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Review

Birds as Bioindicators: Revealing the Widespread Impact of Microplastics

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Simple Summary: Plastic waste, especially microplastics (MPs) and nanoplastics (NPs), poses a significant threat to birds and ecosystems worldwide. These pollutants are ingested directly or indirectly through prey or contaminated habitats, affecting birds across various environments. Species in coastal and urban areas are particularly vulnerable, with seabirds often exposed to fishing-related debris and terrestrial birds to urban and industrial waste. MPs have been detected in a variety of avian tissues, feathers, feces, and regurgitations, with fibers being the most prevalent form due to their abundance in textiles and susceptibility to environmental transport. Detection efforts span from the Antarctica to the Labrador Sea, with North America, China, Australia, and South Europe being the regions that have invested more research into this issue. MPs and NPs have been shown to accumulate in gastrointestinal systems, inducing tissue damage, and disrupting metabolism and hormonal balance. Moreover, they also act as vectors for harmful chemicals like heavy metals and persistent organic pollutants. Standardizing detection methods and understanding long-term effects on avian health are critical for addressing this pervasive issue and mitigating its ecological consequences.

Abstract: The global crisis of plastic pollution, particularly involving microplastics (MPs) and nanoplastics (NPs), has profound ecological implications. Birds, serving as bioindicators, are especially susceptible to these pollutants. This systematic review synthesizes the current research on the presence, distribution, and impact of MPs and NPs on avian species, alongside advancements in detection methodologies. MPs and NPs have been identified in over 200 bird species across 46 families, encompassing several ecosystems, from Antarctica to Labrador, including Australia, China, and South Europe. Seabirds such as penguins, gulls, and shearwaters exhibit a high burden of MPs in tissues and feces due to fishing debris, while terrestrial species face contamination from urban and agricultural sources. Depending on their composition, MPs can cause gastrointestinal damage, oxidative stress, and bioaccumulation of toxic chemicals, particularly polyethylene and polypropylene. However, challenges in detection persist due to methodological inconsistencies, though advances in spectroscopy and flow cytometry offer improved accuracy. Addressing this pollution is vital for bird conservation and ecosystem health, requiring international collaboration and standardized research protocols.

Keywords: nanoplastics; avian; plastic pollution; marine debris; environmental status; bioaccessibility

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1. Introduction

Plastic has emerged as a transformative alternative for both industry and society, significantly changing healthcare delivery as well as the packaging, storage, and transportation of various products [1]. Globally, it is one of the most common materials and is deeply embedded in modern life. Its flexibility and durability make it highly valuable in everyday applications [2]. After popularization in the 1950s, mass production of plastic has increased intensely in recent decades, and plastic pollution is now recognized as a major environmental problem [2,3]. Over the past century, global plastic production has soared to over 345 million tons annually, most of which is composed of single-use and disposable plastics [4,5]. The combination of high disposability and shortcomings in waste management has resulted in plastic debris being recognized as a significant environmental challenge, leading to widespread contamination of aquatic and terrestrial ecosystems and causing substantial economic and ecological damage [1]. Due to their nearly indestructible morphology and the chemicals they contain, plastics can persist in the environment for extended periods, potentially causing serious harm to ecosystems and their species [6].

Depending on its size, plastic debris can include macroplastics, mesoplastics, microplastics, or nanoplastics [7]: macroplastics (25–1000 mm) threaten marine wildlife through two main interactions: ingestion, where debris is consumed and enters organisms' digestive tracts, and entanglement, often involving packaging tapes, synthetic ropes, or driftnets, which can trap or entangle animals. Entanglement in plastic debris also severely impacts the survival and well-being of marine animals, even in Antarctica [8]. By 2050, it is predicted that 99% of seabird species will ingest plastics [9]. Although macroplastics are the most conspicuous form of plastic pollution in marine environments, growing attention is being directed toward smaller fragments, referred to as mesoplastics (5–25 mm) and microplastics. Microplastics (MPs) are defined as plastic particles smaller than 5 mm; they can either result from the breakdown of larger plastic items due to solar radiation and high temperatures or be intentionally produced [5,10–12]. The former are referred to as secondary MPs, while the latter are known as primary MPs [5]. However, some MPs such as those from textiles, cosmetics, and industrial or medical applications, are directly introduced into the ocean as micron-sized particles [10]. Among these, microfibres are the most abundant—threadlike particles from clothing, carpets, and similar products [13,14]. Depending on their origin, MP particles can have different shapes (fragments, fibers, pellets, films, foam, microbeads, etc.) and colors (transparent, white, blue, red, yellow, green, or black) [15,16]. In this context, many bird species are increasingly exposed to MPs due to their feeding habits and pollution of their habitats [10,15].

Although the definition of MPs is well established, the same does not apply to nanoplastics (NPs). This term is used for particles < 1 µm, as well as for particles < 100 nm [17,18]. Evidence suggests differences in the toxicity mechanisms of MPs and NPs [19]. Due to their smaller size, NPs can easily cross the intestinal barrier and spread to other organs through the blood [20]. Additionally, it has been demonstrated that smaller particles are generally more toxic than their larger counterparts at the same mass concentration [21]. Unfortunately, the detection of NPs is more arduous than that of MPs and there has been little research focused on NPs in birds.

Birds are broad-ranging animals that inhabit a wide variety of ecosystems. They exhibit different feeding habits and are part of many trophic levels and complex food webs, thus rendering them effective sentinels of environmental pollution, including plastic waste [18]. Many studies have reported the presence of plastics in nests, pellets, feces, feathers, and the digestive systems of birds [2,7,10,14,22–24]. Scientific research has demonstrated that both marine and terrestrial birds often consume plastics as they identify them as prey, or indirectly from contaminated food (trophic transfer) [25,26]. In this context, a recent

study on razorbills (*Alca torda*) in the Mediterranean Sea reported the isolation of 41 plastic items of different sizes, colors, and composition from only three individuals [27]. Another example is the long-term research on Inaccessible Island (South Atlantic Ocean) from 1987 to 2018 that revealed that while over 14,000 plastics were recovered from thousands of bird regurgitations, plastic loads varied widely among species (0–70%) and slightly decreased in some of them despite rising global plastic production [28]. The COVID-19 lockdown reduced industrial activity and microplastic pollution, significantly lowering plastics in neotropic cormorant (*Nannopterum brasilianus*) pellets in 2020–2021 [29]. However, the death of a Magellanic penguin (*Sphesnicus magellanicus*) from ingesting a face mask highlights the rising threat of larger plastic pollutants or macroplastics, emphasizing the need for broader risk assessments [30].

Numerous studies have documented MP ingestion in birds across various regions, highlighting the global nature of the problem [2,31–34]. Multi-species studies tend to classify the species according to the ecosystem that they inhabit into seabirds, fresh-water birds, and terrestrial birds. MPs have been detected in the Arctic in little auks (*Alle alle*) from the Greenland Sea and in black-legged kittiwakes (*Rissa tridactyla*) from Alaska, and in Antarctica in gentoo penguins (*Pygoscelis papua*) and king penguins, (*Aptenodytes patagonicus*) [14,35–37]. However, MPs are not exclusive to seabirds; they have also been isolated from terrestrial and freshwater birds, as well as at the interfaces of oceans and rivers [10,22,38]. Estuaries and coastal wetlands are highly productive ecosystems that host important wildlife populations; due to the low water velocity in tidal zones, MP accumulation in sediment beds is frequent in these areas [39]. For this reason, shorebirds (Aves: Charadriiformes) that depend on intertidal sediments to feed on macroinvertebrates are key bioindicators of wetland health [38].

Compared with other animal classes (i.e., fishes), there is a notable lack of information about MPs and NPs in birds [15]. However, there is a consensus on the threat that they may pose to these species, as they can penetrate tissues and accumulate in organs, potentially causing changes in metabolism and even behavior [40]. This systematic review aims to summarize all the scientific information about MPs and NPs in wild birds and their consequences on birds' health. Detection of MPs in avian samples is also addressed in this study, with a discussion of their ecological implications.

2. Materials and Methods

For this research, PubMed and Google Scholar platforms were employed to focus the search on two items: "Plastics" (item 1) and "Birds" (item 2). Different search terms for each item were combined using the Boolean operators "OR" and "AND"; for item 1: "Microplastic" OR "Nanoplastic"; for item 2: "Bird" OR "Avian" OR "Aves". The search was conducted in September 2024, yielding 398 publications. The first screening was based on the titles and abstracts, and both items' suitability were mandatory for the selection of studies. Then, at the eligibility stage, the inclusion criteria were addressing both issues: (1) MPs or NPs and (2) birds; reporting original information or data; and full text available online. In contrast, the exclusion criteria were no focus on birds or MPs/NPs, no original data or contrasting information, and publication in a language other than English or Spanish. The publication year was not considered a limitation; so, all original studies up to 2024 were included. After the inclusion and exclusion criteria were applied, 113 studies were included in the selection (Figure 1). However, many papers were inconsistent in terms of the information they provided. In this regard, only 74 studies detailed the bird species analyzed, and fewer studies assessed the MPs' characteristics (44 for color, 45 for composition, and 64 for shape).

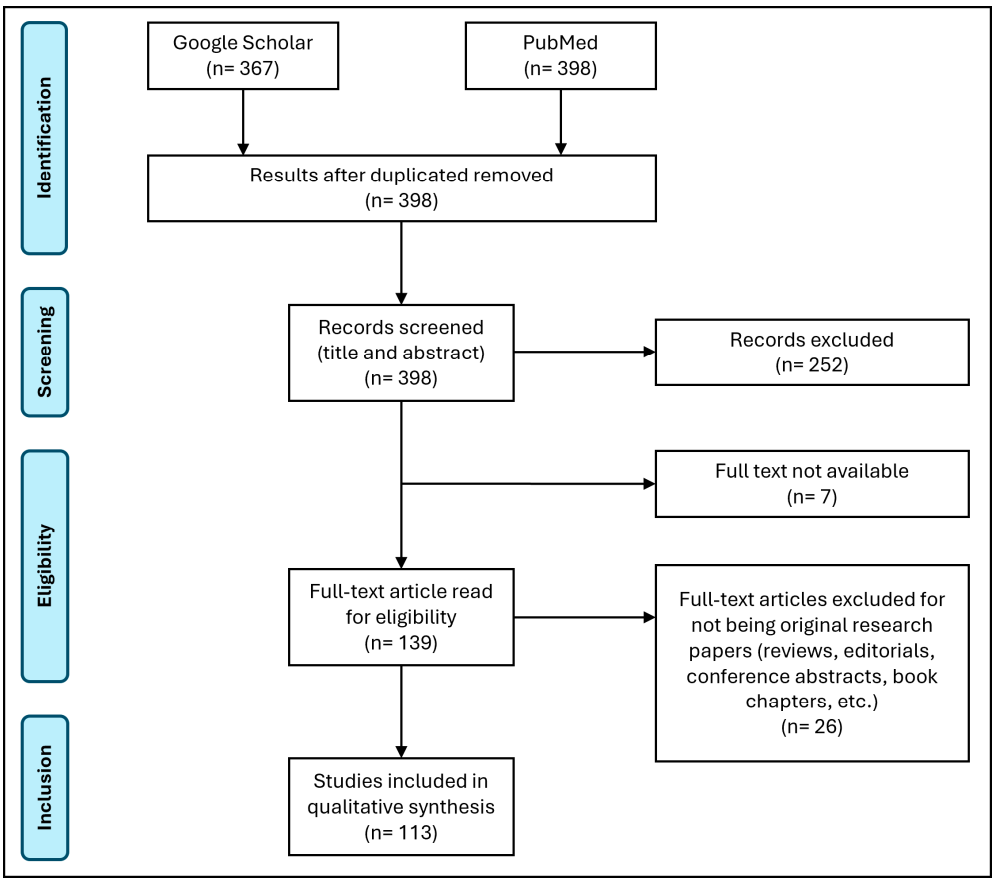


Figure 1. PRISMA flow diagram.

3. Results and Discussion

3.1. Description and Analysis of the Bibliographic Search

Research into MPs and NPs is novel. The first study about MPs in avian species was published in 2012, and since then, the number of publications slightly increased until 2020, when a noticeable uptick started (Figure 2). From 2020 to 2024, the mean number of publications per year has been 25.8.

Considering only the original studies included in the present review, 75.2% (85/113) were descriptive and 24.8% (28/113) experimental. Most of them focused on chickens (*Gallus gallus*) or Japanese quails (*Oturnix japonica*). Among the descriptive studies, 218 avian species from 46 families and 20 orders were assessed (Figure 3). However, not all descriptive articles included information about the species analyzed; so, only 74 of them were considered. While 47.3% of the studies (35/74) were performed with biological samples from live birds, the rest (52.7%, 39/74) analyzed carcasses or euthanatized birds. Thus, the samples for the detection of MPs varied, with the most common being tissue samples (41.9%, 31/74), feces (29.7%, 22/74), and regurgitations or pellets (13.5%, 10/74). Most of the studies employing tissue samples analyzed samples from the gastrointestinal tract (including the liver), and just a few research studies have been performed with respiratory tissue samples or other materials.

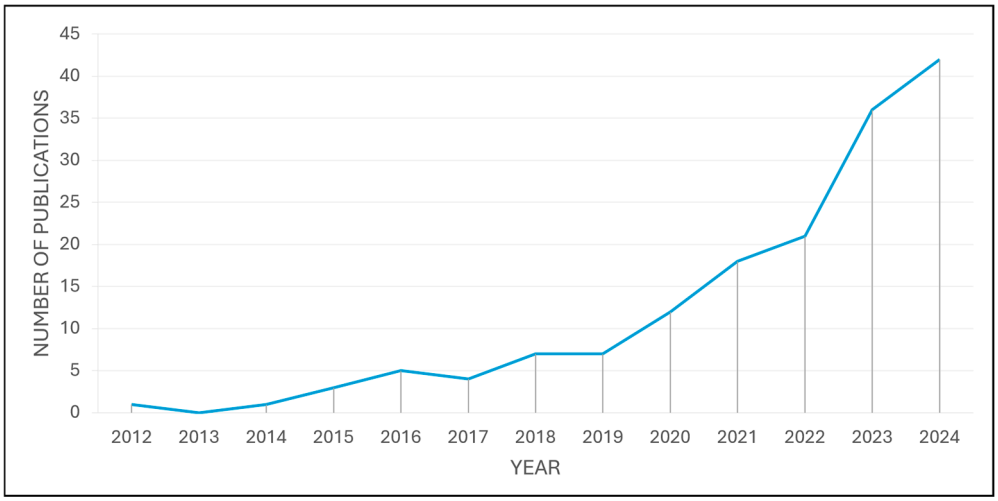


Figure 2. Number of publications about micro- or nanoplastics in birds per year from 2012 to September 2024.

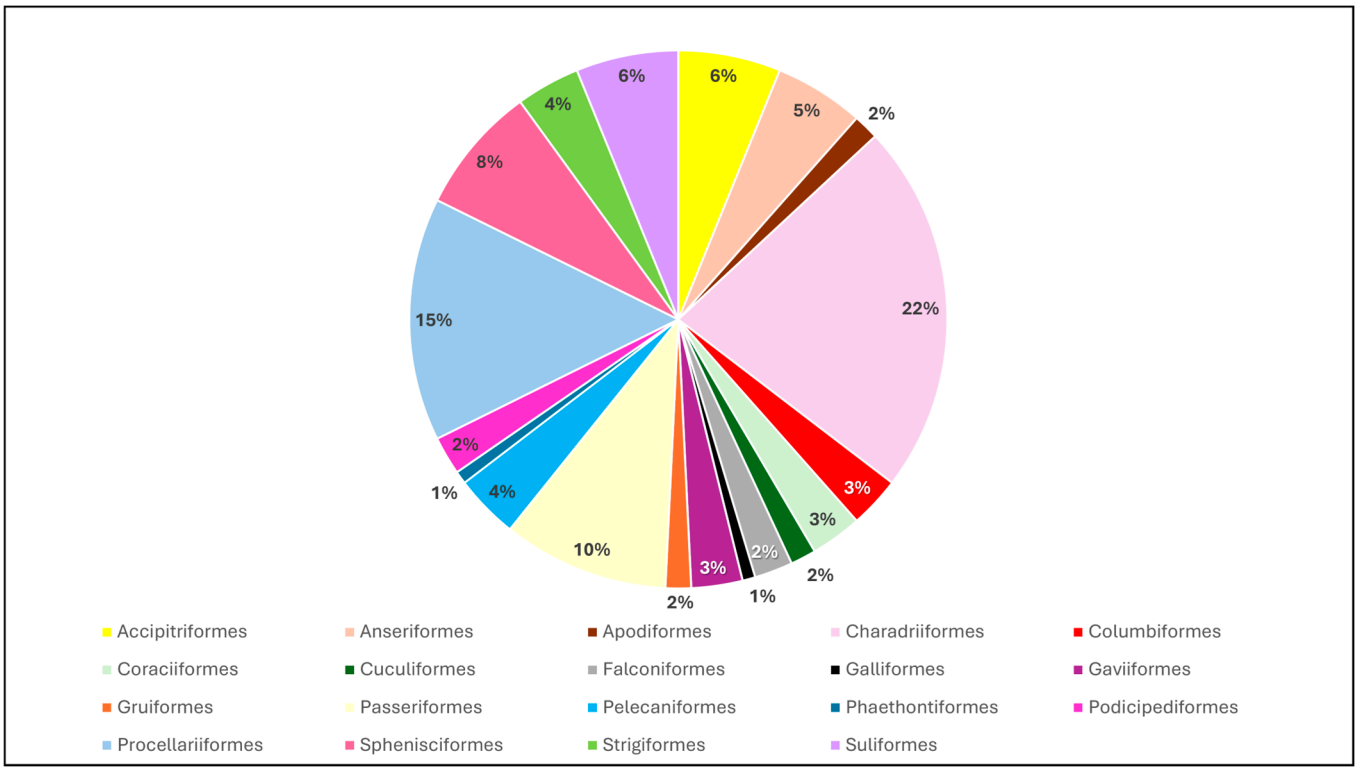


Figure 3. Representation of the taxonomic avian orders across the descriptive papers published on micro- and nanoplastics in birds (considering 74 studies that gave consistent information).

The regions where MPs in birds were investigated most were the Labrador Sea and Antarctica for marine birds, and China and South Europe for terrestrial birds (Figure 4). Most of the research was carried out on seabirds (68.9%, 51/74), followed by terrestrial birds (20.3%, 15/74) and freshwater birds (10.8% 8/74).

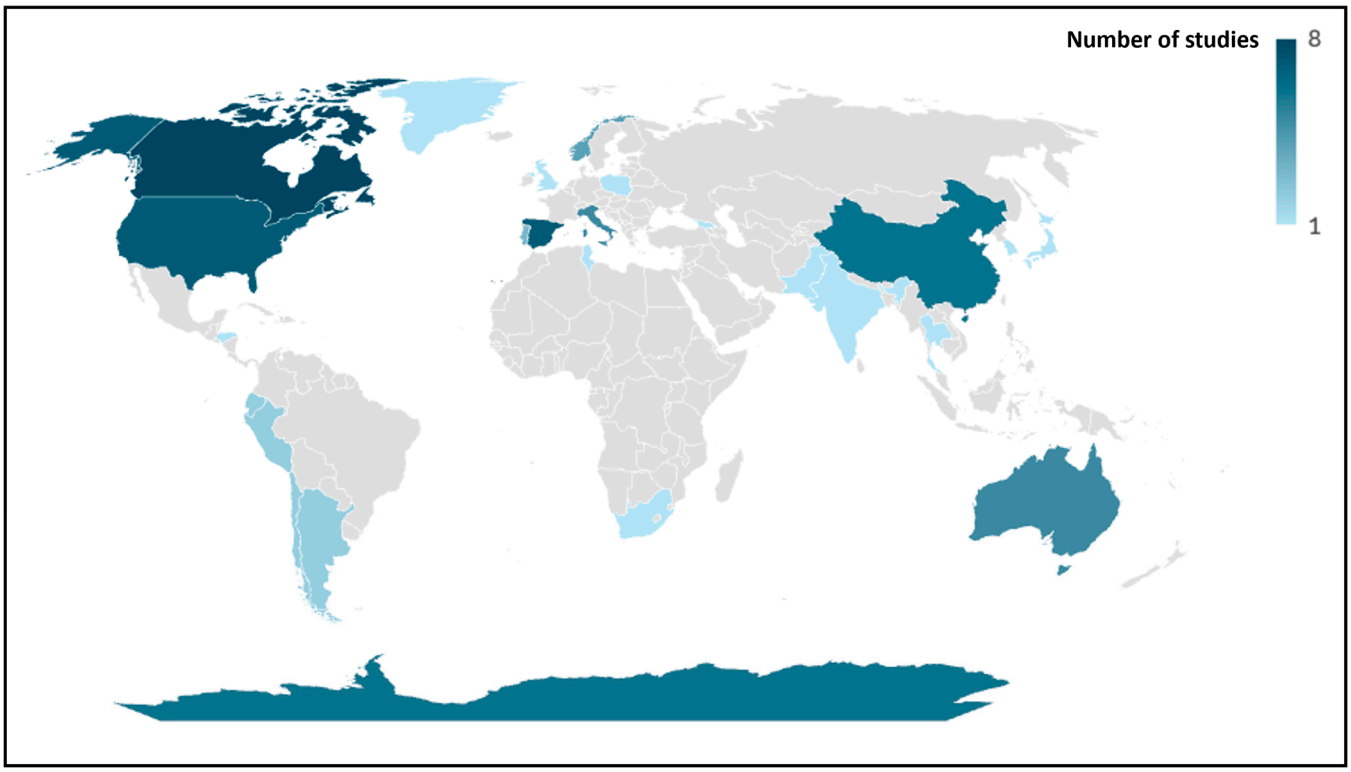


Figure 4. Worldwide distribution of descriptive research published from 2012 to 2024 about micro- and nanoplastics in wild birds. Note that sampling regions have been considered in this figure and do not reflect the affiliation of the researchers.

3.2. Techniques for Micro- and Nanoplastics Detection

Limitations affecting the data on MPs and NPs in wild birds are partly due to the complex detection mechanisms and the wide variety of different techniques used over time. Moreover, as ultrafine plastics can hide within biological tissue, their visual identification can be challenging and time-consuming. As a result, the underestimation of MPs and NPs in wild birds leaves a gap in the understanding of this emerging threat [1]. On the other hand, comparison between studies that employ different protocols may be inexact [41]. Thus, the implementation of monitoring efforts using standardized methods may be required to ensure comparability between studies [42,43]. In this regard, the meticulous work of some authors to standardize detection protocols has been crucial in addressing these issues [15,36].

Traditionally, plastic ingestion in birds has been assessed by examining the stomach contents of deceased individuals. This method provides a detailed understanding of the types and quantities of plastics ingested. Sample collection often includes the dissection of gastrointestinal tracts, specifically the gizzard and crop, where ingested materials accumulate [3,15].

Tissue analysis, while informative, is limited by the availability of specimens and ethical considerations regarding the use of dead birds. Regurgitates, pellets, and feces are alternatives that can be collected easily and non-invasively and can also be used to identify and quantify the presence of MPs, following similar procedures [22,44–46]. Studies on gentoo and king penguins revealed 20% and 77% of fecal samples contained MPs, respectively [14,36]. However, this approach may underestimate the total amount of MPs ingested as it only accounts for excreted particles [10]. In contrast, some authors have suggested that regurgitates, pellets, and feces can be exposed to environmental contamination leading to overestimation [42]. Stomach flushing is a non-invasive technique

that can also be used to extract MPs from the gastrointestinal tract of birds but requires handling of the individuals [47]. Moreover, this method primarily retrieves the contents of the proventriculus and not the gizzard, where most plastics tend to accumulate. Thus, it may underestimate the total plastic ingested by the bird [48].

Whatever the sample is, chemical agents such as potassium hydroxide (KOH), hydrogen peroxide (H_2O_2), Fenton's reagent, acids, or a combination of these are needed to eliminate all organic matter while preserving the MPs' integrity [10,41,49]. After digestion, density separation techniques can be employed, often utilizing sodium chloride solutions to facilitate the separation of MPs from other materials based on buoyancy [10,46]. Finally, vacuum filtration through various mesh sizes allows the collection of MPs on a dried filter paper, where they can subsequently be identified and characterized [15] (Figure 5).

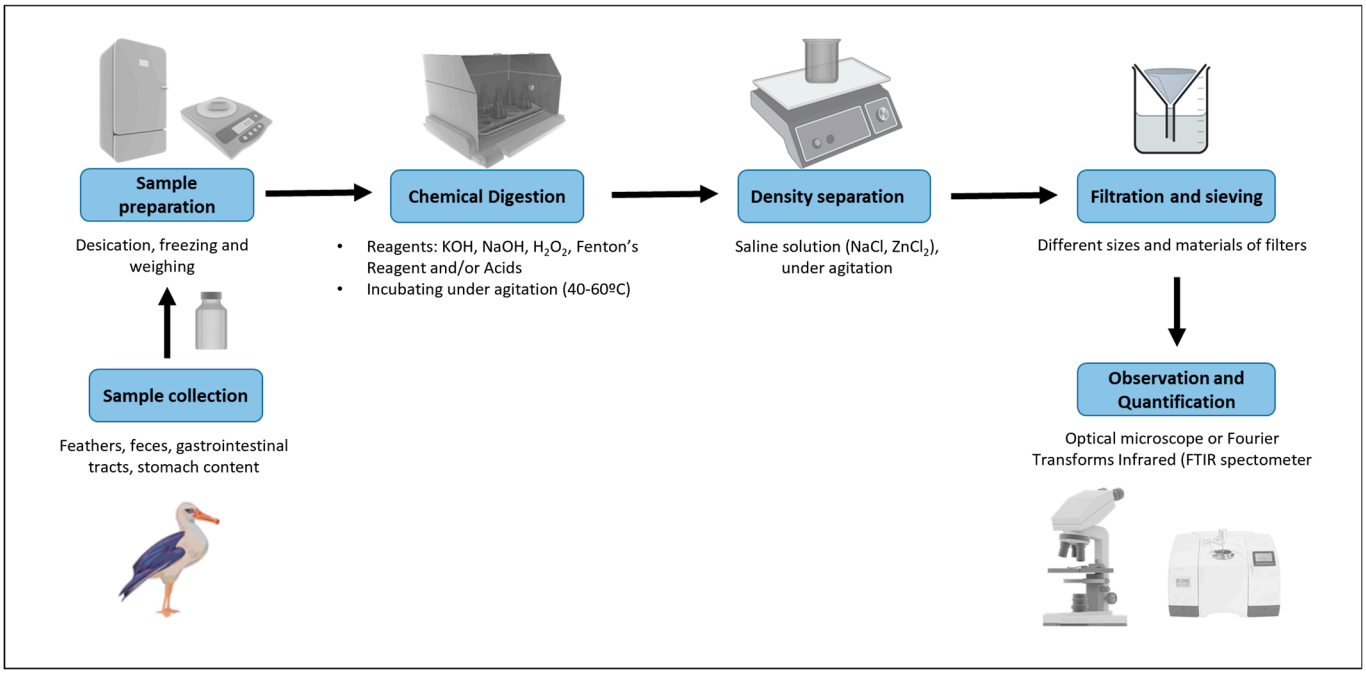


Figure 5. Simplified protocol for the detection of microplastics in biological samples.

The identification and quantification of MPs can be carried out under optic microscopy or SEM. Then, the polymer composition is determined via FTIR, which involves directing infrared light at the sample and measuring the absorbance to obtain a spectrum that can be compared with known polymers in the Bio-Rad and SLoPP/SLoPP-E libraries [10]. This technique allows discrimination between synthetic polymers and other anthropogenic fibers [36,37,50–56]. Particles can be now categorized based on their material composition. The use of a stereomicroscope to identify anthropogenic particles has also been demonstrated, with 95% accuracy [53]. However, it is important to note that the identified polymers may not fully represent the total composition of plastics in the bird but instead reflect the composition of the selected MPs samples [51]. The detection and quantification of MPs and NPs represent a further challenge in this field, as a significant number of these plastics have frequently been overlooked in the literature [57]. Flow cytometry has recently been employed as an innovative method to quantify these materials, with successful results. Its combination with FTIR allows the identification of polymers and provides efficient detection of the smallest plastic particles [57,58]. Raman spectroscopy is another technique used to detect MPs and NPs, particularly in cases where FTIR may not be suitable due to the small size of the particles [36]. This method provides information on the molecular vibrations of the particles, enabling detailed identification of polymer types [36].

Spectra can be compared with the same reference libraries as FTIR results to identify the composition [59]. In this context, particles have previously been categorized as follows: anthropogenic cellulosic (dyed cellulose fibers), cellulose (undyed cellulose fibers), synthetic dyed (spectra matching only with synthetic dyes), anthropogenic unknown (unsuccessful match but with an unnatural color, such as bright blue), and unknown (unsuccessful match with an unnatural color) [60].

Finally, one of the biggest challenges in MPs research is to avoid false positives. Because of the wide use of plastics in daily routines, contamination of samples during their collection or handling at the laboratory is plausible. Some studies have reported the contamination of samples thanks to the characterization of MPs and comparison with those derived from gloves and other materials [42]. The use of plastic instruments therefore poses a risk, and whenever possible, glass or metal should be used instead. Gloves, whether made of nitrile or other materials, are a crucial biosecurity measure for researchers, as biological samples may contain infectious agents. However, these gloves can release MPs that could contaminate samples during analysis. For this reason, it is essential to take extra precautions with handling. This emphasizes the need for meticulous handling of the samples and even extra precautions throughout the analysis. Also, quality control of the procedure is highly recommended, including blank controls to prevent overestimation, as well as good practice in the cleaning and disinfection of the laboratory, and the control of airflow to prevent contamination by airborne MPs. In this regard, the handling of samples in a controlled laminar airflow cabinet can improve the quality assurance of the technique [20].

3.3. Presence of Micro- and Nanoplastics in Birds

The presence of plastic in seabirds has been extensively documented and many studies have revealed their high susceptibility to ingesting plastics and debris [9,15,61–63]. These usually are long-lived apex predators with a lifespan ranging from 5 to 30 years, depending on the species; e.g., the northern fulmar (*Fulmarus glacialis*) can live for 30 years and its stomach contents have been used as a biological monitor of marine plastic pollution in the North Sea since the 1980s under OSPAR [15,61]. Other species like the common murre (*Uria aalge*) and black-legged kittiwake have also been studied [61,64]. Some seabirds such as northern fulmars are valuable indicators for studying plastic pollution in marine environments, due to their feeding behavior and limited regurgitation ability [61]. The exposure of seabirds to small plastics can occur through direct ingestion, secondary ingestion via prey, or the fragmentation of larger items during digestion [15]. In recent years, Magellanic penguins have been identified as carriers of high burdens of MPs (i.e., 82 particles per bird in Argentina), mostly fibers from sewage and fishing nets [65]. Abundant MPs have also been found in the gastrointestinal tracts of gentoo and chinstrap penguins (*Pygoscelis antarcticus*), with polyethylene (PE) and polypropylene (PP) being the most common types [41,52]. Interestingly, according to some authors, a latitudinal gradient in plastic pollution is evidenced in these species; the nearer to the poles, the lower the ingestion of plastics [8,15,66]. In consequence, the daily intake of MPs is also expected to vary depending on plastic pollution levels and latitude. In this context, few studies have provided approximate estimates of MPs intake across different species, due to the complexity of such investigations. For example, it has been estimated that the Galapagos penguin (*Spheniscus mendiculus*) may ingest between 2881 and 9602 MPs per day [67].

Seagulls from the genus *Larus* have recently been suggested as ideal sentinel species for MPs surveillance [68]. The presence of MPs in those species seems to be related to the presence of meso- and macroplastics (5–10 mm and >10 mm, respectively) in nests [7]. Blue microfibers of PP have been detected as the most common MPs in Dominican gulls

(*Larus dominicanus*), yellow-legged gulls (*Larus michahellis*), herring gulls (*Larus argentatus*), and black-backed gulls (*Larus marinus*) from different regions [24,69,70]. Among the most studied seabirds are the northern fulmars, which can spread up to 3.3 million MPs fibers and other anthropogenic particles into the environment during their breeding period [60]. For this reason, the northern fulmar is considered a sentinel species and is already included in monitoring programs as an ecosystem bioindicator. Research suggests that northern fulmars are not the primary source of MPs, but they contribute to the overall MPs load in the coastal ecosystem; so, they have been considered a good bioindicator of marine plastics in the North Sea region [53,71]. Seabird studies reveal widespread incidence of MPs ingestion, with species-specific variations (Supplementary Table S1). In Korea, MP ingestion rates ranged from 0.9% in ancient murrelets (*Synthliboramphus antiquus*) to 93.7% in Swinhoe's storm petrels (*Hydrobates monorhis*) [72]. Rates of ingestion in Mediterranean seabirds were 45% in storm petrels (*Hydrobates pelagicus*) and 70–94% in shearwaters (Procellariidae) [32,42,44]. In the Canary Islands, 88.89% of Cory's shearwaters (*Calonectris borealis*) had ingested MPs, primarily fishing-related PE and PP waste [73]. Among terns, adult common terns (*Sterna hirundo*) were found to carry larger fibers, whereas roseate tern nestlings (*Sterna dougallii*) had 2.8 times more microplastics (MPs) than common tern chicks [50]. These discrepancies may be influenced by species-specific ecological niches, habitat characteristics, and anthropogenic presence [5,74]. Furthermore, differences between adults and chicks could be linked to variations in prey selection by adults during chick-rearing periods. To remain close to the colony, adults may also forage in areas different from those they would typically use for self-feeding and may target distinct prey species. Such variations in foraging behavior probably contribute to the differential occurrence of plastic debris between adults and chicks. For example, northern fulmars, which have a larger foraging area, showed higher presence of MPs in comparison with black-legged kittiwake in the Canadian Arctic. The latter showed a higher load of persistent organic pollutants, demonstrating how feeding behavior influences exposure to contaminants and differences in pollution patterns [75]. The type of foraging and prey selection can also influence the presence of MPs and NPs [58,76]. For instance, significant differences were observed in the numbers of MPs found in the guano of two Australian shorebird species: eastern hooded plovers (*Thinornis cucullatus*) and Australian pied oystercatchers (*Haematopus longirostris*). MPs were detected in 100% of guano samples from surface-feeding eastern hooded plovers and 90% of guano samples from the Australian pied oystercatchers, a species that forages for coastal invertebrates at depths of 60–90 mm. On average, the eastern hooded plovers' guano contained 32 times more plastic than that of Australian pied oystercatchers. However, analysis of MPs in sediments collected from the birds' foraging sites showed no significant differences, indicating that the abundance of plastics in sediments did not directly correlate with ingestion rates. Instead, these discrepancies were probably attributable to species-specific factors such as prey selection [58]. Similarly, MPs were found to be more prevalent in species employing dual foraging strategies, such as the Cape Verde shearwater (*Calonectris edwardsii*) and coastal feeders like the brown booby (*Sula leucogaster*) and red-billed tropicbird (*Phaethon aethereus*), compared with pelagic foragers such as Bulwer's petrel (*Bulweria bulwerii*) and Boyd's shearwater (*Puffinus boydi*). This pattern further underscores the role of foraging behavior and habitat use in determining the ingestion of plastic debris by avian species [77].

Furthermore, another study conducted in shorebirds in the Yellow Sea revealed that birds that foraged through visual and tactical cues (like dunlins (*Calidris alpine*)) tended to ingest MPs with lower diversity of color that were smaller in size and had lower roughness index, compared with birds that foraged using visual cues alone (like red-necked stints (*Calidris ruficollis*), Kentish plovers (*Charadrius alexandrinus*), and lesser sand plovers

(*Charadrius mongolus*)) [76]. In general terms, avian predators such as seabirds have a greater abundance of MPs than insectivores or granivorous birds [78].

While the presence of MPs in seabirds has been well studied, the publications include no comparisons with freshwater species, even though Anseriformes species have great representation as poultry in some countries [79,80]. Plastic contamination in agricultural soils is linked to compost from livestock manure. Wu et al. [56] found 115 MPs in manure and 18 in feed from 19 farms, identifying swine and poultry manure application as key routes for MPs, risking soil health and crop productivity. Enclosed water bodies can acquire MPs from the atmosphere and stormwater runoff [81]. There is now strong evidence that MPs are widely present in freshwater systems and that their abundance varies greatly with proximity to urban centers, population density, and the quality of wastewater treatment [82]. Recently, a few studies have demonstrated that MP pollutants are also ingested by freshwater birds. In the study published by Reynolds and Ryan [82], 5% of fecal samples and 10% of feathers from seven duck species from southern Africa contained plastic microfibers. A study found pervasive MPs in ducks raised exclusively on riverbanks, confirming the river as the source. A total of 2033 MP particles were recovered, averaging 44.6 $\pm$ 15.8 MPs in crops and 57.05 $\pm$ 18.7 MPs in gizzards [10]. Previously, in Canada, 11.1% of species evaluated had ingested anthropogenic waste [79]. An initial assessment of MP contamination in regurgitated pellets of the common kingfisher (*Alcedo atthis*) conducted in rivers within highly urbanized regions revealed that 7.5% of the analyzed pellets contained MPs, most of them fibers. As apex predators, kingfishers are likely to ingest microplastics indirectly through their prey; however, they efficiently eliminate indigestible plastic particles via regurgitation [55]. Multiple polymers, including polyester (PS) and PP fibers, have been also found in Eurasian dippers (*Cinclus cinclus*), with higher concentrations in urbanized areas [83]. These findings highlight the transfer of plastics through freshwater food webs and the potential ecological risks of plastic pollution.

Only a few relevant studies in terrestrial birds have been carried out. It has been documented that plastic pollution in terrestrial ecosystems is higher than in the ocean [84]. Thus, the presence of plastic particles may be higher in terrestrial birds. Moreover, as we highlighted before, feeding strategies are key to the acquisition of MPs, and most terrestrial birds are granivores and frugivores. It is important to note at this point that some of the avian species feed their offspring by regurgitating directly from mouth to mouth (e.g., Apodiformes) or into the nest (e.g., Accipitriformes), representing an interesting route for transference of MPs from parents to nestlings [85]. This type of behavior is not exclusive to terrestrial birds and is also observed in seabirds, which implies the possibility of MPs transfer between adults and their chicks [86]. Inhalation of atmospheric particles is another pathway for acquisition of MPs that has also been confirmed in birds [22,87]. Interestingly, the presence of mesoplastics and macroplastics in raptors has been reported as significantly lower than in other bird species, but not the presence of MPs [51,68]. Scavengers seem to be associated with the carriage of MPs and NPs in the gastrointestinal tract [68,88]. Accordingly, the prevalence of MPs in the pellets and respiratory system of cinereous vulture (*Aegypius monachus*), common buzzard (*Buteo buteo*), black kite (*Milvus migrans*), and red kite (*Milvus milvus*) has been described as higher than in other raptor species [22,89]. In Andean condors (*Vultur gryphus*), 85–100% of the pellets analyzed carried MPs, with the highest prevalence in coastal populations. In these individuals, the majority of the MPs were blue fibers [90]. A statistical association between the presence of MPs in barn owls (*Tyto alba*) and the anthropized level of the landscape has been described; higher anthropization is associated with higher burden of MPs, which has also been described in other raptor species [89,91]. Proximity to a local road, a garbage dump, a human settlement,

or a forest, as well as the land use in the region, was found to be associated with the burden of MPs in wild animals [92]. Due to their unique biology and feeding behavior, common swifts (*Apus apus*) and common house martins (*Delichon urbicum*) are highly exposed to suspended atmospheric MPs. Accordingly, studies carried out on those species found MPs in up to 75% of the birds examined [22,85]. While Costanzo et al. [85] only assessed fecal samples, Wayman et al. [22] included all of the gastrointestinal tract and the respiratory system, finding higher concentrations of MPs in the former. MPs were found in tree swallow (*Tachycineta bicolor*) nestlings and in adult migratory birds, primarily as microfibers, and also as fragments and beads [54]. Regarding the morphology of the MPs, most of the studies consider only two shapes (fibers or fragments), while some authors have been more accurate and described other shapes such as beads, microbeads, pellets, foams, etc. Again, the lack of standardization in the classification of the MPs makes it difficult to compare studies and regions. Overall, fibers seem to be the most common shape described in marine, terrestrial, and freshwater birds [2,20,22,37,44,54,85,88]. In this context, Zhao et al. [93] reported that 87.7% of the MPs obtained from Shanghai birds were plastic fibers. These results correspond with the production of plastic fibers worldwide, which is significantly high [93]. Moreover, fibers are lighter than fragments, so they are more prone to aerial transport and dissemination [20]. MP fibers are usually related to the textile, automobile, or construction industry [22]. A recent review reported that microfibers often represent over 80–90% of ingested items in Mediterranean biota and other taxa worldwide. However, many of these fibers have for years been misclassified as MPs, despite evidence that most are natural fibers or cellulosic materials (e.g., cotton or rayon) rather than synthetic polymers [94].

Moving on to the characteristics of MPs, their color is related to their macroplastic origin and industrial history. Although the identification of colors under the microscope can be challenging in some cases, blue and black are the most common colors found in marine birds, while transparent and white stand out for terrestrial birds [20,22,37,46] (Figure 6). However, in Northern Fulmars, white fragments have been also confirmed as the main plastics in Svalbard, Norway [71,95]. It is important to highlight that some studies suggest color and structural modifications may occur when MPs are ingested, due to the digestive function and environment [96].

Regarding the composition, Athira et al. [74] and Hoang and Mittle [54] found polystyrene (PS) particles to be the most frequent in shorebirds, followed by PE, PP, polyvinyl chloride (PVC), and nitrile, in decreasing order. However, the highest global production is that of PE, as it is used in the manufacture of cosmetics and fishing nests [36,97]. In a study performed on Adélie penguins (*Pygoscelis adeliae*), the main polymer found was PE, frequently found in plastic bags, bottles, and other residues that constitute the famous plastic islands in oceans [20,98]. Another study performed in the northern fulmar also found that PE was the most prevalent polymer present [71]. The biodegradation of these plastics in the ocean by fungi from Antarctica and other microorganisms aligns with those results [20]. In contrast, the main plastic particles found in common swift and common house martin were polyester, matching the MPs found in raptors' pellets [22,99]. Notably, the prevalence of different particles depends on the region sampled and the associated industry. In fact, other authors reported that polyester and nylon were the most frequent polymers identified in their studies [2,44] (Figure 7).

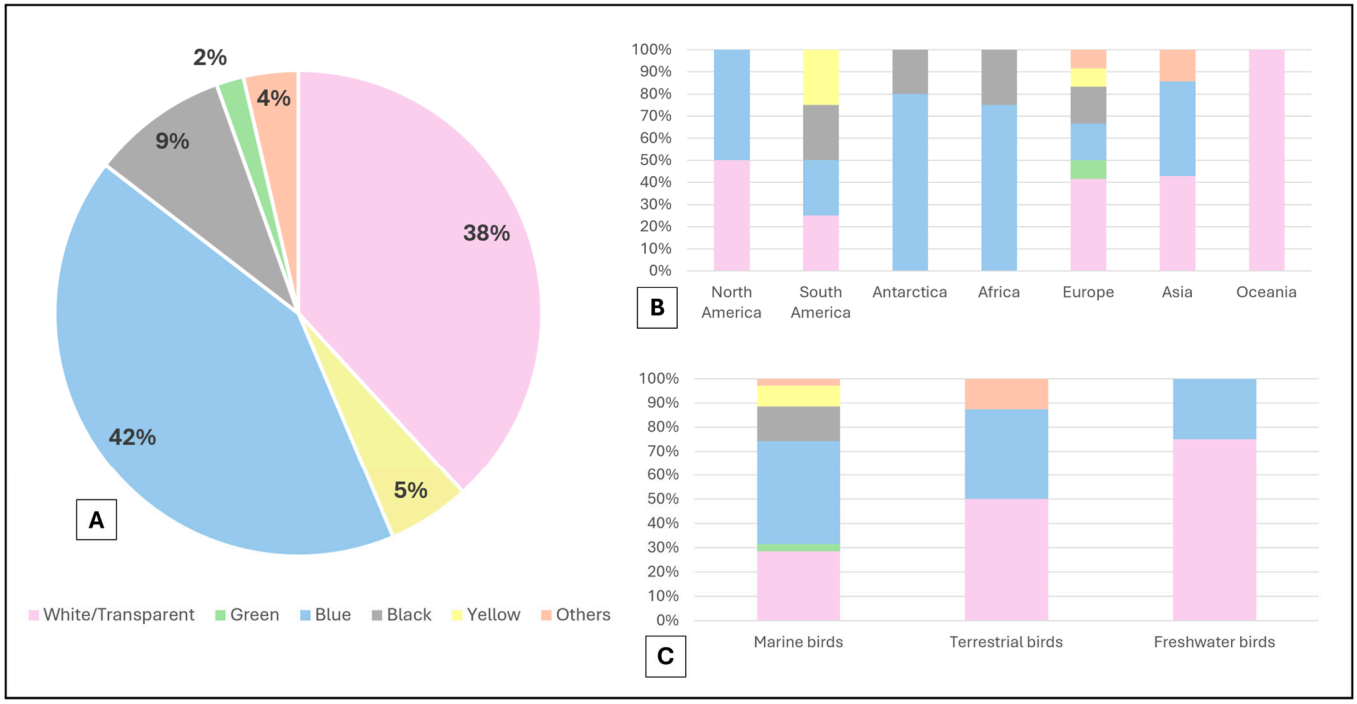


Figure 6. (**A**) Proportion of the most common colors described for the MPs detected in avian species of the reviewed studies. Note that only 44 studies reported the colors. (**B**) Proportion of colors according to continent. The number of studies describing the MPs' color was 12 for North America, 4 for South America, 5 for Antarctica, 4 for Africa, 11 for Europe, 6 for Asia, and 1 for Oceania. (**C**) Proportion of colors according to the species' habitat. The number of studies describing the MPs' color was 35 for marine birds, 8 for terrestrial birds, and 4 for freshwater birds.

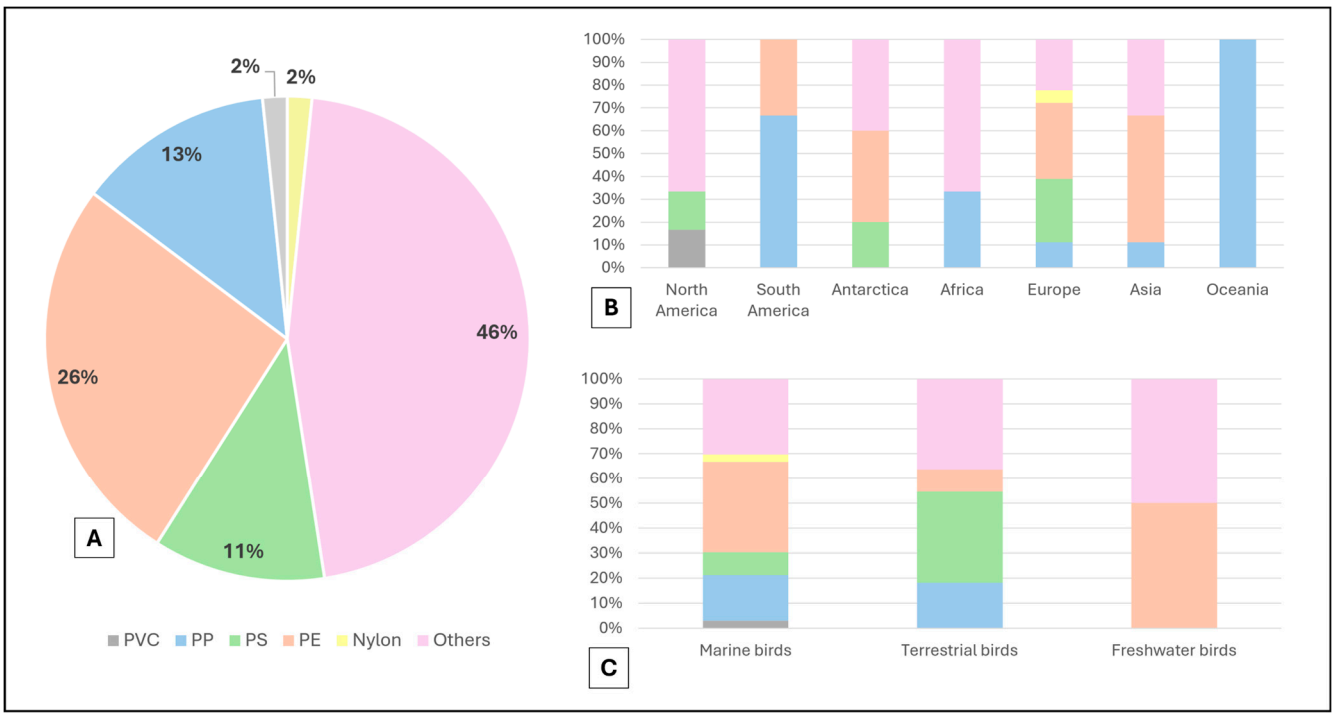


Figure 7. Distribution of polymer MPs described in the literature. The most prevalent were polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and polyethylene (PE). However,

other polymers were reported in lower proportions (nylon, polyamide, ethylene vinyl acetate, acrylonitrile, butadiene rubber, polyurethane, polyethylene terephtalate, and acrylonitrile butadiene styrene, among others). (**A**) Most common proportional composition described for the MPs detected in avian species in the reviewed studies. Note that only 45 studies reported polymer composition. (**B**) Most frequent polymers according to continent. The number of studies describing MPs' composition was 6 for North America, 3 for South America, 5 for Antarctica, 3 for Africa, 17 for Europe, 9 for Asia, and 2 for Oceania. (**C**) Most frequent polymers according to species' habitat. The number of studies describing MPs' color was 33 for marine birds, 11 for terrestrial birds, and 4 for freshwater birds. PVC: polyvinyl chloride; PP: polypropylene; PS: polystyrene; PE: polyethylene.

Regarding possible associations or risk factors relating to MPs acquisition in birds, the age, the season, and the sex were disregarded in studies of some species, including common blackbirds (*Turdus merula*), song thrushes (*Turdus philomelos*), and northern fulmar [71,88]. Nevertheless, the association between animal bodyweight and the load of MPs in the carcasses of terrestrial birds has been confirmed [93].

3.4. Health Consequences of Micro- and Nanoplastics in Birds

Assessing the health consequences of MPs exposure in birds is relatively complex, as it requires detailed studies on the kinetics of these MPs within the organism, their ability to cross biological barriers and reach other organs, and their potential structural and functional effects. Moreover, to obtain consistent conclusions, such studies require a specific number of individuals kept under highly controlled conditions, divided into a control group and an exposed group. However, in practice, this is extremely challenging with wild species, particularly those that are threatened. As a result, there have been very few studies providing data on the organ-level effects of MPs in wild birds. Nonetheless, several experimental studies on poultry have been conducted, from which the potential consequences for wild birds can be estimated.

As a result of their ingestion, MPs and NPs may accumulate in the organism and lead to several adverse effects such as physical harm or chemical toxicity. Their shape and size influence their retention in the different organs, with smaller particles passing through while larger fragments accumulate [10,100]. Recent studies indicate that ingested plastic can lead to gut inflammation and smaller particles may penetrate the digestive tract barrier, entering the bloodstream or other organs and disrupting their function [5,14]. A study performed in flesh-footed shearwaters (*Ardenna carneipes*) analyzed the effects of MPs in the kidney, spleen, and proventriculus tissues of exposed individuals. The presence of MPs led to tissue damage characterized by inflammation, fibrosis, and loss of structure [101]. The presence of MPs was linked to macroplastics in the proventriculus, suggesting the fragmentation of these into MPs in the digestive tract [101]. Contrary to these results, Keys et al. [57] suggested that smaller particles were probably also the result of bioaccumulation.

While numerous studies have demonstrated the harmful effects of MPs on tissue health, recent research on flesh-footed shearwaters found no conclusive evidence directly linking MPs to chronic damage in organs such as the liver, kidney, or stomach. Observed pathologies were instead associated with nutritional deficiencies and starvation, suggesting that multiple concurrent stressors may play a larger role [102]. These findings, while not dismissing the impact of MPs, highlight the need for cautious interpretation of statistical data and the importance of considering ecological context and multifactorial interactions to fully understand the effects of MPs on wildlife health.

3.4.1. Physical and Physiological Impact

To date, MPs have been associated with a wide range of physical, physiological, and hormonal issues [10,33,103]. At a cell level, MPs have been confirmed to induce apoptosis or ferroptosis in many organs in mammals, including digestive, respiratory, renal,

reproductive, and nervous systems [82]. However, the scientific literature focused on birds is scarce. The main target of studies involving birds has been the digestive system, followed by the respiratory system.

Overall, as a physical alteration, MPs can cause internal injuries or in some cases, the animal's death [10]. More frequently, micro-injuries at the lamina propria, microvilli damage, and mechanical obstructions of the gastrointestinal tract due to MPs presence have been documented, leading to reduced feeding efficiency and nutrient absorption and consequent malnutrition [15,33,104]. A recent study by Bilal et al. [10] found that ducks from the Panjkora River had an average of 44.6 MP particles in their crops and 57.05 MP particles in their gizzards, with a mean size of 150–500 µm. Larger particles are more likely to remain in the gastrointestinal tract, causing damage [10]. In the cecum of Japanese quails, the histological changes in the lamina propria and the muscularis externa due to MPs were dose-dependent; the higher the dose of MPs, the higher the damage. So, the integrity of the physical and chemical barriers of the cecum is susceptible to the presence of MPs [104]. In addition, inhibition of gastric, hepatic, and pancreatic enzymatic activity, decreased gland function, cytotoxicity, and lipid oxidative damage have been reported [10,80,103,104]. MPs exposure in quails reduced body biomass and induced oxidative stress, with increased reactive oxygen species (ROS) and lipid peroxidation in several organs. Analysis of biomarkers revealed distinct profiles, with lipid peroxidation being the most sensitive indicator of toxicity [45].

The impact of MPs on gut health and metabolic function has been experimentally investigated. After 28 days of exposition to PE-MPs, chickens exhibited lower daily weight gain, lower bodyweight, and reduced antioxidant capacity. In contrast, Japanese quail exposed to PP and PE-MP showed no significant differences in body mass or nutritional status, but they suffered a slightly decreased growth rate [105]. Metabolomic analysis revealed changes in key metabolites that could harm gut function, nutrient absorption, and antioxidant response [106]. MPs can also alter lipid metabolism and composition in female Japanese quails, as their ingestion affects the composition of fatty acids in the liver and causes a decrement in monounsaturated fatty acids [107]. Specifically, PS-MPs can inhibit energy and lipid metabolism in chickens [108].

The balance of the microbiota composition in the presence of MPs has been also assessed [104,106,109]. While beneficial bacteria such as *Lactococcus*, *Bifidobacterium*, or *Butyricicoccus* decrease, pathogens such as *Enterococcus* and *Turicibacter* increase [106]. Exposure to PS-MPs significantly altered the gut microbiota in Muscovy ducks (*Cairina moschata*) increasing the abundance of pathogenic bacteria such as *Streptococcus* and *Helicobacter*, which are linked to intestinal damage. This dysbiosis can impair nutrient absorption and immune function [110]. In that study, the combination of PS-MPs and chlortetracycline increased the abundance of beneficial bacteria like *Prevotella* and *Faecalibacterium*. Additionally, it significantly raised the levels of antibiotic resistance genes, particularly those related to tetracycline resistance. The exposition of chickens to PE-MPs resulted in a negative impact on cecal microbiota: the Firmicutes–Bacteroides ratio decreased, which is associated with poor digestive health in chickens [104,109]. Moreover, chronic ingestion of MPs significantly alters the gut microbiome: commensal microbiota decrease while zoonotic pathogens, antimicrobial-resistant microbes, and plastic-degrading microbes increase [111]. These alterations in the digestive and hepatic systems have been observed through transcriptomic and metabolomic studies in chickens exposed to PS-MPs [112].

Regarding the cardiorespiratory system, the lungs are the organs with the next highest accumulation of MPs, after the digestive system [20]. Obstruction has been also associated with the deposition of MPs in the parabronchi [20,113]. Lung toxicity has been attributed to an increase in oxidative stress, autophagy, and apoptosis of the lung cells; these mechanisms

contributed to a dose-dependent deterioration of lung structure and function [114]. Also, it has been demonstrated that PS-MPs exposure can result in lung stress and myocardial dysplasia, with dose-dependent pyroptosis and inflammation of both tissues, activation of the stress-regulated autophagic pathway, and accumulation of reactive oxygen species (ROS) [115–117].

PS has been described as causing structural harm to the reproductive tract, specifically the testis, and histopathological changes such as inflammation have been observed, as well as an induced imbalance of the redox system [118]. In ducks, PVC-MPs reduce the number of viable follicles via ferroptosis, a distinctive type of non-apoptotic cell death due to mitochondria alteration and iron overload in the cell. The associated histological changes and the proteomics of the ovarian tissue were described as concentration-dependent [81]. In addition, a recent study described the effects of PS and PE on chicken ovalbumin protein structure [119]. Regarding the effect on bird embryo development, exposure to MPs or NPs can lead to a decrease in wet weight and body length, and to an increase in hepatosomatic index indicating enhanced liver development [120]. These results suggest that MPs and NPs can impact critical aspects of avian embryonic growth and could thus have negative implications for conservation of biodiversity.

Moreover, PS-MPs can alter the renal structure, producing hemorrhage, inflammation, or rupture of renal tubular epithelial cells, with mitochondrial dysfunction at the cellular level [105,121]. The severity of these lesions has been described as dose-dependent [121].

The immune system is also a target for MPs. Exposure to these particles causes micro- and ultrastructural damage in the spleen, leading to oxidative stress, apoptosis stimulation, and splenic inflammation [122,123]. Similar results were obtained in the thymus, where MPs induced oxidative stress triggering an inflammatory response accompanied by apoptosis and autophagy [106]. Consequently, MPs have been described as disruptors of the immune response in species including ducks and quails [104]. Specifically, in Japanese quails after exposure to PS-MPs, the cecal tonsils showed inflammation, congestion, and cell vacuolation even in germinal centers [104]. These are considered mucous-associated lymphoid tissues or MALTs and have a key function in the immunity response within the digestive mucous [124]. Cellular vacuolation and damage to the germinal centers can alter the natural immune response and the production of antibodies and cytokines [104].

3.4.2. Chemical Toxicity

Plastics are associated with relatively high concentrations of other potentially toxic elements (i.e., bromine, cadmium, plumb, or antimony) and/or brominated compounds that are non-compliant or potentially non-compliant with current regulations on hazardous plastic waste [125,126]. Brominated compounds are additives incorporated during manufacturing, such as brominated flame retardants (BFRs) or polybrominated diphenyl ether compounds (PBDEs). The latter have been described as endocrine disruptors, specifically of thyroid function, which is essential to growth, and reproductive hormones [127–129]. Specifically, a positive correlation was reported between the burden of MPs and PBDE209 in northern fulmar fledglings, suggesting the potential role of PBDEs as an indicator for plastic ingestion [130]. Moreover, a higher concentration of these compounds was found in nestlings, probably altering their development [130]. Their feeding through parental regurgitation seems to be the main transmission pathway of MPs and brominated compounds. Matos et al. [128] monitored the amounts of plastics in feces and organobromine compounds ingested or assimilated in feathers by adults and chicks of Cape Verde shearwater and Bulwer's petrel. They found a positive correlation between the quantity of MPs detected in fecal samples from Cape Verde shearwaters and the global burden of brominated analogs. In addition, they indicated that the observed differences in organochlorine

contamination among seabird species were probably due to their different feeding and foraging strategies [128]. A significant positive correlation between the presence of MPs and PBDEs was confirmed in adult brown boobies, suggesting that MPs may be a key route for PBDEs [128]. In contrast, Navarro et al. [73] found no direct correlation between the burden of MPs and PBDEs or polychlorinated biphenyls (PCBs) and also suggested that diet may be the primary source of exposure. Previous studies have described the presence of other chemicals related to plastics, such as dechloranes or phthalates, in birds. Among dechloranes can be found some isomers of organochlorides, pesticides widely used in the past with a great impact on ecosystems due to their toxicity and persistence [131]. Meanwhile, phthalates are plastic additives associated with severe health effects in fish, amphibians, and humans [130]. Both dechloranes and phthalates are known because of their bioaccumulative and biomagnification effect within the trophic web [132]. However, the study of these chemicals related to plastics in birds remains insufficient.

Many studies describe MPs as vectors for harmful chemicals such as persistent organic pollutants (POPs) or heavy metals that can be absorbed onto the surface of plastic particles in the environment [125,126]. Although some authors described no significant correlation between levels of heavy metals and the MPs ingested, MPs have been described as enhancers for the absorption of metals into the tissues of birds, potentially leading to hormonal disruptions, immune system impairments, and reproductive issues [33,75,133]. In this context, exposition of ducks to PVC MPs and cadmium contributed to a decrease in pancreas weight and functional disruption worse than observed with exposition to only cadmium. Specific signs observed in the pancreas were inflammation and fibrosis, with alteration of mitochondrial structure and function and inhibition of antioxidant enzyme activity [133]. Among the main heavy metals related to MPs, zinc, copper, cobalt, chromium, lead, cadmium, and manganese stand out [33,74]. Holmes et al. [33] demonstrated that these metals adsorbed by MPs can become bioaccessible under avian gastric conditions. Even in low concentrations, these metals can lead to systemic diseases and affect reproductive success, neuronal development, or even the survival of the bird [74]. The combination of PVC particles with cadmium resulted in a morphological and functional alteration of hepatocytes in ducks via oxidative stress, potentially resulting in lipid and glycogen accumulation and fibrosis [80]. Thus, the adsorption of these metals onto MPs' surfaces poses a double threat for affected individuals, combining physical harm from the plastic itself with toxicity, and presenting serious consequences for populations [10,74]. Moreover, these pollutants or metals can accumulate and persist in organisms, entering the food web [15,36].

3.4.3. Trophic Transfer and Bioaccumulation

Trophic transfer is the spread of an agent through the food web from lower trophic levels, such as zooplankton, to higher-level predators, such as raptors. In this sense, trophic transfer of MPs is a significant concern in birds [2,89,99]. While some studies have discarded this pathway of MPs acquisition, trophic transfer has been extensively documented [2,89,99]. For instance, studies on European shags (*Gulosus aristotelis*) suggest that MPs may be transferred through benthic fish species consumed as part of their diet [2]. Similarly, studies on seabirds including northern fulmars, revealed significant ingestion of MPs, which is likely to have originated from lower trophic-level prey [33]. In common terns, MPs were found in 100% of gastrointestinal tracts (GITs) and 53% of regurgitations, highlighting the potential to move from prey to predators [49]. These differences in abundance of MPs between birds and their prey further corroborate the occurrence of trophic transfer. Recent findings revealed that 68% of pellets from six different species of birds of prey (three Accipitriformes, two Strigifomes, and one Falconiformes) harbored MPs,

and 81% contained other anthropogenic fibers [99]. Early evidence of trophic MP transfer in riverine ecosystems was provided by D'Souza et al. [83], who documented MPs in the feces and regurgitates of dippers (*Cinclus mexicanus*). This underscores the connections within food webs, linking consumers to apex predators and parents to offspring through prey provisioning. Such contamination may pose conservation risks, as seen in penguins, where MPs and associated pollutants potentially threaten the broader polar food web [15,36].

However, a study conducted at an e-waste recycling center in China reported habitats rather than trophic levels or diet to be the main determinants of MPs exposure in wildlife. The study revealed the presence of rare polymers including silicone and acrylates, resulting from the decomposition of electronic waste. Notably, birds at the upper levels of the food chain did not display significantly higher levels of MP retention compared with other animals in the food chain. This suggests that MPs are rapidly eliminated from the digestive tract in these birds, thereby reducing the potential for bioaccumulation and biomagnification [134]. It is important to remember that bioaccumulation occurs within an organism, while trophic transfer moves substances between trophic levels. These findings highlight the importance of addressing plastic pollution from an ecosystems perspective.

At this point, it is important to mention that the presence of MPs has even been demonstrated in chickens for human consumption, which could pose a potential risk to global health [3]. A study performed on laying hens found that PS-MPs were poorly absorbed and rapidly excreted within the first 24 h; fewer than 1% of the MPs were detected in blood and tissues, and only small amounts were found in eggs. However, this low absorption in tissues may be attributed to single-dose administration, leaving it unknown how absorption might differ with continuous exposure to MPs in terrestrial birds [135].

3.4.4. Interference in Natural Behavior

The presence of MPs in the diet has been linked to altered foraging behavior, as birds may mistake plastic particles for food [10]. This misidentification can lead to a false sense of satiety, potentially impacting reproductive success and overall population dynamics [15]. Moreover, some studies have suggested that birds may be attracted by colored plastics, leading to increased ingestion of MPs [136]. However, recent studies suggest that this attraction is due to the color coincidence between plastics and prey [137,138].

Trophic interactions in marine environments are partially mediated by infochemicals like dimethyl sulfide (DMS) and its precursor, dimethylsulfoniopropionate (DMSP) [139]. These molecules act as infochemicals across various trophic levels, from microfauna to macrofauna, influencing foraging cascades [139,140]. In pelagic ecosystems, DMS is produced by the enzymatic breakdown of DMSP in marine phytoplankton, which triggers foraging activity in tube-nosed seabirds (Procellariiformes) such as albatrosses, petrels, and shearwaters [141]. These seabirds are known for their strong sense of smell and wide-ranging foraging behavior, and they use DMS as a cue to locate prey. DMS is increasingly being recognized as a "keystone" infochemical in marine trophic dynamics [139]. Floating plastic debris, which is highly susceptible to biofouling [142], may serve as a substrate for biota that produce infochemicals like DMS or DMSP. If such biota colonize plastic debris, the debris could develop a chemical profile that attracts DMS-responsive species, potentially leading them to ingest it [139].

Furthermore, the long-term ecological implications of MP ingestion in birds remain largely understudied, requiring further research in order to understand the broader impacts on avian biodiversity and ecosystem health.

4. Study Limitations and Opportunities for Improvement

Systematic reviews of microplastics in birds offer valuable insights but can be improved by expanding search strategies to include more databases and gray literature. Addressing publication bias, heterogeneity in study designs, and challenges in data synthesis will enhance clarity and comparability. Broader searches, standardized methods, and regular updates can significantly boost the reliability and impact of future research. Unfortunately, the available scientific information on MPs in birds is still limited in several respects, particularly regarding the health consequences of exposure. It is important to consider that the class Aves comprises a vast number of species with significant anatomical and metabolic differences. Therefore, extrapolating data on the effects of MPs from poultry to wild species should always be done with caution. In the same line, studies about the presence and effects of NPs in wild birds are currently scarce, so further studies are urgently needed to better understand these issues.

5. Conclusions

Microplastics pose a significant and growing threat to bird populations worldwide, with critical implications for their health and the ecosystems they inhabit. Our review highlights the widespread ingestion of MPs by birds, underscoring the pervasive nature of this pollutant. Advances in methodologies for detecting MPs in avian species have facilitated a deeper understanding of the extent of this issue and its potential consequences. However, significant gaps in the knowledge persist, particularly regarding the long-term effects of ingesting MPs on avian physiology, behavior, and population dynamics.

To address these gaps, future research must prioritize the standardization of MP and NP detection protocols, enabling more consistent and comparable results across studies. Additionally, long-term investigations are needed to evaluate how MPs and NPs impact bird health, reproduction, and survival rates over time.

Given the role of birds as bioindicators of ecosystem health, understanding the impacts of MPs and NPs pollution on these species is vital for informing broader conservation and management strategies. Conservation efforts should focus on reducing plastics pollution at its source, mitigating its impacts on wildlife, and preserving avian biodiversity. By bridging current knowledge gaps and implementing targeted conservation strategies in the face of this growing environmental challenge, we can better safeguard bird populations and the ecosystems they support.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/birds6010010/s1: Table S1: Prevalence of MPs reported in previous studies according to bird species and sample types.

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