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Plastic Pollution and its Impacts on Waterbirds and Their Habitats: A Narrative Review of Current Evidence and Research Gaps

Nahdema abed abaas jasim
Department of Ecology, Faculty of Sciences, University of Kufa, Iraq.

ABSTRACT

Plastic pollution is a chronic and ubiquitous environmental stressor in aquatic ecosystems, with a rapidly accumulating body of evidence indicating negative impacts on wildlife. Although much attention has been paid to the impacts of plastic pollution on marine species, far less is known about the impacts on waterbirds (including wetland birds), which inhabit terrestrial habitats and are often in close proximity to water, sediments, benthic prey and shoreline environments. We summarise studies reporting on the behaviour of waterbirds in relation to plastics, assessing the ingestion of, and entanglement in, plastics, the translocation of plastics into bird nests, ingestion of microplastics, gut microbiome shifts, tissue and histological alterations, changes in the morphology of the gut, microplastic and nanoplastic contamination, and changes to habitats. Plastic ingestion in waterbirds can occur through the ingestion of plastic debris, or the ingestion of prey and environmental contaminants. Ingested larger debris can lead to gut impaction, leading to tissue necrosis, decreased food intake, chronic damage and poor condition, and even death from starvation. Entanglement with fishing gear and plastic litter such as rope and netting can cause obstruction, chronic injuries, increased risk of drowning, and poor condition. Ingested plastics are increasingly recognised as environmental contaminants, and evidence has been found of shifts in the composition of the gut microbiome and the incidence of fibrotic plastic contamination (a condition dubbed 'plasticosis') in some species of seabird. Although the existing data are limited and geographically patchy and focus on a narrow number of waterbird taxa, freshwater and terrestrial systems remain severely underrepresented, and plastispheres and nanoplastics deserve more attention. Finally, plastic ingestion may negatively affect waterbird habitats, for example, by impeding sediment mobility, decreasing prey abundance and diversity, increasing the risk of entanglement, and changing the composition of nesting materials. Given their broad spatial distribution and taxonomic diversity, waterbirds can potentially be used as bioindicators of plastic pollution, but future research should prioritise freshwater habitats, especially those in data-sparse regions, and should employ standardised methods for sampling and analysis, non-invasive data collection, long-term data collection, and models that describe both the dose of ingested plastics and their effects. Pollution should be abated through the reduction of plastic sources, improved waste management practices, collection of lost fishing gear, implementation of wastewater treatment strategies, wetland management, and long-term waterbird protection and conservation strategies.

KEYWORDS: plastic pollution; waterbirds; freshwater ecosystems; wetlands; microplastics; plastic ingestion; entanglement; bioindicators; habitat contamination; plasticosis.

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Corresponding Author:
Nahdema abed abaas jasim

1. INTRODUCTION

Plastic pollution is now a permanent environmental challenge impacting all terrestrial, freshwater, coastal and marine ecosystems. The pervasiveness of use of plastic materials, coupled with weak collection, waste management and recycling systems has led to a steady stream of plastics that is released into the environment. Given that many plastics are extremely resistant to biological degradation, larger objects can remain in the environment for years and be gradually fragmented into smaller pieces. Rivers, lakes, wetlands, floodplains, shorelines, and estuarine systems can therefore serve not only as a transport mechanism, but also temporary or semi-permanent sink of plastics (Charlton-Howard et al., 2023). Birds are especially relevant for this evaluation of environmental plastic pollution because of their hierarchical position in the food chain, their ability to use multiple habitat compartments and to show potential for exposure by ingesting water, sediments, prey and nesting material. However, reviews of plastic pollution in birds so far have been mostly based on data from species living in the ocean and on the coast, while a recent synthesis of the freshwater and terrestrial perspective shows that the freshwater realm is still very underrepresented in the literature (Mansfield et al., 2024). Their synthesis of 106 reports illustrates a severe overall underrepresentation of freshwater species, with a strong bias against smaller particles and global coverage.

The likely pathways by which waterbirds are exposed to plastics are numerous. They include: ingestion of plastics from the environment, ingestion of prey containing plastics, contact with plastics in sediments and water, plastic entanglement and entry of plastics and plastic fibers into nests. Possible biological effects of these pathways of exposure range from physical injury to the digestive system to nutritional stress, tissue injury and behavioural effects, possibly even to effects on reproductive success and population dynamics (Charlton-Howard et al., 2023).

The main constrain of the current literature is a lack of proportional representation from habitats and bird groups. When reviewing waterbird-plastic interactions in Brazil, de daudt et al. (2023) compiled 96 related documents, within which the most common form of interaction was plastic ingestion (67%), while seabirds accounted for 79% of the bird species studied. They also highlighted to large gaps in space, taxonomy, and methods. The same was found by mansfield et al. (2024), in that freshwater and terrestrial studies have a bias for macroplastics, while microplastics and nano plastics are studied far less. Thus, this review aims to compile current knowledge on the relationship between plastic pollution and waterbirds, focusing on freshwater and wetland environments. The review considers primary pathways of exposure, biological and ecological impacts, habitat-level effects, the potential of waterbirds as bioindicators, methodological constraints and research priorities (Daudt et al. (2023).

2. SCOPE AND APPROACH OF THE REVIEW

This paper is a narrative synthesis and not a formal systematic review or meta-analysis. Literature was obtained from core scientific journal databases and publisher platforms by the use of combinations of descriptors: plastic pollution, waterbirds, freshwater birds, wetlands, microplastics, plastic ingestion, entanglement, nest material, gut microbiome, plasticosis, bioindicators and habitat contamination. Particular focus was given to more recent peer reviewed literature from the past ten years, although older research was retained if it provided the appropriate background (Daudt et al. 2023).

The assembly prioritized evidence from studies that directly dealt with the birds and plastic debris, with wider evidence examined if it provided, a greater insight into microplastic exposure in a mechanistic or ecological context. Evidence from fresh and marine systems differ, so this was interpreted with respect to seabirds in freshwater and wetlands, not necessarily generalising (Fackelmann et al.,2023).

3. PLASTIC POLLUTION IN AQUATIC AND WETLAND ECOSYSTEMS

Plastic pollution can be present in various aquatic environment and arrives into these systems through domestic or urban refuse, wastewater, industrial operation, farming drainage, urban surface water, recreation and sport, commercial fishery and disposed waste. Plastic debris can be transported for hundreds of kilometers in flows of rivers and can be contributed by water bodies (wetlands, lakes, slow-flowing channel, nearshore zones) as a result of water velocity and other associated water chemistry (Fackelmann et al.,2023). Plastic contamination includes a wide size range and physical forms. Macroplastics include larger pieces of plastic such as bags, bottles, containers, ropes, fishing line, packaging, and other waste products. Microplastics are generally defined as plastics that are smaller than 5 mm in size, and nanoplastics can be much smaller than microplastics, generally considered as plastics smaller than 1 μm (or 100 nm in some cases) (Kibria, 2024).

A new worldwide search of plastics in coastal and marine birds found contamination from 39 sites or nations on every continent except Antarctica and included a variety of polymer plastics, forms such as polypropylene, PE, PS, PET, fibres, fragments, pellets, threads, films and fishing lines. Whilst predominantly oceanic in nature, the evidence demonstrates the sort of plastics birds are exposed to in the water bodies (Kibria, 2024).

4. MAJOR EXPOSURE PATHWAYS OF WATERBIRDS

4.1 Direct Ingestion

Eating plastic is a typical interaction between birds and plastic debris. Birds often inadvertently eat tiny plastic pieces while they are feeding, as these bits of plastic are often similar to their food in terms of size, shape, colour or behaviour, such as in the case of species that sift sediment, skim the water's surface, dive or catch tiny aquatic animals (Mansfield et al., 2024). Plastic ingestion may refer to one or any combination of fragments, fibres, films, pellets, threads, pieces of fishing-line or other such synthetic debris. The probability of ingestion is related to feeding ecology, prey type, degree of habitat contamination, characteristics of the particles and other available food sources. Once ingested larger plastics may be retained in the gastrointestinal tract and produce overt effects; these may include blockage, mechanical damage to intestinal mucosa, irregularity in transit of food and reduced absorptive capacity, altered satiety and reduced intake of food, the severity of these effects will be related to the size, shape and polymer characteristics of the plastic particle, the length of time it is retained, quantity ingested and the individual state of health. As with all exposures the presence of plastic in the gastrointestinal tract should not be used as evidence of clinically significant disease, a careful differentiation should be maintained between plastic exposure, ingested plastic, biological response and clinical consequence (Mansfield et al., 2024).

4.2 Indirect Exposure Through Contaminated Prey

Waterbirds may also ingest plastic indirectly through prey organisms. Fish, crustaceans, molluscs, aquatic insects, and other organisms may contain or carry plastic particles, creating a pathway for trophic transfer. This pathway is particularly relevant for predatory or opportunistic waterbirds that consume large numbers of aquatic organisms. However, trophic transfer should be interpreted cautiously because the extent to which ingested microplastics move through aquatic food webs and subsequently accumulate in bird tissues remains uncertain. The presence of microplastics in prey does not necessarily demonstrate biomagnification in birds. Future studies should therefore quantify both environmental and biological compartments to distinguish exposure pathways from actual accumulation (Ryan, 2018).

4.3 Entanglement

Entanglement is another significant pathway through which plastic pollution impacts birds. Abandoned fishing nets, monofilament lines, cords, synthetic straps, wrappings, and other flexible plastics become trapped on wings, legs, necks, and beaks. A worldwide survey in Ryan (2018) documented 265 species of birds were stuck in plastic or other man-made materials, including 147 seabird species and 69 species that rely on freshwater or coastal habitats. Fishery gear was the cause of the greatest number of species impacted. Entanglement can limit movement, impinge on feeding and flight, cause cuts or chronic wounds and lead to depredation. When birds are in the water, entanglement may impair swimming or diving and ultimately lead to drowning. The effects of the entanglement depend on where and for how long the bird was entangled, what the material was, the age of the bird and if the material is removed.

Since entanglement can result in either instant death or a long-term sub-lethal injuries, surveys of population effects should document both entanglement deaths and non-lethal entanglement, (Ryan, 2018).

4.4 Plastic Materials in Nests

Some birds incorporate anthropogenic materials into their nests. Plastic fibers, strings, ropes, synthetic threads, films, and packaging materials may become available in urbanized or contaminated habitats and can subsequently be collected by nesting birds. The use of plastic in nests has two important implications. First, flexible synthetic materials may entangle adults or chicks, potentially causing injury or mortality. Second, plastic incorporated into nests provides information about the availability and distribution of anthropogenic debris within the habitat. Nest material can therefore function as both an ecological consequence of plastic pollution and a potential monitoring matrix. However, the interpretation of plastic in nests should account for species-specific nest-building behavior, habitat accessibility, and local availability of natural versus synthetic materials (Baak *et al*., 2024).

5. BIOLOGICAL AND PHYSIOLOGICAL EFFECTS OF PLASTIC EXPOSURE

5.1 Gastrointestinal Injury and Nutritional Effects

The GI tract was one of the first organs to be in direct contact with the ingested plastic. Large ingested plastic fragments can cause physical damage (abrasion, impaction, or reduced mobility of gut contents), inflammation, or impaired transit of the gastrointestinal contents. The accumulation of plastic may also limit the functional capacity of the gastrointestinal tract and have an effect on feeding behavior. A decrease in food intake may result if the accumulated plastic causes a feeling of being full without providing any nutrition energy. This hypothesis has been proposed as a potentially significant pathway for the effect of plastic ingestion on body condition.

Nonetheless, population-level nutritional impacts have yet to be demonstrated for numerous freshwater waterbird species (Charlton-Howard et al., 2023).

5.2 Microplastic-Associated Effects

Microplastics raise a more complex biological challenge as their small size allows interaction with tissues and physiological processes in addition to the straightforward mechanical effects seen with larger debris. Experimental work has identified links with inflammation, oxidative stress, and other physiological effects, and changes in cellular or tissue processing.

However, laboratory studies often employ exposure levels, particle properties or durations of exposure that differ from conditions experienced in the free-living environment. Therefore, experimental results are best used for developing a plausible mechanism rather than assuming identical effects are occurring in the free-living environment.

This difference is especially true for the freshwater and wetland birds, in which exposure data from field study are still lacking. (Daudt et al. (2023).

6. PLASTIC-ASSOCIATED CHEMICALS

As for the chemicals in microplastic particles, they might be additives that were added during the manufacture of the plastic, or chemicals that adhered to the plastic surface in the environment. Chemicals associated with plastic pollution are phthalates, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides and other hydrophobic chemicals.

Therefore the effects of exposure to plastic could be the result of one or more of the following: injury from the plastic particle; chemical exposure to plastic additives; or exposure to environmental contaminants hitching a ride on and in the plastic. However, that does not mean the contaminant found in a bird originated from plastic. A bird could be exposed to those same chemicals through their food, water, sediments, air and other sources of pollution. In the future, we need to distinguish between the proportion of exposure originating from plastic and all other sources of contaminant exposure in the environment, says Fackelmann et al.(2023).

7. EFFECTS ON THE GUT MICROBIOME

Gut bacteria is a new endpoint of plastic exposure In 2023, Fackelmann et al. examined wild northern fulmars and Cory's shearwaters, and found relationships between the makeup and diversity of bacteria in the gut and the number of plastics found. They found greater numbers of plastics in the gut were associated with less of some of the good bacteria and more of bacteria known to cause disease, carry antibiotic resistance and degrade plastics.

However, these results could also imply that plastic ingestion could affect other biological processes besides "being a physical blow." However, this study was conducted on seabirds, and it is unclear whether freshwater and wetland birds would show similar outcomes.

The correlation of microplastic load with microbiome composition, alone, does not suggest that plastics are the cause of disease. An array of factors, including diet, habitat, age, condition, and other environmental stressors, may bring about a change to the microbiome. Long term studies are needed to determine causality and whether microbiome changes adversely impact health, survival, and reproduction (Jeong et al. 2024).

8. PLASTICOSIS AND HISTOPATHOLOGICAL EFFECTS

"Most recently new concepts in relation to plastic effects in birds have emerged through the description of "plasticosis". Charlton-Howard et al. (2023) observed pervasive fibrosis, and scar tissue formation, in relation to plastic occurrence within the gastrointestinal tissue of seabirds and described this as plastic-associated fibrotic pathology of the stomach and used the new term of "plasticosis" in referring to this phenomenon.

Plasticosis would therefore be relevant as it demonstrates that ingesting plastic could be associated with a chronic tissue remodelling response in addition to a possible presentation as an acute gastrointestinal blockage. However, this evidence base is currently limited to seabirds. It is therefore too early to define plasticosis as a broad water pathology.

Another key avenue of research will be to determine if comparable histopathological responses occur in freshwater and wetland species of bird exposed to plastics (Kibria, 2024). Histological studies should be paired with quantification of plastic burden, plastic types, localization of plastic pieces, and presence of inflammation and fibrosis (Kibria, 2024).

9. EFFECTS OF PLASTIC POLLUTION ON WATERBIRD HABITATS

Plastic pollution should not be viewed solely as contamination of individual birds but also as a change in the waterbird habitat. Plastic debris can be caught in wetlands, along rivers, on the shores of lakes, in marshlands, as well as in rice paddies and freshwater lakes. It can alter the structural characteristics of sediments and beaches, provide greater opportunity for artificial food,

alter nesting material and may increase exposure to plastic debris. Plastic pollution may also have adverse effects on aquatic organisms that are prey for waterbirds. Plastic in or on sediments can serve as a substrate for colonization by micro-organisms and interactions with other contaminants, and may alter the exposure environment to water and sediment dwelling organisms in the habitat. Observations made on little egrets (Egretta garzetta) in tropical rice fields gave the first indication that this habitat was contaminated by birds, along with microplastic ingestion. Microplastic levels appeared to be higher on the feathers than in the faeces and there was a significant correlation between the plastic content of the feathers and of the habitat, demonstrating how feathers can be used as a non-destructive marker of habitat contamination (Han-Xun et al., 2025). This research highlights the crucial need to quantify plastic pollution both in birds and the environment and to treat the organism as a composite exposure unit.

10. WATERBIRDS AS BIOINDICATORS OF PLASTIC POLLUTION

Waterbirds possess a number of traits that argue in favour of their use as bioindicators. They can have different trophic levels, interact with water and sediments, feed on aquatic prey, disperse among habitats and act as accumulators of pollutants.

Possible biological matrices for detection monitoring are gastrointestinal contents, feces, feathers, blood, tissues from killed individuals and nest material. Feces and feathers are desirable because they do not necessarily require the killing of individuals. A new review confirms this. Mansfield et al. (2024) highlighted the potential of birds as indicators, but called for greater consistency in collection procedures in the field, and laboratory methodology, to ensure data can be compared across studies – especially for micro- and nanoplastics. They suggest publication of plastic concentrations, composition (size and type), morphology and background concentrations (Li et al., 2023).

For freshwater and wetland studies, a useful monitoring framework should integrate:

- plastic abundance in water and sediments;
- plastic characteristics, including size, shape, color, and polymer;
- plastic burden in bird feces or feathers;
- frequency of gastrointestinal plastic ingestion;
- entanglement frequency;
- body condition and nutritional indicators;
- hematological and biochemical biomarkers where appropriate;
- reproductive parameters;
- habitat characteristics; and
- long-term population trends.

Such an integrated approach would provide substantially stronger evidence than simply reporting whether plastic was present or absent.

11. MARINE–FRESHWATER RESEARCH IMBALANCE

The marine bias is one of the most significant biases of this review.

Kibria (2024) found overwhelming evidence of plastic ingestion for a wide suite of bird groups and diets (feeding guilds) around the globe, including numerous freshwater and terrestrial bird groups.

In a recent review, Mansfield et al. (2024) found that out of 106 studies on terrestrial and freshwater avian species, most of the studies examined macroplastics, while research on microplastics was much less prevalent and no nanoplastic exposure was investigated in the studies they reviewed. Likewise, Daudt et al. (2023) showed the existence of a dominant marine bias and taxonomic bias even in the Brazilian literature considering the large amount of freshwater and wetlands habitats in this country. Such imbalance has important consequence for global environmental assessment. Bird conclusions based on seabirds cannot be easily applied to piscivorous birds using rivers, lakes, marsh, rice fields, artificial ponds and inland wetlands foraging. Feeding behavior, habitat contamination, hydrological regime, prey assemblage, plastic transport and exposure duration may significantly alter exposure as well as biological response. (Taglialegna, 2023).

12. FROM INDIVIDUAL EXPOSURE TO POPULATION-LEVEL CONSEQUENCES

A key conceptual difference in plastic-pollution work is whether we are showing how individuals are exposed to it or how populations are affected. Finding a plastic in a bird is not in itself evidence that plastic pollution is lowering population size. A population consequence can be inferred if there is evidence of a biologically plausible pathway from contamination in the environment to ingested plastic, to physical damage and poor body condition, to reproductive damage, reduced survival and to population dynamics. Needs longitudinal studies and dose-response analysis. Key outcomes of interest may include breeding success, clutch or brood survival, chick growth, fledging success, adult survival, migration ability, and long-term abundance of population.

Currently, the evidence for such complete causal pathways is much stronger for marine systems than for freshwater and wetland birds. Therefore, future research should go past prevalence estimates and focus on developing integrated exposure-response pathways (Veríssimo, et al., 2024).

13. METHODOLOGICAL CHALLENGES AND STANDARDIZATION

Comparison between studies is already limited by the differences in sampling design, definitions of particle-size range, laboratory procedures, analytical quality control and quality assurance, analytical methods, and reporting metrics. Microplastic testing is extremely vulnerable to contamination in the lab, whereby synthetic and airborne fibres can contaminate samples through the collection, extraction, filtration and processing processes. Negative controls, blanks, a non-contaminated laboratory environment and proven analytical methods are essential.

Finally, and in connection to the above, is the issue of polymer identification. Visual identification may not be sufficient for most microplastic studies because visually similar particles could potentially be chemically dissimilar. FTIR and Raman spectroscopy provide more conclusive methods of polymer identification (Wilcox, et. Al. 2015).. In their recent publication, Mansfield et al. (2024) highlighted analytical methods (e.g., micro- and nanoplastics analysis using standardised field sampling and laboratory analytical techniques e.g., Raman spectroscopy).

Future studies should consistently report at least:

1. number of birds examined;
2. species, age, and sex where relevant;
3. sampling location and habitat characteristics;
4. number, mass, and concentration of plastic particles;
5. particle size and size class;
6. shape and color;
7. polymer composition;
8. anatomical location or biological matrix;
9. analytical technique;
10. contamination-control procedures; and
11. environmental background concentrations.

Standardization would substantially improve the comparability of results among species, habitats, regions, and years.

14. CONCLUSIONS

Plastic pollution is one of the increasingly important pressures on waterbirds and their aquatic habitats. The most recognised pathways are ingestion and entanglement, but nests are also constructed using plastic and microplastics present an additional risk of exposure.

Even less is known about the potential effects of plastic ingestion, but more recent work has taken the field out of just plastic ingestion observations and into the potential effects on gut microbiomes and plasticosis (i.e. Plastic associated gastrointestinal fibrosis) observed in certain seabirds. However, so far these novel findings have only been in marine species and are not applicable to freshwater or wetland birds. As such, we believe the main conclusion that can be drawn from the literature so far is the following: waterbirds are exposed to plastics, and the evidence is very heterogeneous. It is also important to highlight that marine waterbirds have been much better studied than waterbirds from freshwater systems and wetlands, especially regarding microplastics and nanoplastics, and different scientific studies differ strongly in sampling and analysis methodology, which complicates quantitative synthesis.

Future research will thus need to go beyond counting up the presence of plastics in the environment to measure plastics exposure levels, the identities of polymers, biological impacts and final ecological consequences. Future long-term monitoring involving plastics presence, ecological condition and bird productivity will be key in understanding the ecological significance of plastics pollution. Their feeding ecology and food items make waterbirds particularly important sentinel species because they incorporate contamination in the water, sediments, prey and habitat. Establishing standardised, non-invasive, and reproducible monitoring techniques could improve the effectiveness of monitoring efforts and conservation planning. Avoidance of plastic sources, improved waste and wastewater management, retrieval of lost fishing gear and wetland habitat protection should still be the primary measures to reduce the risk of plastics to waterbirds.

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