research should focus on highly populated and rapidly developing countries in Asia, including India, Bangladesh, the Philippines and Pakistan, as all four countries were predicted to, and indeed have experienced, significant increases in mismanaged plastic waste from 2010 to 2025 (4.8%, 2.8%, 2.71% and 2.54% percentage increase in million metric tonnes per year, respectively) (Jambeck et al., 2015). Countries in Africa should also be prioritised, particularly Nigeria, which is predicted to have a 45.1% increase in coastal population between 2010 and 2025, accompanied by a 2.92% increase of mismanaged plastic waste in million metric tonnes per year. Senegal's coastal population is also predicted to increase by 44.3%, placing it eighteenth globally for annual volumes of mismanaged waste by 2025, despite not previously having been ranked within the top 20 countries in 2010. Research should also be continued in South American countries, as they are important from a conservation perspective, with high bird species richness, and many bird species which are ecologically rare (Loiseau et al., 2020). In order to determine with accuracy hot spots of plastic pollution, future work should also consider approaches to normalise the emissions per capita and/or land or coastal surface area to allow differences in population densities to be disaggregated from differences in waste management or mismanagement approaches.

4.2.7. Apply a wider range of sampling methods to a wider range of geographical locations

Undertaking studies in a wider range of countries might involve developing novel methods to obtain samples from species that have not been previously investigated and must incorporate indigenous knowledge and respect the CARE (collective benefit, authority to control, responsibility and ethics) principles for indigenous data governance (Jennings et al., 2023). Comparing terrestrial and freshwater plastics in bird populations intercontinentally or across countries would be a useful tool for highlighting potential variations in plastic pollution due to contrasting waste management strategies.

4.2.8. Standardising field methodologies to quantify environmental plastic pollution

Comparative systematic reviews are of limited worth if studies cannot be directly compared. This is difficult when different methodological approaches have been adopted by the different studies under scrutiny; this certainly applies to research that documents environmental plastic pollution in terms of quantifying exposure of birds and other animal taxa to plastics. We urge researchers to adopt the CSIRO Global Leakage Baseline Project survey methodologies (http://hdl.handle.net/102.100.100/389141?index=1) (Schuyler et al., 2017) to determine and report environmental plastics.

4.2.9. Increase collaborative research, especially with marginal and emerging research groups

Emerging and less established research groups can often be based in economic areas where there is less funding support available to develop their own research facilities. Therefore, collaboration across research groups, particularly focusing on supporting these smaller groups should be encouraged. In addition, increasing the number of open access spectral libraries for Raman and FTIR analysis, and other plastic identification techniques will also make research within this field more inclusive. In return, this will increase our overall understanding of global plastic pollution by expanding the geographical areas of research.

Research into terrestrial and freshwater bird species as bioindicators of plastic pollution is in its infancy and, therefore, synergistic research efforts across multiple disciplines (e.g., atmospheric chemistry, ecology and material sciences) are crucial. This will enable researchers to highlight potential uptake routes of nanoplastics, and to identify specific taxa that are most at risk based on their distributions, foraging ecology, behavioural traits and physiology. In summary, advancing research in this interdisciplinary direction will reinforce the use of avian biological samples collected to measure plastic pollution in terrestrial and freshwater ecosystems. This will increase our understanding of the real and potential sources of plastic pollution and the fundamental role that bird species play in bioaccumulating and transporting plastic in the environment. Growth in this area of applied ornithology is certain to have positive implications for wildlife conservation as well as providing human health benefits.

CRediT authorship contribution statement

I. Mansfield: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **S.J. Reynolds:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **I. Lynch:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **T.J. Matthews:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **J.P. Sadler:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors gratefully acknowledge provision of a CENTA studentship award to IM by the UK Natural Environment Research Council (NERC ref. NE/S007350/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.123790.

References

Acampora, H., Schuyler, Q.A., Townsend, K.A., Hardesty, B.D., 2014. Comparing plastic ingestion in juvenile and adult stranded short-tailed shearwaters (Puffinus tenuirostris) in eastern Australia. Mar. Pollut. Bull. 78, 63–68. https://doi.org/10.1016/j.marpolbul.2013.11.009.

Acampora, H., Lyashevska, O., Van Franeker, J.A., O'Connor, I., 2016. The use of beached bird surveys for marine plastic litter monitoring in Ireland. Mar. Environ. Res. 120, 122–129. https://doi.org/10.1016/j.marenvres.2016.08.002.

Akhbarizadeh, R., Dobaradaran, S., Nabipour, I., Tajbakhsh, S., Darabi, A.H., Spitz, J., 2020. Abundance, composition, and potential intake of microplastics in canned fish. Mar. Pollut. Bull. 160, 111633 https://doi.org/10.1016/j.marpolbul.2020.111633.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., Galop, D., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12, 339–344. https://doi.org/10.1038/s41561-019-0335-5.

Amato-Lourenço, L.F., Dos Santos Galvão, L., de Weger, L.A., Hiemstra, P.S., Vijver, M. G., Mauad, T., 2020. An emerging class of air pollutants: potential effects of microplastics to respiratory human health? Sci. Total Environ. 749, 141676 https://doi.org/10.1016/j.scitotenv.2020.141676.

Antczak, M., Hromada, M., Czechowski, P., Tabor, J., Zabłocki, P., Grzybek, J., Tryjanowski, P., 2010. A new material for old solutions—the case of plastic string used in great grey shrike nests. Acta Ethol. 13, 87–91. https://doi.org/10.1007/s10211-010-0077-2.

Arnold, Z.J., Wenger, S.J., Hall, R.J., 2021. Not just trash birds: quantifying avian diversity at landfills using community science data. PLoS One 16, e0255391. https://doi.org/10.1371/journal.pone.0255391.

Ashton, K., Holmes, L., Turner, A., 2010. Association of metals with plastic production pellets in the marine environment. Mar. Pollut. Bull. 60, 2050–2055. https://doi.org/10.1016/j.marpolbul.2010.07.014.

Avery-Gomm, S., Provencher, J.F., Morgan, K.H., Bertram, D.F., 2013. Plastic ingestion in marine-associated bird species from the eastern North Pacific. Mar. Pollut. Bull. 72, 257–259. https://doi.org/10.1016/j.marpolbul.2013.04.021.

Avery-Gomm, S., Provencher, J.F., Liboiron, M., Poon, F.E., Smith, P.A., 2018. Plastic pollution in the Labrador Sea: an assessment using the seabird northern fulmar Fulmarus glacialis as a biological monitoring species. Mar. Pollut. Bull. 127, 817–822. https://doi.org/10.1016/j.marpolbul.2017.10.001.

Avio, C.G., Gorbi, S., Regoli, F., 2017. Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. Mar. Environ. Res. 128, 2–11. https://doi.org/10.1016/j.marenvres.2016.05.012.

Aziz, B., Zubair, M., Irshad, N., Ahmad, K.S., Mahmood, M., Tahir, M.M., Shah, K.H., Shaheen, A., 2021. Biomonitoring of toxic metals in feathers of birds from North-Eastern Pakistan. Bull. Environ. Contam. Toxicol. 106, 805–811. https://doi.org/10.1007/s00128-021-03184-w.

Baines, C., Lerebours, A., Thomas, F., Fort, J., Kreitsberg, R., Gentes, S., Meitern, R., Saks, L., Ujvari, B., Giraudeau, M., Sepp, T., 2021. Linking pollution and cancer in aquatic environments: a review. Environ. Int. 149, 106391 https://doi.org/10.1016/j.envint.2021.106391.

Ballejo, F., Plaza, P., Speziale, K.L., Lambertucci, A.P., Lambertucci, S.A., 2021. Plastic ingestion and dispersion by vultures may produce plastic islands in natural areas. Sci. Total Environ. 755, 142421 https://doi.org/10.1016/j.scitotenv.2020.142421.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

BBC, 2020. Plastics an 'unfolding disaster' for US marine life BBC US & Canada [viewed 27 April 2022]. Available from: https://www.bbc.co.uk/news/world-us-canada-55006333.

Beraldi-Campesi, H., 2013. Early life on land and the first terrestrial ecosystems. Ecol. Process. 2, 1. https://doi.org/10.1186/2192-1709-2-1.

Berglund, Å.M., Rainio, M.J., Eeva, T., 2015. Temporal trends in metal pollution: using bird excrement as indicator. PLoS One 10, e0117071. https://doi.org/10.1371/journal.pone.0117071.

Beriot, N., Peek, J., Zornoza, R., Geissen, V., Huerta Lwanga, E., 2021. Low density-microplastics detected in sheep faeces and soil: a case study from the intensive vegetable farming in Southeast Spain. Sci. Total Environ. 755, 142653 https://doi.org/10.1016/j.scitotenv.2020.142653.

Bessa, F., Barría, P., Neto, J.M., Frias, J., Otero, V., Sobral, P., Marques, J.C., 2018. Occurrence of microplastics in commercial fish from a natural estuarine environment. Mar. Pollut. Bull. 128, 575–584. https://doi.org/10.1016/j.marpolbul.2018.01.044.

Bilal, M., Yaqub, A., Hassan, H.U., Akhtar, S., Rafiq, N., Ali Shah, M.I., Hussain, I., SalmaN Khan, M., Nawaz, A., Manoharadas, S., Rizwan Khan, M., Arai, T., Ríos-Escalante, P.L., 2023. Microplastic quantification in aquatic birds: biomonitoring the environmental health of the Panjkora river freshwater ecosystem in Pakistan. Toxics 11, 972. https://doi.org/10.3390/toxics11120972.

BirdLife International, 2021a. Country Profile: Brazil [viewed 9 August 2021]. Available from: http://datazone.birdlife.org/country/brazil.

BirdLife International, 2021b. Country Profile: Argentina [viewed 9 August 2021]. Available from: http://datazone.birdlife.org/country/argentina.

BirdLife International, 2021c. Country Profile: India [viewed 9 August 2021]. Available from: http://www.birdlife.org/datazone/country/india.

Blettler, M.C.M., Abrial, E., Khan, F.R., Sivr, i N., Espinola, L.A., 2018. Freshwater plastic pollution: recognizing research biases and identifying knowledge gaps. Water Res. 143, 416–424. https://doi.org/10.1016/j.watres.2018.06.015.

Bond, A., Hobson, K., 2012. Reporting stable-isotope ratios in ecology: recommended terminology, guidelines and best practices. Waterbirds 35, 324–331. https://doi.org/10.1675/063.035.0213.

Bond, A.L., Hutton, I., Lavers, J.L., 2021. Plastics in regurgitated flesh-footed shearwater (Ardenna carneipes) boluses as a monitoring tool. Mar. Pollut. Bull. 168, 112428 https://doi.org/10.1016/j.marpolbul.2021.112428.

Borges-Ramírez, M.M., Escalona-Segura, G., Huerta-Lwanga, E., Iñigo-Elias, E., Rendón-von Osten, J., 2021. Organochlorine pesticides, polycyclic aromatic hydrocarbons, metals and metalloids in microplastics found in regurgitated pellets of black vulture from Campeche, Mexico. Sci. Total Environ. 801, 149674 https://doi.org/10.1016/j.scitotenv.2021.149674.

Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., Murphy, E., Jambeck, J., Leonard, G.H., Hilleary, M.A., Eriksen, M., Possingham, H. P., De Frond, H., Gerber, L.R., Polidoro, B., Tahir, A., Bernard, M., Mallos, N., Barnes, M., Rochman, C.M., 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. Science 369, 1515–1518. https://doi.org/10.1126/science.aba3656.

Bravo Rebolledo, E.L., Van Franeker, J.A., Jansen, O.E., Brasseur, S.M., 2013. Plastic ingestion by harbour seals (Phoca vitulina) in The Netherlands. Mar. Pollut. Bull. 67, 200–202. https://doi.org/10.1016/j.marpolbul.2012.11.035.

Brookson, C.B., Solla, S., Fernie, K., Cepeda, M., Rochman, C., 2019. Microplastics in the diet of nestling double-crested cormorants (Phalacrocorax auritus), an obligate piscivore in a freshwater ecosystem. Can. J. Fish. Aquat. Sci. 76, 2156–2163. https://doi.org/10.1139/CJFAS-2018-0388.

Brown, K.M., Ewins, P.J., 1996. Technique-dependent biases in determination of diet composition: an example with ring-billed gulls. Condor 98, 34–41. https://doi.org/10.2307/1369505.

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr. Biol. 23, 2388–2392. https://doi.org/10.1016/j.cub.2013.10.012.

Butler, H.J., Ashton, L., Bird, B., Cinque, G., Curtis, K., Dorney, J., Esmonde-White, K., Fullwood, N.J., Gardner, B., Martin-Hirsch, P.L., Walsh, M.J., McAinsh, M.R., Stone, N., Martin, F.L., 2016. Using Raman spectroscopy to characterize biological materials. Nat. Protoc. 11, 664–687. https://doi.org/10.1038/nprot.2016.036.

Cai, H., Xu, E.G., Du, F., Li, R., Liu, J., Shi, H., 2021. Analysis of environmental nanoplastics: progress and challenges. Chem. Eng. J. 410, 128208 https://doi.org/10.1016/j.cej.2020.128208.

Canal, D., Mulero-Pázmány, M., Negro, J.J., Sergio, F., 2016. Decoration increases the conspicuousness of raptor nests. PLoS One 11, e0157440. https://doi.org/10.1371/journal.pone.0157440.

Cano-Povedano, J., López-Calderón, C., Sánchez, M.I., Hortas, F., Cañuelo-Jurado, B., Martín-Vélez, V., Ros, M., Cózar, A., Green, A.J., 2023. Biovectoring of plastic by white storks from a landfill to a complex of salt ponds and marshes. Mar. Pollut. Bull. 197, 115773 https://doi.org/10.1016/j.marpolbul.2023.115773.

Carey, M.J., 2011. Intergenerational transfer of plastic debris by short-tailed shearwaters (Ardenna tenuirostris). Emu 3, 229–234. https://doi.org/10.1071/MU10085.

Carlin, J., Craig, C., Little, S., Donnelly, M., Fox, D., Zhai, L., Walters, L., 2020. Microplastic accumulation in the gastrointestinal tracts in birds of prey in central Florida, USA. Environ. Pollut. 264, 114633 https://doi.org/10.1016/j.envpol.2020.114633.

Carr, S.A., 2017. Sources and dispersive modes of micro-fibers in the environment. Integr. Environ. Assess. Manag. 13, 466–469. https://doi.org/10.1002/ieam.1916.

Charles, P.E., Sathya, M., Rajaram, R., Al-Sadoon, M.K., Gulnaz, A., Paray, B.A., 2023. First report on occurrence and characterization of microplastics in feces of *Corvus splendens* (Vieillot, 1817). Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-023-05207-x.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Coughlan, N.E., Baker-Arney, C., Brides, K., Dick, J.T.A., Griffith, R.M., Holmes, C., Johnston, R., Kelly, T.C., Lyne, L., Cunningham, E.M., 2021a. First record of synthetic micro-fibre ingestion by mute swans Cygnus olor and whooper swans C. cygnus. Wildfowl 71, 72–82. https://wildfowl.wwt.org.uk/index.php/wildfowl/article/view/2752.

Coughlan, N.E., Cunningham, E.M., Griffith, R.M., Baker-Arney, C., Lyne, L., Dick, J.T.A., Kelly, T.C., 2021b. Ingestion of synthetic micro-fibres by the black-billed magpie Pica pica. Ir. Birds 43, 23–28.

Copat, C., Ferrante, M., Hernout, B.V., Giunta, F., Grasso, A., Messina, A., Spena, M.T., 2020. Trace element bioaccumulation in stone curlew (Burhinus oedicnemus, Linnaeus, 1758): a case study from Sicily (Italy). Int. J. Mol. Sci. 21, 4597. https://doi.org/10.3390/ijms21134597.

Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., Geissen, V., 2019. Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci. Total Environ. 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368.

Costa, R., Eeva, T., Eira, C., Vaqueiro, J., Medina, P., Vingada, J., 2014. Great tits breeding performance and mercury contamination from the paper and pulp industry in the west coast of Portugal. Chem. Ecol. 30, 206–215. https://doi.org/10.1080/02757540.2013.856891.

Cunha, W.A., Freitas, Í.N., Gomes, L.A., de Oliveira Gonçalves, S., Montalvão, M.F., Ahmed, M.A., Gomes, A.R., da Luz, T.M., da Costa Araújo, A.P., Malafaia, G.C., 2021. From carrion-eaters to plastic material plunderers: toxicological impacts of plastic ingestion on black vultures, Coragyps atratus (Cathartiformes: Cathartidae). J. Hazard. Mater. 424, 127753 https://doi.org/10.1016/j.jhazmat.2021.127753.

da Silva, T.L., Cabral, R.B.G., Andrade, L., de, A.S., Nogueira, N.F., Oliveira, M. de S., Ferreira, I., 2018. Comparison of breeding biology aspects of Fluvicola nengeta (Aves: Tyrannidae) between two nesting sites. J. Nat. Hist. 52, 225–235. https://doi.org/10.1080/00222933.2017.1414897.

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., Tassin, B., 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ. Pollut. 221, 453–458. https://doi.org/10.1016/j.envpol.2016.12.013.

de Souza, S.S., Freitas, Í.N., Gonçalves, S.O., Luz, T.M.D., Araújo, A.P.D.C., Rajagopal, R., Balasubramani, G., Rahman, M.M., Malafaia, G., 2022. Toxicity induced via ingestion of naturally-aged polystyrene microplastics by a small-sized terrestrial bird and its potential role as vectors for the dispersion of these pollutants. J. Hazard. Mater. 434, 128814 https://doi.org/10.1016/j.jhazmat.2022.128814.

D'Souza, J.M., Windsor, F.M., Santillo, D., Ormerod, S.J., 2020. Food web transfer of plastics to an apex riverine predator. Global Change Biol. 26, 3846–3857. https://doi.org/10.1111/gcb.15139.

De Pascalis, F., De Felice, B., Parolini, M., Pisu, D., Pala, D., Antonioli, D., Perin, E., Gianotti, V., Ilahiane, L., Masoero, G., Serra, L., Rubolini, D., Cecere, J.G., 2022. The hidden cost of following currents: microplastic ingestion in a planktivorous seabird. Mar. Pollut. Bull. 182, 114030 https://doi.org/10.1016/j.marpolbul.2022.114030.

De Witte, B., Devriese, L., Bekaert, K., Hoffman, S., Vandermeersch, G., Cooreman, K., Robbens, J., 2014. Quality assessment of the blue mussel (Mytilus edulis): Comparison between commercial and wild types. Mar. Pollut. Bull. 85, 146–155. https://doi.org/10.1016/j.marpolbul.2014.06.006.

Deoniziak, K., Cichowska, A., Niedźwiecki, S., Pol, W., 2022. Thrushes (Aves: Passeriformes) as indicators of microplastic pollution in terrestrial environments. Sci. Total Environ. 853, 158621 https://doi.org/10.1016/j.scitotenv.2022.158621.

DuBay, S.G., Fuldner, C., 2017. Bird specimens track 135 years of atmospheric black carbon and environmental policy. Proc. Natl. Acad. Sci. USA 114, 11321–11326. https://doi.org/10.1073/pnas.1710239114.

Duis, K., Coors, A., 2016. Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. Environ. Sci. Eur. 28, 2. https://doi.org/10.1186/s12302-015-0069-y.

Duke, G.E., 1997. Gastrointestinal physiology and nutrition in wild birds. Proc. Nutr. Soc. 56, 1049–1056. https://doi.org/10.1079/pns19970109.

Escalona-Segura, G., Borges Ramirez, M., Estrella-Canul, V., Rendon von Osten, J., 2022. A methodology for the sampling and identification of microplastics in bird nests. Green Anal. Chem. 3, 100045 https://doi.org/10.1016/j.greeac.2022.100045.

Egwumah, F.A., Egwumah, P.O., Edet, D.I., 2017. Paramount roles of wild birds as bioindicators of contamination. Intl. J. Avian Widl. Biol. 2, 194–200. https://doi.org/10.15406/ijawb.2017.02.00041.

English, M.D., Robertson, G.J., Avery-Gomm, S., Pirie-Hay, D., Roul, S., Ryan, P.C., Wilhelm, S.I., Mallory, M.L., 2015. Plastic and metal ingestion in three species of coastal waterfowl wintering in Atlantic Canada. Mar. Pollut. Bull. 98, 349–353. https://doi.org/10.1016/j.marpolbul.2015.05.063.

Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the World's Oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913. https://doi.org/10.1371/journal.pone.0111913.

Espín, S., Martínez-López, E., León-Ortega, M., Calvo, J.F., García-Fernández, A.J., 2014. Factors that influence mercury concentrations in nestling eagle owls (Bubo bubo). Sci. Total Environ. 470–471, 1132–1139. https://doi.org/10.1016/j.scitotenv.2013.10.063.

Ewins, P.J., Weseloh, D.V., Groom, J.H., Dobos, R.Z., Mineau, P., 1994. The diet of herring gulls (Larus argentatus) during winter and early spring on the lower Great Lakes. Hydrobiologia 279, 39–55. https://doi.org/10.1007/BF00027839.

FAO, 2021. Assessment of agricultural plastics and their sustainability – a call for action. Rome. https://doi.org/10.4060/cb7856en.

Francila, F.A., Prasanna, N.S., Shrotri, S., Nawge, V., Gowda, V., 2023. Life amidst debris: urban waste management affects the utilization of anthropogenic waste materials in avian nest construction. Trop. Ecol. https://doi.org/10.1007/s42965-023-00302-z.

Francis, A., Prusty, B.A.K., Azeez, P.A., 2020. Ingestion of unusual items by wetland birds in urban landscapes. Curr. Sci. 118, 977–983. https://doi.org/10.18520/cs%2Fv118%2Fi6%2F977-983.

Furness, R.W., Greenwood, J.J.D., 1993. Birds as Monitors of Environmental Change. Chapman and Hall, London, UK. https://doi.org/10.1007/978-94-015-1322-7.

Galafassi, S., Nizzetto, L., Volta, P., 2019. Plastic sources: a survey across scientific and grey literature for their inventory and relative contribution to microplastics pollution in natural environments, with an emphasis on surface water. Sci. Total Environ. 693, 133499 https://doi.org/10.1016/j.scitotenv.2019.07.305.

Gamarra-Toledo, V., Plaza, P.I., Peña, Y.A., Bermejo, P.A., López, J., Cano, G.L., Barreto, S., Cáceres-Medina, S., Lambertucci, S.A., 2023. High incidence of plastic debris in Andean condors from remote areas: evidence for marine-terrestrial trophic transfer. Environ. Pollut. 317, 120742 https://doi.org/10.1016/j.envpol.2022.120742.

Gasperi, J., Wright, S.L., Dris, R., Collard, F., Mandin, C., Guerrouache, M., Langlois, V., Kelly, F.J., Tassin, B., 2018. Microplastics in air: are we breathing it in? Curr. Opin. Environ. Sci. Health. 1, 1–5. https://doi.org/10.1016/j.coesh.2017.10.002.

Germond, A., Kumar, V., Ichimura, T., Moreau, J., Furusawa, C., Fujita, H., Watanabe, T. M., 2017. Raman spectroscopy as a tool for ecology and evolution. J. R. Soc. Interface 14, 20170174. https://doi.org/10.1098/rsif.2017.0174.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 https://doi.org/10.1126/sciadv.1700782.

Gil-Delgado, J.A., Guijarro, D., Gosálvez, R.U., López-Iborra, G.M., Ponz, A., Velasco, A., 2017. Presence of plastic particles in waterbirds faeces collected in Spanish lakes. Environ. Pollut. 220, 732–736. https://doi.org/10.1016/j.envpol.2016.09.054.

Gill, F., Donsker, D., Rasmussen, P. (Eds.), 2023, v13.1. IOC World Bird List. https://doi.org/10.14344/IOC.ML.13.2.

Girão, J., Bessa, F., Garrido-Bautista, J., Ferreira, B., Santos-Baena, C., Carvalho, L., Ramos, J., Norte, A., 2024. Variation in the use of anthropogenic materials in tit nests: influence of human activities and pandemic restrictions. Urban Ecosyst. 1–11. https://doi.org/10.1007/s11252-023-01502-0.

Goldsworthy, B., Young, M.J., Seddon, P.J., van Heezik, Y., 2016. Stomach flushing does not affect apparent adult survival, chick hatching, or fledging success in yellow-eyed penguins (Megadyptes antipodes). Biol. Conserv. 196, 115–123. https://doi.org/10.1016/j.biocon.2016.02.009.

Gorini, F., Iervasi, G., Coi, A., Pitto, L., Bianchi, F., 2018. The role of polybrominated diphenyl ethers in thyroid carcinogenesis: is it a weak hypothesis or a hidden reality? From facts to new perspectives. Int. J. Environ. Res. Publ. Health 15, 1834. https://doi.org/10.3390/ijerph15091834.

Gutiérrez-Galán, A., Alonso, C., 2016. European turtle dove Streptopelia turtur diet composition in Southern Spain: the role of wild seeds in Mediterranean forest areas. Hous. Theor. Soc. 63, 490–499. https://doi.org/10.1080/00063657.2016.1236070.

Hanmer, H.J., Thomas, R.L., Beswick, G.J., Collins, B.P., Fellowes, M.D., 2017. Use of anthropogenic material affects bird nest arthropod community structure: influence of urbanisation, and consequences for ectoparasites and fledging success. J. Ornithol. 158, 1045–1059. https://doi.org/10.1007/s10336-017-1462-7.

Henry, P.-Y., Wey, G., Balança, G., 2014. Rubber band ingestion by a rubbish dump dweller, the White Stork (Ciconia ciconia). Waterbirds 34, 504–508. https://doi.org/10.1675/063.034.0414.

Hidalgo-Ruiz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46, 3060–3075. https://doi.org/10.1021/es2031505.

Hirai, H., Takada, H., Ogata, Y., Yamashita, R., Mizukawa, K., Saha, M., Kwan, C., Moore, C., Gray, H., Laursen, D., Zettler, E.R., Farrington, J.W., Reddy, C.M., Peacock, E.E., Ward, M.W., 2011. Organic micropollutants in marine plastic debris from the open ocean and remote and urban beaches. Mar. Pollut. Bull. 62, 1683–1692. https://doi.org/10.1016/j.marpolbul.2011.06.004.

Hoang, T.C., Mitten, S., 2022. Microplastic accumulation in the gastrointestinal tracts of nestling and adult migratory birds. Sci. Total Environ. 838, 155827 https://doi.org/10.1016/j.scitotenv.2022.155827.

Holland, E.R., Mallory, M.L., Shutler, D., 2016. Plastics and other anthropogenic debris in freshwater birds from Canada. Sci. Total Environ. 571, 251–258. https://doi.org/10.1016/j.scitotenv.2016.07.158.

Huerta Lwanga, E., Mendoza Vega, J., Ku Quej, V., de los Angeles Chi, J., Sanchez del Cid, L., Chi, C., Escalona Segura, G., Gertsen, H., Salánki, T., van der Ploeg, M., Koelmans, B., Geissen, V., 2017. Field evidence for transfer of plastic debris along a terrestrial food chain. Sci. Rep. 7, 14071 https://doi.org/10.1038/s41598-017-14588-2.

Hurley, R., Horton, A., Lusher, A., Nizzetto, L., 2020. Plastic Waste and Recycling: Environmental Impact, Societal Issues, Prevention, and Solutions. Academic Press, London, UK. https://doi.org/10.1016/B978-0-12-817880-5.00007-4.

Inger, R., Bearhop, S., 2008. Applications of stable isotope analyses to avian ecology. Ibis 150, 447–461. https://doi.org/10.1111/j.1474-919X.2008.00839.x.

IUCN, 2021. The IUCN red list of threatened species. Version 2021-2. https://www.iucnredlist.org. Downloaded on 26/10/21.

Jagiello, Z., Dylewski, Ł., Tobolka, M., Aguirre, J.I., 2019. Life in a polluted world: a global review of anthropogenic materials in bird nests. Environ. Pollut. 251, 717–722. https://doi.org/10.1016/j.envpol.2019.05.028.

Jagiello, Z., López-García, A., Aguirre, J.I., Dylewski, L., 2020. Distance to landfill and human activities affects the debris incorporation into the white stork nests in urbanized landscape in central Spain. Environ. Sci. Pollut. Res. 27, 30893–30898. https://doi.org/10.1007/s11356-020-09621-3.

Jagiello, Z., Reynolds, S.J., Nagy, J., Mainwaring, M.C., Ibáñez-Álamo, J.D., 2023. Why do some bird species incorporate more anthropogenic materials into their nests than others? Philos. Trans. R. Soc. B: Biol. Sci. 378, 20220156 https://doi.org/10.1098/rstb.2022.0156.

Jakubowicz, I., Enebro, J., Yarahmadi, N., 2021. Challenges in the search for nanoplastics in the environment—a critical review from the polymer science perspective. Polym. Test. 93 (2021), 106953 https://doi.org/10.1016/j.polymertesting.2020.106953.

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T., Perryman, M., Andrady, A., Narayan, R., Law, K., 2015. Marine pollution. Plastic waste inputs from land into the ocean. Science 347, 768–771. https://doi.org/10.1126/science.1260352.

Jennings, L., Anderson, T., Martinez, A., Sterling, R., Chavez, D.D., Garba, I., Hudson, M., Garrison, N.A., Carroll, S.R., 2023. Applying the 'CARE principles for indigenous data governance' to ecology and biodiversity research. Nat. Ecol. Evol. 7, 1547–1551. https://doi.org/10.1038/s41559-023-02161-2.

Jeong, I.Y., Seo, J.H., Yoo, J.C., 2023. First report on the detection of microplastics from the feathers of black-tailed gulls in South Korea. Mar. Pollut. Bull. 196, 115592 https://doi.org/10.1016/j.marpolbul.2023.115592.

Kalaronis, D., Ainali, N.M., Evgenidou, E., Kyzas, G.Z., Yang, X., Bikiaris, D.N., Lambropoulou, D.A., 2022. Microscopic techniques as means for the determination of microplastics and nanoplastics in the aquatic environment: a concise review. Green Anal. Chem. 3, 100036 https://doi.org/10.1016/j.greeac.2022.100036.

Kang, K.H., Nam, K.B., Jeong, B.S., Kim, J.S., Yoo, J.C., 2023. The use of plastic litter as nesting material by the azure-winged magpie Cyanopica cyanus in an agricultural environment of South Korea. Environ. Sci. Pollut. Res. 30, 84814–84821. https://doi.org/10.1007/s11356-023-28409-9.
Katlam, G., Prasad, S., Aggrawal, M., Kumar, R., 2018. Trash on the menu: patterns of animal visitation and animal behavior at garbage dumps. https://www.researchgate.net/publication/331374509_Trash_on_the_menu_patterns_of_animal_visitation_and_foraging_behaviour_at_garbage_dumps.
Kelber, A., 2019. Bird colour vision – from cones to perception. Curr. Opin. Behav. Sci. 30, 34–40. https://doi.org/10.1016/j.cobeha.2019.05.003.
Kelly, A., Kelly, S., 2004. Fishing tackle injury and blood lead levels in mute swans. Waterbirds 27, 60–68. http://www.jstor.org/stable/1522488.
Kirkwood, A.F., 2020. Life in plastic, not fantastic: development of analytical techniques to detect plastic contaminants in egg matrices. MRes Thesis. University of Birmingham, Birmingham, UK.
Klasing, K.C., 1999. Avian gastrointestinal anatomy and physiology. Seminars Avian Exot. Pet Med. 8, 42–50. https://doi.org/10.1016/S1055-937X(99)80036-X.
Krause, S., Baranow, V., Nel, H., Drummond, J., Kukkola, A., Sambrook Smith, G., Sadler, J.P., Baranova, V., Lewandowski, J., Bonnet, B., Packman, A., Hoellein, T., Lynch, I., 2021. Gathering at the top? Environmental controls of microplastic uptake and biomagnification in aquatic food webs. Environ. Pollut. 268, 115750.
Kühn, S., Booth, A.M., Sørensen, L., van Oyen, A., van Franeker, J.A., 2020. Transfer of additive chemicals from marine plastic debris to the stomach oil of Northern fulmars. Front. Environ. Sci. 138, 1–14. https://doi.org/10.3389/fenvs.2020.00138.
Lato, K.A., Thorne, L.H., Fuirst, M., Brownawell, B.J., 2021. Microplastic abundance in gull nests in relation to urbanization. Mar. Pollut. Bull. 164, 112058. https://doi:10.1016/j.marpolbul.2021.112058.
Laurich, B., Drake, C., Gorman, O.T., Irvine, C., MacLaurin, J., Chartrand, C., Hebert, C. E., 2019. Ecosystem change and population declines in gulls: shifting baseline considerations for assessing ecological integrity of protected areas. J. Great Lake. Res. 45, 1215–1227. https://doi.org/10.1016/j.jglr.2019.08.009.
Lavers, J.L., Bond, A.L., Hutton, I., 2014. Plastic ingestion by flesh-footed shearwaters (Puffinus carneipes): implications for fledgling body condition and the accumulation of plastic-derived chemicals. Environ. Pollut. 187, 124–129. https://doi.org/10.1016/j.envpol.2013.12.020.
Le Guen, C., Suaria, G., Sherley, R.B., Ryan, P.G., Aliani, S., Boehme, L., Brierley, A.S., 2020. Microplastic study reveals the presence of natural and synthetic fibres in the diet of king penguins (Aptenodytes patagonicus) foraging from South Georgia. Environ. Int. 134, 105303 https://doi.org/10.1016/j.envint.2019.105303.
Lear, G., Kingsbury, J.M., Franchini, S., Gambarini, V., Maday, S.D.M., Wallbank, J.A., Weaver, L., Pantos, O., 2021. Plastics and the microbiome: impacts and solutions. Environ. Microbiome. 16, 2. https://doi.org/10.1186/s40793-020-00371-w.
Lehner, R., Weder, C., Petri-Fink, A., Rothen-Rutishauser, B., 2019. Emergence of nanoplastic in the environment and possible impact on human health. Environ. Sci. Technol. 53, 1748–1765. https://doi.org/10.1021/acs.est.8b05512.
Leviner, A., Perrine, J.D., 2023. Documentation of microplastics in the gastrointestinal tracts of terrestrial raptors in central California, USA. Calif. Fish Wildl. J. 109, e6.
Liebezeit, G., Liebezeit, E., 2013. Non-pollen particulates in honey and sugar. Food Addit. Contam. 30, 2136–2140. https://doi.org/10.1080/19440049.2013.843025.
Lim, S.L., Ng, C.T., Zou, L., Lu, Y., Chen, J., Bay, B.H., Shen, H.-M., Ong, C.N., 2019. Targeted metabolomics reveals differential biological effects of nanoplastics and nanoZnO in human lung cells. Nanotoxicology 13, 1117–1132. https://doi.org/10.1080/17435390.2019.1640913.
Liu, Q., Chen, Z., Chen, Y., Yang, F., Yao, W., Xie, Y., 2022. Microplastics contamination in eggs: detection, occurrence and status. Food Chem. 397, 133771 https://doi.org/10.1016/j.foodchem.2022.133771.
Löder, M.G.J., Gerdts, G., 2015. Methodology used for the detection and identification of microplastics—a critical appraisal. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-16510-3_8.
Loiseau, N., Mouquet, N., Casajus, N., Grenié, M., Guéguen, M., Maitner, B., Mouillot, D., Ostling, A., Renaud, J., Tucker, C., Velez, L., Thuiller, W., Violle, C., 2020. Global distribution and conservation status of ecologically rare mammal and bird species. Nat. Commun. 11, 5071. https://doi.org/10.1038/s41467-020-18779-w.
Lopes, C.S., Paiva, V.H., Vaz, P.T., Pais de Faria, J., Calado, J.G., Pereira, J.M., Ramos, J. A., 2021. Ingestion of anthropogenic materials by yellow-legged gulls (Larus michahellis) in natural, urban, and landfill sites along Portugal in relation to diet composition. Environ. Sci. Pollut. Res. 28, 19046–19063. https://doi.org/10.1007/s11356-020-12161-5.
MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373, 61–65. https://doi.org/10.1126/science.abg5433.
Mahon, A.M., O'Connell, B., Healy, M.G., O'Connor, I., Officer, R., Nash, R., Morrison, L., 2017. Microplastics in sewage sludge: effects of treatment. Environ. Sci. Technol. 51, 810–818. https://doi.org/10.1021/acs.est.6b04048.
Markic, A., Niemand, C., Bridson, J.H., Mazouni-Gaertner, N., Gaertner, J.C., Eriksen, M., Bowen, M., 2018. Double trouble in the South Pacific subtropical gyre: increased plastic ingestion by fish in the oceanic accumulation zone. Mar. Pollut. Bull. 136, 547–564. https://doi.org/10.1016/j.marpolbul.2018.09.031.
Martí, E., Martin, C., Galli, M., Echevarría, F., Duarte, C.M., Cózar, A., 2020. The colors of the ocean plastics. Environ. Sci. Technol. 54, 6594–6601. https://doi.org/10.1021/acs.est.9b06400.
Martin, G.R., 2022. Avian vision. Curr. Biol. 32, 1079–1085. https://doi.org/10.1016/j.cub.2022.06.065.
Mecozzi, M., Pietroletti, M., Monakhova, Y.B., 2016. FTIR spectroscopy supported by statistical techniques for the structural characterization of plastic debris in the marine environment: application to monitoring studies. Mar. Pollut. Bull. 106, 155–161. https://doi.org/10.1016/j.marpolbul.2016.03.012.
Méndez, A., Montalvo, T., Aymí, R., Carmona, M., Figuerola, J., Navarro, J., 2020. Adapting to urban ecosystems: unravelling the foraging ecology of an opportunistic predator living in cities. Urban Ecosyst. 23, 1117–1126. https://doi.org/10.1007/s11252-020-00995-3.
Minor, E.C., Lin, R., Burrows, A., Cooney, E.M., Grosshuesch, S., Lafrancois, B., 2020. An analysis of microlitter and microplastics from Lake Superior beach sand and surface-water. Sci. Total Environ. 744, 140824 https://doi.org/10.1016/j.scitotenv.2020.140824.
Møller, A.P., 2017. Fashion and out of fashion: appearance and disappearance of a novel nest building innovation. Avian Res. 8, 14. https://doi.org/10.1186/s40657-017-0072-7.
Moser, M., Lee, D., 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. Colon. Waterbirds 15, 83–94. https://doi.org/10.2307/1521357.
Movalli, P., Bode, P., Dekker, R., Fornasari, L., van der Mije, S., Yosef, R., 2017. Retrospective biomonitoring of mercury and other elements in museum feathers of common kestrel Falco tinnunculus using instrumental neutron activation analysis (INAA). Environ. Sci. Pollut. Res. 24, 25986–26005. https://doi.org/10.1007/s11356-017-0157-1.
Nel, H.A., Chetwynd, A.J., Kelleher, L., Lynch, I., Mansfield, I., Margenat, H., Onoja, S., Goldberg Oppenheimer, P., Sambrook Smith, G.H., Krause, S., 2021. Detection limits are central to improve reporting standards when using Nile red for microplastic quantification. Chemosphere 263, 127953. https://doi.org/10.1016/j.chemosphere.2020.127953.
Nelms, S.E., Barnett, J., Brownlow, A., Davison, N.J., Deaville, R., Galloway, T.S., Lindeque, P.K., Santillo, D., Godley, B.J., 2019. Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory? Sci. Rep. 9, 1075. https://doi.org/10.1038/s41598-018-37428-3.
Nessi, A., Winkler, A., Tremolada, P., Saliu, F., Lasagni, M., Ghezzi, L.L.M., Balestrieri, A., 2022. Microplastic contamination in terrestrial ecosystems: a study using barn owl (Tyto alba) pellets. Chemosphere 308, 136281. https://doi.org/10.1016/j.chemosphere.2022.136281.
Nguyen, B., Claveau-Mallet, D., Hernandez, L.M., Xu, E.G., Farner, J.M., Tufenkji, N., 2019. Separation and analysis of microplastics and nanoplastics in complex environmental samples. Acc. Chem. Res. 52, 858–866. https://doi.org/10.1021/acs.accounts.8b0'602.
Ntziouni, A., Thomson, J., Xiarchos, I., Li, X., Bañares, M.A., Charitidis, C., Portela, R., Lozano Diz, E., 2022. Review of existing standards, guides, and practices for Raman spectroscopy. Appl. Spectrosc. 76, 747–772. https://doi.org/10.1177/00037028221090988.
O'Hanlon, N.J., Bond, A.L., Masden, E.A., Lavers, J.L., James, N.A., 2021. Measuring nest incorporation of anthropogenic debris by seabirds: an opportunistic approach increases geographic scope and reduces costs. Mar. Pollut. Bull. 171, 112706 https://doi.org/10.1016/j.marpolbul.2021.112706.
OFCOM, 2019. Annual production of plastics worldwide from 1950 to 2020 (in million metric tons). Statista [viewed 9 August 2021]. Available from: https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/.
Parmar, T.K., Rawtani, D., Agrawal, Y.K., 2016. Bioindicators: the natural indicator of environmental pollution. Front. Life Sci. 9, 1–9. https://doi.org/10.1080/21553769.2016.1162753.
Partridge, H.C., Barnett, S., Amodeo, J., Snyder, J., Gagné, S.A., 2023. Vultures in the southeastern United States ingest more plastic in landscapes with more developed landcover. Front. Ecol. Evol. 11, 1158453. https://doi:10.3389/fevo.2023.1158453.
Perkins, M.J., McDonald, R.A., van Veen, F.J.F., Kelly, S.D., Rees, G., Bearhop, S., 2014. Application of nitrogen and carbon stable isotopes (δ15N and δ13C) to quantify food chain length and trophic structure. PLoS One 9, e93281. https://doi.org/10.1371/journal.pone.0093281.
Pierce, K.E., Harris, R.J., Larned, L.S., Pokras, M.A., 2004. Obstruction and starvation associated with plastic ingestion in a northern gannet morus bassanus and a greater shearwater Puffinus gravis. Mar. Ornithol. 32, 187–189.
Pivnenko, K., Granby, K., Eriksson, E., Astrup, T.F., 2017. Recycling of plastic waste: screening for brominated flame retardants (BFRs). J. Waste Manag. 69, 101–109. https://doi.org/10.1016/j.wasman.2017.08.038.
Poon, F.E., Provencher, J.F., Mallory, M.L., Braune, B.M., Smith, P.A., 2017. Levels of ingested debris vary across species in Canadian Arctic seabirds. Mar. Pollut. Bull. 116, 517–520. https://doi.org/10.1016/j.marpolbul.2016.11.051.
Potvin, D.A., Opitz, F., Townsend, K.A., Knutie, S.A., 2021. Use of anthropogenic-related nest material and nest parasite prevalence have increased over the past two centuries in Australian birds. Oecologia 196, 1207–1217. https://doi.org/10.1007/s00442-021-04982-z.
Prata, J.C., da Costa, J.P., Girão, A.V., Lopes, I., Duarte, A.C., Rocha-Santos, T., 2019. Identifying a quick and efficient method of removing organic matter without damaging microplastic samples. Sci. Total Environ. 686, 131–139. https://doi.org/10.1016/j.scitotenv.2019.05.456.
Provencher, J.F., Bond, A., Avery-Gomm, S., Borrelle, S., Bravo Rebolledo, E., Lavers, J., Mallory, M.L., Trevail, A., Van Franeker, J., Hammer, S., Kühn, S., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. Anal. Methods 9, 1454–1469. https://doi.org/10.1039/C6AY02419J.
Provencher, J.F., Borrelle, S.B., Bond, A.L., Lavers, J.L., van Franeker, J.A., Kühn, S., Hammer, S., Avery-Gomm, S., Mallory, M.L., 2019. Recommended best practices for plastic and litter ingestion studies in marine birds: collection, processing, and reporting. FACETS 4, 111–130. https://doi.org/10.1139/facets-2018-0043.
Provencher, J.F., Avery-Gomm, S., Braune, B.M., Letcher, R.J., Dey, C.J., Mallory, M.L., 2020. Are phthalate ester contaminants in northern fulmar preen oil higher in birds

that have ingested more plastic? Mar. Pollut. Bull. 150, 110679 https://doi.org/10.1016/j.marpolbul.2019.110679.
Puskic, P.S., Lavers, J.L., Bond, A.L., 2020. A critical review of harm associated with plastic ingestion on vertebrates. Sci. Total Environ. 743, 140666 https://doi.org/10.1016/j.scitotenv.2020.140666.
Qaiser, N., Sidra, S., Javid, A., Iqbal, A., Amjad, M., Azmat, H., Arooj, F., Farooq, K., Nimra, A., Ali, Z., 2023. Microplastics abundance in abiotic and biotic components along aquatic food chain in two freshwater ecosystems of Pakistan. Chemosphere 313, 137177. https://doi.org/10.1016/j.chemosphere.2022.137177.
Rashid, B., Zubair, M., Irshad, N., Ahmad, K.S., Mahmood, M., Tahir, M.M., Shah, K.H., Shaheen, A., 2021. Correction to: biomonitoring of toxic metals in feathers of birds from North-Eastern Pakistan. Bull. Environ. Contam. Toxicol. 106, 909. https://doi.org/10.1007/s00128-021-03221-8.
Reynolds, C., Ryan, P.G., 2018. Micro-plastic ingestion by waterbirds from contaminated wetlands in South Africa. Mar. Pollut. Bull. 126, 330–333. https://doi.org/10.1016/j.marpolbul.2017.11.021.
Reynolds, S.J., Davies, C.S., Elwell, E., Tasker, P.J., Williams, A., Sadler, J.P., Hunt, D., 2016. Does the urban gradient influence the composition and ectoparasite load of nests of an urban bird species? Avian Biol. Res. 9, 224–234. https://doi.org/10.3184/175815516X14725499175665.
Rist, S., Hartmann, N.B., 2018. Freshwater Microplastics. The Handbook of Environmental Chemistry. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-61615-5_2.
Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, I.T., Teh, F.C., WeroriIgi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5, 14340 https://doi.org/10.1038/srep14340.
Ryan, P.G., Jackson, S., 1987. The lifespan of ingested plastic particles in seabirds and their effect on digestive efficiency. Mar. Pollut. Bull. 18, 217–219. https://doi.org/10.1016/0025-326X(87)90461-9.
Sazima, I., D'Angelo, G.B., 2015. Dangerous traps: Anhingas mistake anthropogenic debris for prey fish at an urban site in south-eastern Brazil. Rev. Bras. Ornitol. 23, 380–384. https://doi.org/10.1007/BF03544312.
Schorderet Weber, S., Kaminski, K.P., Perret, J.L., Leroy, P., Mazurov, A., Peitsch, M.C., Ivanov, N.V., Hoeng, J., 2019. Antiparasitic properties of leaf extracts derived from selected Nicotiana species and Nicotiana tabacum varieties. Food Chem. Toxicol. 132, 110660 https://doi.org/10.1016/j.fct.2019.110660.
Schuyler, Q., Hardesty, B.D., Wilcox, C., Townsend, K., 2013. Global analysis of anthropogenic debris ingestion by sea turtles. Conserv. Biol. 28, 129–139. https://doi.org/10.1111/cobi.12126.
Schuyler, Q., Willis, K., Mann, V., Wilcox, C., Hardesty, B.D., 2017. Handbook of Survey Methodology – Plastics Leakage. CSIRO, Australia. http://hdl.handle.net/102.100.100/389141.
Seif, S., Provencher, J.F., Avery-Gomm, S., Daoust, P.-Y., Mallory, M.L., Smith, P.A., 2018. Plastic and non-plastic debris ingestion in three gull species feeding in an urban landfill environment. Arch. Environ. Contam. Toxicol. 74, 349–360. https://doi.org/10.1007/s00244-017-0492-8.
Sepp, T., Ujvari, B., Ewald, P.W., Frédéric, T., Giraudeau, M., 2019. Urban environment and cancer in wildlife: available evidence and future research avenues. Proc. R. Soc. B. 286, 20182434 https://doi.org/10.1098/rspb.2018.2434.
Sergio, F., Blas, J., Blanco, G., Tanferna, A., López, L., Lemus, J.A., Hiraldo, F., 2011. Raptor nest decorations are a reliable threat against conspecifics. Science 331, 327–330. https://doi.org/10.1126/scienCe.1199422.
Sharkey, M., Harrad, S., Abdallah, M.A., Drage, D., Berresheim, H., 2020. Phasing-out of legacy brominated flame retardants: the UNEP Stockholm Convention and other legislative action worldwide. Environ. Int. 144, 106041 https://doi.org/10.1016/j.envint.2020.106041.
Shellie, R.A., 2013. Gas chromatography. In: Siegel, J.A., Saukko, P.J., Houck, M.M. (Eds.), Encyclopedia of Forensic Sciences, second ed. Academic Press, London, UK, pp. 579–585 https://doi:10.1016/B978-0-12-382165-2.00245-2.
Sherlock, C., Fernie, K.J., Munno, K., Provencher, J., Rochman, C., 2022. The potential of aerial insectivores for monitoring microplastics in terrestrial environments. Sci. Total Environ. 807, 150453 https://doi.org/10.1016/j.scitotenv.2021.150453.
Shim, E.K., Lee, S., 2020. Calcite deposits differentiate cave from house-farmed edible bird's nest as shown by SEM-EDX, ATR-FTIR and Raman microspectroscopy. Chem. Asian J. 15, 2487–2492. https://doi:10.1002/asia.202000520.
Silva-Cavalcanti, J.S., Silva, J.D.B., França, E.J., Araújo, M.C.B., Gusmão, F., 2017. Microplastics ingestion by a common tropical freshwater fishing resource. Environ. Pollut. 221, 218–226. https://doi.org/10.1016/j.envpol.2016.11.068.
Suárez-Rodríguez, M., Garcia, C.M., 2014. There is no such a thing as a free cigarette; lining nests with discarded butts brings short-term benefits, but causes toxic damage. J. Evol. Biol. 27, 2719–2726. https://doi.org/10.1111/jeb.12531.
Suárez-Rodríguez, M., López-Rull, I., Garcia, C.M., 2013. Incorporation of cigarette butts into nests reduces nest ectoparasite load in urban birds: new ingredients for an old recipe? Biol. Lett. 9, 20120931 https://doi.org/10.1098/rsbl.2012.0931.
Suárez-Rodríguez, M., Garcia, C.M., 2017. An experimental demonstration that house finches add cigarette butts in response to ectoparasites. J. Avian Biol. 48, 1316–1321. https://doi.org/10.1111/jav.01324.
Thaysen, C., Sorais, M., Verreault, J., Diamond, M.L., Rochman, C.M., 2020. Bidirectional transfer of halogenated flame retardants between the gastrointestinal tract and ingested plastics in urban-adapted ring-billed gulls. Sci. Total Environ. 730, 138887 https://doi.org/10.1016/j.scitotenv.2020.138887.
The Guardian, 2020. Deadliest plastics: bags and packaging biggest marine life killers, study finds [viewed 17 January 2022]. Available from: Guardian https://www.theguardian.com/environment/2020/dec/14/deadliest-plastics-bags-and-packaging-biggest-marine-life-killers-study-finds.
Tokunaga, Y., Okochi, H., Tani, Y., Niida, Y., Tachibana, T., Saigawa, K., Katayama, K., Moriguchi, S., Kato, T., Hayama, S.I., 2023. Airborne microplastics detected in the lungs of wild birds in Japan. Chemosphere 321, 138032. https://doi.org/10.1016/j.chemosphere.2023.138032.
Tongue, A.D.W., Reynolds, S.J., Fernie, K.J., Harrad, S.J., 2019. Flame retardant concentrations and profiles in wild birds associated with landfill: a critical review. Environ. Pollut. 248, 646–658. https://doi.org/10.1016/j.envpol.2019.01.103.
Tongue, A.D.W., Fernie, K.J., Harrad, S., Drage, D.S., McGill, R.A.R., Reynolds, S.J., 2021. Interspecies comparisons of brominated flame retardants in relation to foraging ecology and behaviour of gulls frequenting a UK landfill. Sci. Total Environ. 764, 142890 https://doi.org/10.1016/j.scitotenv.2020.142890.
Torres-Mura, J., Lemus, M., Hertel, F., 2015. Plastic material in the diet of the turkey vulture (Cathartes aura) in the Atacama Desert, Chile. Wilson J. Ornithol. 127 (1), 134–138. https://doi.org/10.1676/14-107.
Townsend, A.K., Barker, C.M., 2014. Plastic and the nest entanglement of urban and agricultural crows. PLoS One 9, 1–5. https://doi.org/10.1371/journal.pone.0088006.
Turzańska-Pietras, K., Chachulska, J., Polechońska, L., Borowiec, M., 2018. Does heavy metal exposure affect the condition of whitethroat (Sylvia communis) nestlings? Environ. Sci. Pollut. Res. Int. 25 (8), 7758–7766. https://doi.org/10.1007/s11356-017-1064-1.
United Nations Environment Programme (UNEP) and Secretariat of the Basel, Rotterdam and Stockholm (BRS) Conventions, 2023. Chemicals in Plastics: a Technical Report. Geneva. https://www.unep.org/resources/report/chemicals-plastics-technical-report.
United Nations, 2019. World Population Prospects: the 2019 Revision. United Nations, New York. https://population.un.org/wpp/Publications/Files/WPP2019_DataBooklet.pdf.
Vasquez, M.P., Rylander, R.J., Tleimat, J.M., Fritts, S.R., 2022. Use of anthropogenic nest materials by black-crested titmice along an urban gradient. J. Fish Wildl. Manag. 13, 236–242. https://doi.org/10.3996/JFWM-21-058.
van Franeker, A., Lavender, K.L., 2015. Seabirds, gyres and global trends in plastic pollution. Environ. Pollut. 203, 89–96. https://doi.org/10.1016/j.envpol.2015.02.034.
von Moos, N., Burkhardt-Holm, P., Köhler, A., 2012. Uptake and effects of microplastics on cells and tissue of the blue mussel Mytilus edulis L. after an experimental exposure. Environ. Sci. Technol. 20, 11327–11335. https://doi.org/10.1021/es302332w.
Votier, S., Archibald, K., Morgan, G., Morgan, L., 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Mar. Pollut. Bull. 62, 168–172. https://doi.org/10.1016/j.marpolbul.2010.11.009.
Walker, D.I., Baker-Austin, C., Smith, A., Thorpe, K., Bakir, A., Galloway, T., Ganther, S., Gaze, W., Lewis, C., Quill, E., Russel, J., van Hoytema, N., 2022. A critical review of microbiological colonisation of nano- and microplastics (NMP) and their significance to the food chain. Cefas. https://doi.org/10.46756/sci.fsa.xdx112.
Wang, Y., Chen, S., Blair, R.B., Jiang, P., Ding, P., 2009. Nest composition adjustments by Chinese bulbuls (Pycnonotus sinensis) in an urbanized landscape of Hangzhou (E. China). Acta Ornithol. 44, 185–192. https://doi.org/10.3161/000164509X482768.
Winkler, A., Nessi, A., Antonioli, D., Laus, M., Santo, N., Parolini, M., Tremolada, P., 2020. Occurrence of microplastics in pellets from the common kingfisher (Alcedo atthis) along the Ticino River, North Italy. Environ. Sci. Pollut. Res. Int. 27, 41731–41739. https://doi.org/10.1007/s11356-020-10163-x.
Witteveen, M., Brown, M., Ryan, P.G., 2017. Anthropogenic debris in the nests of kelp gulls in South Africa. Mar. Pollut. Bull. 114, 699–704. https://doi.org/10.1016/j.marpolbul.2016.10.052.
Wright, S.L., Ulke, J., Font, A., Chain, K.L.A., Kelly, F.J., 2020. Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environ. Int. 136, 105411 https://doi.org/10.1016/j.envint.2019.105411.
Xu, J.L., Thomas, K.V., Luo, Z., Gowen, A.A., 2019. FTIR and Raman imaging for microplastics analysis: state of the art, challenges and prospects. Trends Anal. Chem. 119, 115629 https://doi.org/10.1016/j.trac.2019.115629.
Yang, Y., Liu, W., Zhang, Z., Grossart, H.P., Gadd, G.M., 2020. Microplastics provide new microbial niches in aquatic environments. Appl. Microbiol. Biotechnol. 104, 6501–6511. https://doi.org/10.1007/s00253-020-10704-x.
Yorio, P., Marinao, C., Kasinsky, T., Ibarra, C., Suárez, N., 2020. Patterns of plastic ingestion in kelp gull (Larus dominicanus) populations breeding in northern Patagonia, Argentina. Mar. Pollut. Bull. 156, 111240 https://doi.org/10.1016/j.marpolbul.2020.111240.
Zalasiewicz, J., Waters, C.N., Ivar do Sul, J.A., Corcoran, P.L., Barnosky, A.D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R., McNeill, J.R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A.P., Yonan, Y., 2016. The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. Anthropocene 13, 4–17. https://doi.org/10.1016/j.ancene.2016.01.002.
Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K.H., Wu, C., Lam, P.K.S., 2021. Understanding plastic degradation and microplastic formation in the environment: a review. Environ. Pollut. 274, 116554 https://doi.org/10.1016/j.envpol.2021.116554.

Zhao, S., Zhu, L., Wang, T., Li, D., 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar. Pollut. Bull. 86, 562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032.

Zhao, S., Zhu, L., Li, D., 2016. Microscopic anthropogenic litter in terrestrial birds from Shanghai, China: not only plastics but also natural fibers. Sci. Total Environ. 550, 1110–1115. https://doi.org/10.1016/j.scitotenv.2016.01.112.

Zheng, X., Wu, X., Zheng, Q., Mai, B.-X., Qiu, R., 2022. Transfer of Microplastics in Terrestrial and Aquatic Food Webs: the Impact of E-Waste Debris and Ecological Traits, vol. 57, pp. 1300–1308. https://doi.org/10.1021/acs.est.2c06473.