ISSN-1996-918X

Cross Mark

Pak. J. Anal. Environ. Chem. Vol. 26, No. 2 (2025) 160 – 182

http://doi.org/10.21743/pjaec/2025.12.01

A Critical Review of Microplastic Effects on Wildlife and Biodiversity with Notes on Current Analytical Detection Techniques

Nur Hidayah Amran[1], Thevarajan Narrshen[1], Nur Hartini Sariyati[1], Nursyuhada Othman[1], Hidayah Haris[1], Nurfatiha Akmal Fawwazah Abdullah-Fauzi[1], Farah Farhana Ramli[1], Kayal Vizi Karuppannan[2], Mohd Akmal Mahazar[3], Raja Zubaidah Raja Sabaradin[3], Mohd Sanusi Mohamed[4], Siti Khadijah Abdul Gani[5], Mohd Hairul Khamidun[6], Mohd Shahir Shamsir Omar[7], Dwi Sendi Priyono[8] and Muhammad Abu Bakar Abdul-Latiff[1]*

[1]Environmental Management and Conservation Research Unit (eNCORe), Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia (Pagoh Campus), 84600, Muar, Johor, Malaysia.

[2]National Wildlife Forensic Laboratory (NWFL), Department of Wildlife and National Parks (PERHILITAN), Kuala Lumpur, Malaysia.

[3]ALS Technichem (M) Sdn Bhd, 21, Jalan Astaka U8/84, Bukit Jelutong, 40150 Shah Alam, Selangor, Malaysia.

[4]Copenhagen Zoo, Roskildevej 32, 2000 Frederiksberg, Denmark.

[5]Department of Mineral and Geoscience, Ministry of Natural Resources and Sustainability (NRES), Putrajaya, Malaysia.

[6]Micropollutant Research Centre (MPRC), Institute for Integrated Engineering (I2E), Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, Johor, 86400, Malaysia.

[7] Faculty of Science, Universiti Teknologi Malaysia, Skudai, Johor, 81310, Malaysia.

[8]Universitas Gadjah Mada, Faculty of Biology, Department of Tropical Biology, Jl. Teknika Selatan, Yogyakarta, 55281, Indonesia.

*Corresponding author Email:latiff@uthm.edu.my

Received 03 February 2025, Revised 02 October 2025, Accepted 14 October 2025
Academic Editor: Sarafraz Ahmed Mahesar

Abstract

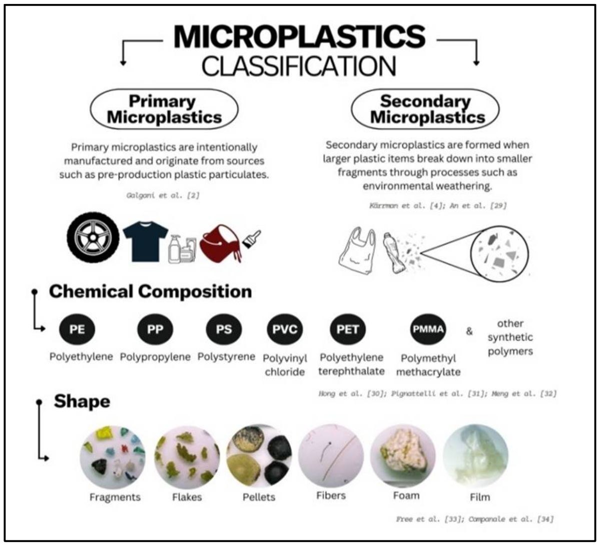
Microplastics are plastic particles of various shapes that are typically less than 5 mm in size. Microplastics have emerged as a significant environmental and health concern due to their persistence, bioavailability, and potential toxicity. These particles contain chemical compounds that may cause adverse effects on both the environment and living organisms. Extensive research has been conducted on the impact of microplastics. However, studies have largely focused on invertebrates and marine species, leaving significant gaps in understanding their effects on other wildlife groups. Hence, this review aims to comprehensively assess the general effects of microplastic pollution on wildlife and biodiversity, as well as the detection techniques used. Under a thorough systematic review of the SCOPUS database, the impacts of microplastic exposure on wildlife can be categorized into physiological, behavioral, toxicological, ecological, emerging areas, and effects on population growth. The findings reveal that 32% of reviewed studies focus on ecological impacts, primarily centered on invertebrates rather than fish, plants, mammals, birds, amphibians, and reptiles. In addition, this review identifies key trends and critical knowledge gaps across all animal groups. As standardized methods for identifying microplastics have yet to be established, emerging detection techniques such as spectroscopic methods like Fourier-Transform Infrared Spectroscopy (FTIR) and Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) are still evolving. Further research is needed to fully understand the impact of microplastics on wildlife, which could influence long-term conservation management.

Keywords: Microplastic, Polymer, Ecotoxicology, Biodiversity, Bioaccumulation.

Introduction

Plastics have become indispensable in modern life, revolutionizing industries ranging from packaging, construction to healthcare and technology. Plastics are widely utilized due to their remarkable properties, including lightweight nature, high plasticity and flexibility, thermal and electrical insulation, corrosion resistance, and affordability [1]. Despite their durability, plastics can break down into smaller particles through various processes such as biological, mechanical, and ultraviolet (UV) degradation [2]. The term "microplastics", introduced in 2004, refers to tiny plastic particles, but no clear definition fully describes their diverse characteristics [3]. However, current research generally defines microplastics as plastic particles ranging in size from smaller than 5 mm to larger than 100 nm [1,4-6]. Microplastic pollution has become a global environmental concern with smaller and fiber-shaped microplastics typically presenting higher toxicity risks to organisms [7].

Microplastics can be categorized based on their origin, shape and chemical composition as summarized in Fig. 1. In terms of origin, they are classified into primary and secondary microplastics; where primary microplastics include plastic pellets, microbeads in personal care products, paint residues, wastewater from washing synthetic textiles, sewage sludge, artificial turf, rubberized roads and tire wear particles [8-10]. Secondary microplastics, on the other hand, are produced through the breakdown of mismanaged plastic waste on land or at sea, leakage during transportation of goods, weathering of plastic materials, and the wear of fishing gear or farming films. Other contributors include municipal debris such as plastic bags and bottles, farming films, and wastewater effluents [4,11]. Microplastics exist in various shapes as illustrated in Fig. 1 where; 1) pellets refer to pre-production resin particles used in manufacturing; 2) fragments are irregularly shaped pieces formed by the physical breakdown of larger plastics; 3) films are thin, flexible pieces typically originating from degraded plastic bags or wraps; 4) fibers are thread-like particles shed from synthetic clothing or ropes; 5) foams such as polystyrene are porous materials often used in packaging or insulation; and 6) beads are spherical particles, including microbeads and nurdles [12,13]. This multifaceted classification can provide a comprehensive understanding of microplastic diversity and its environmental implications.



Primary microplastics are intentionally manufactured and originate from sources such as pre-production plastic particulates.

Galgani et al. [2]

Secondary microplastics are formed when larger plastic items break down into smaller fragments through processes such as environmental weathering.

Kärrman et al. [4]; An et al. [29]

Hong et al. [30]; Pignattelli et al. [31]; Meng et al. [32]

Free et al. [33]; Campanale et al. [34]

Figure 1. **The characterization of microplastics based on origin, shape, and chemical composition**

The sources of microplastic pollution can be divided into land-based and ocean-based origins [14]. Land-based microplastics are commonly contributed from plastic bottles, plastic bags, personal care products, and household items, while the ocean-based microplastics primarily originate from fishing gear, marine vessels, and plastic litter. Annually, over 600,000 tons of fishing gear, such as plastic monofilament lines and nylon nets, are discarded into the ocean, contributing to microplastics floating at various depths in the ocean [14]. Additionally, the release of toxic microplastic particles, such as synthetic fibers is commonly found in industrial areas and domestic textile laundry [15]. Previous studies have indicated that microplastic pollution is more prevalent in industrial areas than in residential zones, as industrial waste discharge is a major source of microplastic contamination in aquatic ecosystems, including oceans, rivers, and lakes [16]. One of the most concerning yet often overlooked sources of microplastic pollution is microbeads found in cosmetics and personal care products. These particles are continuously released into the environment through activities such as washing, showering, or bathing, posing potential threats to the aquatic ecosystem and human health [17]. As early as 1991, studies identified that cosmetics and personal care products such as skin scrubs contained toxic chemicals like polystyrene (PS), which can create environmental issues due to their persistence in the environment and contribute to long-term pollution [18].

Over the past few decades, plastics have emerged as a global environmental crisis alongside climate change, ocean acidification, and biodiversity loss [19]. The production of plastics often involves the use of toxic chemical additives that can cause irreversible morphological damage in organisms, particularly when exposure occurs during developmental stages [20]. According to Guerranti et al. [21], microplastics pose even greater risks than macroplastics due to their ability to infiltrate organisms and induce further toxicity. These harmful effects arise from both their chemical composition and physical properties. The abundance and distribution of microplastics are primarily influenced by environmental and anthropogenic factors, with environmental forces often playing a more significant role [22]. Key environmental factors include wave currents, tidal movements, cyclones, wind directions [23], and river hydrodynamics [24], all of which affect the dispersal and accumulation of microplastics. As a result, several countries, including the United States, European countries, and New Zealand, have implemented bans on microplastics while others, such as Ireland, Italy, India, Taiwan, and South Korea, are in the process of drafting legislation. The global scale of microplastic pollution has also prompted discussions on its inclusion in international policy frameworks. Besides, the international microplastics standard ISO 24187 has been introduced to provide guidelines to enhance the harmonization of microplastics analysis.

The exposure of animals to microplastics is a growing concern, affecting terrestrial, aquatic, and aerial ecosystems. In aquatic ecosystems, microplastics have been shown to absorb and release harmful chemicals, posing risks to aquatic life [25]. On land, microplastics have been detected in the guts and feces of various wildlife species, including birds, small mammals, and insects, highlighting their ingestion and potential trophic transfer. Airborne microplastics have also been documented, though their impact on terrestrial wildlife remains poorly understood [26,27]. However, the consequences of microplastic pollution on biodiversity, particularly terrestrial wildlife are often underexplored compared to its effects on human health and environmental systems. Therefore, the primary aim of this study is to review the potential impacts of microplastics on biodiversity focusing on wildlife. Due to advancements in technology, various techniques for microplastic analysis have been developed and can be categorized into three main types: (1) physical characterization technologies (e.g., size, color, and shape), (2) chemical composition identification technologies (e.g., polyethylene, polystyrene, and polypropylene) and (3) quantitative analysis technologies (e.g., concentration and mass concentration) [28]. This study will provide a comprehensive assessment of the risks posed by microplastics to wildlife and emphasize the need for further research to fully understand the interactions between microplastic pollution, wildlife, and environmental health.

METHODOLOGY

Literature Search and Data Gathering

Bibliographic searches were conducted to gather data on previous studies related to microplastics. A qualitative analysis was conducted to collect, organize, and summarize existing research related to microplastics and biodiversity. Peer-reviewed articles were retrieved from the SCOPUS database using indexed titles, abstracts, keywords, and topics along with a set of relevant keywords.

***Table 1*. List of keywords used for publications mining.**

No	Search topics	No	Search topics
1	“Microplastics” + “Terrestrial”	10	“Microplastics” + “Amphibians”
2	“Microplastics” + “Biodiversity”	11	“Microplastics” + “Herpetofaunas”
3	“Microplastics” + “Flora”	12	“Microplastics” + “Birds ”
4	“Microplastics” + “Fauna”	13	“Microplastics” + “Avians ”
5	“Microplastics” + “Wildlife”	14	“Microplastics” + “Insects”
6	“Microplastics” + “Animals ”	15	“Microplastics” + “Invertebrates ”
7	“Microplastics” + “ Mammals”	16	“Microplastics” + “Fishes”
8	“Microplastics” + “Marines”	17	“Microplastics” + “Aquatics”
9	“Microplastics” + “Reptiles”	18	“Microplastics” + “Ecology”
19	“Microplastics” + “Megafaunas”	26	“Microplastics” + “Herbicides”
20	“Microplastics” + “Pesticides”	27	“Microplastics” + “Ichthyofaunas”
21	“Microplastics” + “Vertebrates”	28	“Microplastics” + “Freshwater”
22	“Microplastics” + “Plants”	29	“Microplastics” + “Organisms”
23	“Microplastics” + “Conservations”	30	“Microplastics” + “Livestocks”
24	“Microplastics” + “Aquacultures ”	31	“Microplastics” + “Agricultures ”
24	“Microplastics” + “Avifaunas ”		

Studies including theses, books, conference proceedings, reports, and other scientific publications related to microplastics and biodiversity were also considered. Initially, a list of 31 keywords (Table 1) was employed for the search before further filtering by using "Microplastics" as the main keyword. Information such as the authors' names, affiliations, publication years, and covered aspects was used to create infographics, which helped to visualize trends, identify research gaps, and highlight areas for future study.

Criteria Selection and Process

The criteria for study inclusion were refined to include articles that met the following conditions: (a) focused on the impact of microplastics on biodiversity (including research and reports but excluding review papers) and (b) investigated wildlife or domesticated/farm animals affected by microplastics, excluding experimental studies on laboratory animals such as mice. The initial search resulted in 36,595 articles involving 31 keywords. Only peer-reviewed research articles published in English were included. A few articles were also excluded if they were inaccessible or absence of clear information in the study abstract or aims. Database search records were then imported for screening and listing without duplication, where in this process, full-text articles were retrieved and screened before a comprehensive Excel list of acceptable articles was developed. A complete Excel list was utilized to ease the extraction of information for each article. Data were extracted concerning the taxonomy group studied, ecosystem, and focus topics as mentioned in Table 2. All the information gathered was then collated and summarized, and the data were presented in tables or graphs.

Table 2. **List of focus topics in microplastics study.**

Category	Definition
Physiological	-Ingestion can lead to blockages in the digestive system, thus this may reduce feeding efficiency and starvation. -Alterations to the organ's functions due to the changes or damage on its part.
Behavioral	-A false sense of fullness may reduce consumption of their natural diet due to feeding misjudgement. -Predator-Prey Dynamics may be impaired, thus disrupting their behaviors such as hunting or evading predators.
Toxicological	-Chemical leaching into the tissues of organisms can cause hormonal disruptions or other health issues. -This leaching toxic will act as a contaminant transport or toxicology vector.
Population growth	-Reproductive hormones are interfered, thus reducing the organism's fertility. -Developmental abnormalities can result in malformations or stunted growth.
Ecological	-Habitat disruption can alter substrate characteristics, impacting benthic organisms or soil-dwelling species. -Bioaccumulation that disrupts food chain may affect higher trophic levels and destabilize ecosystems over time.
Emerging Areas (Long exposure)	-Occur due to microbiome alteration and mutation or DNA damage.

Study Selection and Data Extraction

This review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [35] to ensure a systematic and transparent approach. PRISMA was chosen for its effectiveness in improving the clarity and consistency of systematic reviews by providing a structured framework for study selection and reporting [35]. The PRISMA flow diagram was utilized to illustrate the review process, encompassing four key stages: identification, screening, eligibility assessment, and final inclusion. To align with the objectives of this review, specific adjustments were introduced during the study selection process. These included refining the inclusion criteria to focus on studies addressing the impacts of microplastics on wildlife and biodiversity. A two-stage screening strategy was employed, beginning with a review of titles, keywords, and abstracts, followed by an in-depth examination of full-text articles, as shown in Fig. 2.

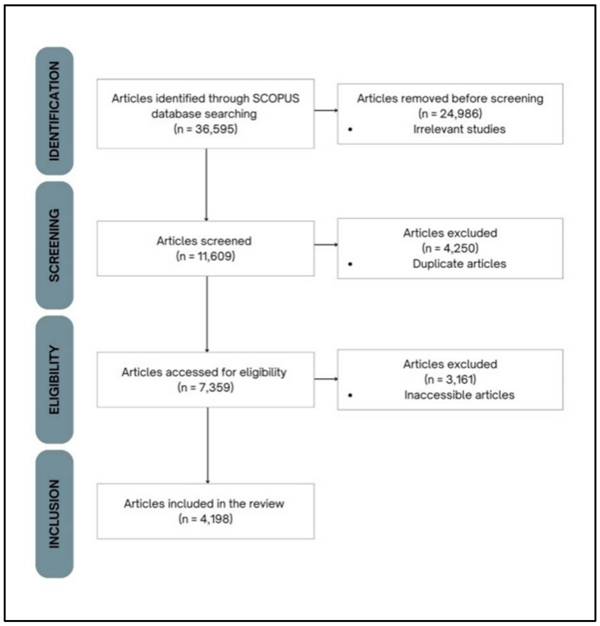


Figure 2. **PRISMA flow diagram that illustrates the systematic process of study selection and data extraction**

Results and Discussion

Overview of Extracted Articles

The systematic review process followed the PRISMA framework as illustrated in Fig. 2. A total of 36,595 articles were initially identified through SCOPUS database searches. Following the identification phase, 24,986 articles were excluded due to irrelevance based on the study's inclusion criteria. In the screening phase, 11,609 articles were assessed for relevance, with 4,250 articles removed due to duplication. This reduced the dataset to 7,359 articles, which were then evaluated for eligibility. During the eligibility phase, 3,161 articles were excluded due to inaccessibility, leaving 4,198 articles suitable for inclusion in the review.

Table 3. **List of search strings used and number of research articles in each bibliographic search.**

No	Keywords	Number of Publications (SCOPUS)	
		Total of Research Articles Available	Total of Extracted Paper
1.	*Microplastics* AND *Marines*	1,911	6,601
2.	*Microplastics* AND *Animals*	670	5315
3.	*Microplastics*AND *Organisms*	497	4,489
4.	*Microplastics*AND *Freshwater*	236	2,480
5.	*Microplastics* AND *Fish*	103	2,437
6.	*Microplastics* AND *Terrestrial*	223	1,719
7.	*Microplastics* AND *Aquatic*	86	4,030
8.	*Microplastics* AND *Mammals*	57	557
9.	*Microplastics*AND *Aquacultures*	61	555
10.	*Microplastics* AND *Plants*	142	3,087
11.	*Microplastics*AND *Biodiversity*	38	469
12.	*Microplastics*AND *Invertebrate*	22	630
13.	*Microplastics* AND *Insects*	26	188
14.	*Microplastics* AND *Ecology*	14	489
15.	*Microplastics* AND *Birds*	15	242
16.	*Microplastics*AND *Conservations*	10	419
17.	*Microplastics* AND *Pesticides*	17	511
18.	*Microplastics*AND *Vertebrates*	3	137
19.	*Microplastics*AND Agriculture*	22	776
20.	*Microplastics* AND *Wildlife*	9	270
21.	*Microplastics* AND *Fauna*	11	372
22.	*Microplastics* AND *Herbicide*	9	45
23.	*Microplastics* AND *Livestock*	7	88
24.	*Microplastics*AND *Amphibian*	3	63
25.	*Microplastics* AND *Avian*	0	29
26.	*Microplastics*AND *Ichthyofauna*	2	14
27.	*Microplastics*AND *Megafauna*	1	13
28.	*Microplastics* AND *Flora*	1	551
29.	*Microplastics* AND *Reptiles*	1	12
30.	*Microplastics* AND *Avifauna*	0	4
31.	*Microplastics* AND *Herpetofauna*	1	3

From the literature based on 31 search strings, a total of 7,336 related research articles were found throughout the SCOPUS database (Table 3). After excluding the redundant articles, 4,198 articles remained across all keyword searches. The selected peer-reviewed articles were then classified based on taxonomic groups, ecosystems, and research focus within microplastics studies. Microplastics research exhibits a clear bias toward aquatic ecosystems, particularly marine environments, as these are often perceived as the primary repositories for plastic waste [36]. This bias arises from the logistical ease of sampling in aquatic settings and the high visibility of plastic pollution in marine environments [37].

The majority of studies focus on invertebrates (1,833 articles) and fish (1,470 articles), largely due to their direct exposure to waterborne microplastics and their economic and ecological significance [38]. In contrast, amphibians (54 articles) and reptiles (27 articles) are vastly underrepresented, despite their exposure to microplastics in both aquatic and terrestrial environments. Similarly, the aerial ecosystem, which includes birds and airborne microplastics, remains critically understudied, with only 118 articles available. While, 226 articles have examined microplastic exposure in mammals, 481 articles have explored its effects on plants, as summarized in Fig. 3. This uneven representation creates a skewed understanding of how microplastics impact biodiversity across different ecosystems. From a total of 4,198 articles analyzed, approximately 78% focus on aquatic ecosystems, whereas terrestrial (856 articles) and aerial ecosystem (77 articles) receive significantly less attention. Terrestrial ecosystems, which serve as both reservoirs and transit points for microplastics from land-based sources are also inadequately explored [39]. For example, soil organisms such as earthworms which play a crucial role in nutrient cycling, are known to interact with microplastics, potentially altering soil structure and function [40]. However, these interactions remain poorly studied compared to those in marine and freshwater ecosystems. Similarly, the aerial ecosystem remains significantly under-researched, particularly concerning the impact of airborne microplastics on birds and other aerial species [26]. For example, worker bees can retain microplastic fibers from the environment on their cuticle and within their digestive tract, subsequently transferring them to different levels of the hive, including larvae, honey, and wax. Insects can act as airborne carriers of microplastics, as suspended particles in the atmosphere may adhere to the surface of their bodies. Through their movement, insects can transport and disperse these particles across ecosystems, potentially affecting insect populations, plants, soils, and ultimately entering the food chain [41].

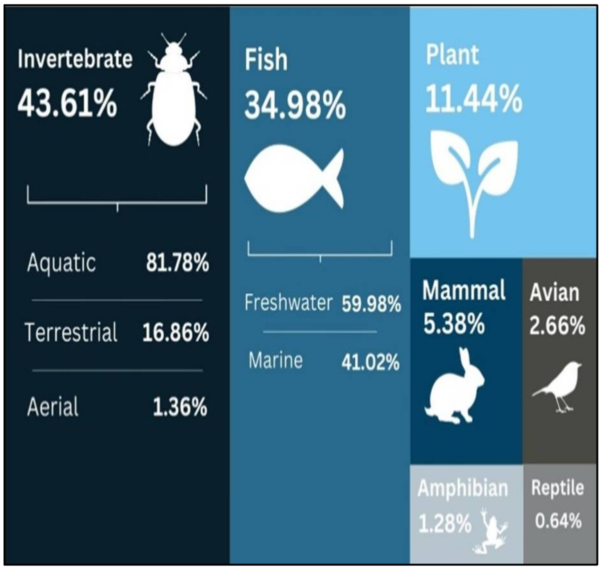


Figure 3. **Total number of articles found based on the taxonomic group trends in microplastic study**

Among the conducted research, a significant proportion comprising 32% (1,344 articles) focuses on the wildlife ecology highlighting the crucial role of microplastics in affecting ecosystems. After ecology, studies on the toxicity and physiological impacts of microplastics on biodiversity dominate the literature, reflecting growing concerns about their adverse effects, as shown in Fig. 4. Despite the potential for exposure through ingestion, inhalation or dermal contact in terrestrial settings, limited research has been explored on how the microplastics affect the behavior and health of mammals [42]. However, ruminal impaction has been seen in terrestrial animals such as cattle, sheep, and goats following the ingestion of large plastic items. This condition occurs when ingested plastic accumulates in the rumen, leading to impaired digestion, bloating, and potentially death [43]. Invertebrates dominate the literature due to their ecological significance and abundance, whereas taxa such as amphibians, reptiles, and aves remain significantly understudied [44]. Amphibians in particular are highly vulnerable to microplastic pollution in aquatic-terrestrial transition zones, yet research on their exposure and physiological responses remains minimal [45]. The expanding research on taxonomic groups and ecosystems is essential to understanding the broader ecological impacts of microplastics, particularly in emerging areas of study. Hence, investigating microbiome changes is crucial as such alterations may lead to new health risks, potentially caused by microplastic toxicity through various exposure routes [46,47]. Understanding the impacts of microplastic exposure on various animal species is crucial for biodiversity conservation. In marine organisms such as cephalopod molluscs, crustaceans, and fish obtained from market ports, microplastics were detected in the digestive tracts of 69% of the 240 specimens examined [47]. In another study, Lackner and Branka [48], found microplastics in the gastrointestinal tracts of 30.27% of fish from a total of 417 samples. Similarly, Altunışık et al. [49] reported microplastic accumulation in the gastrointestinal tracts of lizard species, affecting 33 out of 152 specimens across 18 populations. Since the 1960s, it is estimated that up to 78% of identified seabird species have ingested microplastics that can be found in their digestive tracts. Additionally, microplastics were detected in the gastrointestinal tracts of 16 out of 17 examined terrestrial bird species [50].

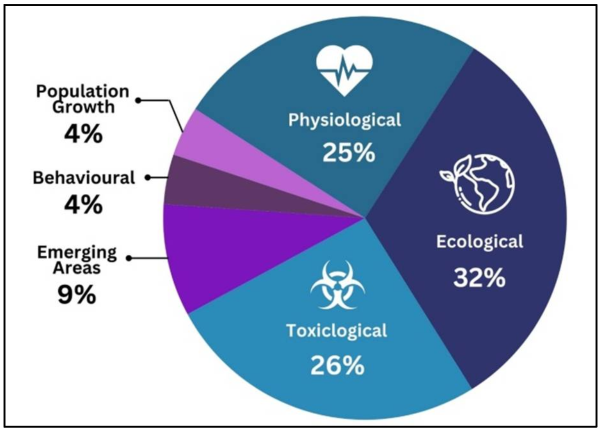


Figure 4. **Percentage distribution of research based on focus topics on microplastics**

Mechanisms and Impacts of Microplastics on Wildlife and Biodiversity

As a critical environmental threat, microplastics have significantly impacted wildlife across ecosystems through various physiological, ecological, and toxicological pathways (Fig. 5). Their effects include reduced survival rates, altered feeding behavior, oxidative stress, impaired reproduction, and stunted growth [24,51]. Each year, approximately 11 million tonnes of plastic waste pollute the oceans and lands, harming wildlife through entanglement, ingestion, and toxic exposure. As broad-ranging animals, birds can inhabit a wide range of ecosystems [52]. Plastic debris may be unintentionally ingested by the birds at various points along their migratory routes and can persist in the gastrointestinal tract for several months. For example, several seabird species, such as Cory's shearwater (*Calonectris borealis*), the yellow-legged gull (*Larus michahellis*), and the Madeiran storm-petrel (*Oceanodromacastro*), commonly use the Canary Islands as stopover or breeding sites during their migration [53]. They are also considered effective indicators of environmental pollution, including plastic waste, due to their diverse feeding habits and presence across multiple trophic levels in the food chain [52]. When microplastics are absorbed, they can damage the cell membrane by altering the lipid bilayer and inducing pore formation. This disruption leads to an increased production of reactive oxygen species (ROS), which may result in mitochondrial dysfunction, trigger inflammatory responses, and cause overall cellular damage [54]. Proactive measures should be taken to mitigate these impacts [55]. Exposure to microplastics varies across species and is usually influenced by specific traits and the physicochemical properties of the pollutants [56,57]. Among aquatic species, filter feeders like mollusks, which process large volumes of water tend to ingest microplastics more frequently than other organisms [58].

Ingestion is one of the primary exposure pathways, particularly concerning because wildlife often mistake microplastics for food, which leads to digestive issues, reduced feeding efficiency and nutritional deficiencies. Plastic pollution is also an increasing threat to terrestrial wildlife, as evidenced by a study in western Thailand that found microplastics in 92% of examined animals [59]. This highlights the urgent need for enhanced waste management, conservation education, and further research for tackling the microplastic issues. In marine ecosystems, trophic transfer plays a significant role in the bioaccumulation of microplastics. Contaminated prey, such as flying fish consumed by tuna, illustrates how plastics move up the food chain, affecting higher predators [60]. Similar findings have been documented in mussels, crabs [61], and plankton species [62]. In the study by Hou and Rao [63], it was hypothesized that the toxic effects of microplastics on amphibians and reptiles differ due to variations in microplastics concentrations. For instance, amphibians such as tadpoles function as essential primary consumers in freshwater ecosystems; thus, the accumulation of microplastics in their bodies may facilitate the transfer of contaminants across trophic levels. Reptiles, including turtles and snakes, are usually susceptible to physical harm such as asphyxiation and internal organ damage, as they can easily become entangled in plastic debris or ingest large plastic fragments. Filter-feeders like oysters experience impaired feeding, nutrient absorption, reproduction and offspring growth due to microplastic ingestion, destabilizing the entire ecosystem [64]. Furthermore, microplastics act as carriers for toxic substances such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals, which magnify through food webs, threatening biodiversity and ultimately affecting human health [56]. Marine animals, including turtles, seabirds, fish, and whales, are particularly susceptible. Ingested plastics by wildlife can cause gastrointestinal blockages, internal injuries, and exposure to harmful chemicals [13]. Species like baleen whales, which use non-selective feeding methods such as skimming and gulping, are particularly vulnerable, as plastic particles can clog their filters and lead to severe health issues [65,66].

Predators are highly vulnerable to microplastic accumulation through contaminated prey. Smith et al. [67] highlighted that microplastics accumulate within food chains, complicating exposure tracing and amplifying toxicity at higher trophic levels. Terrestrial species, though less studied, are not exempt from the dangers. Thrift et al. [68] documented high rates of direct ingestion among mammals such as bears, foxes, elephants, and rodents, particularly in landfill areas. Keystone species such as leopard cats and golden snub-nosed monkeys are indirectly exposed to microplastics through contaminated prey, with human activities and domestic waste further increasing the risk [69]. Terrestrial animals, including livestock, are also at risk of experiencing toxic effects similar to those observed in marine species, as microplastics ingested through contaminated feed or water can accumulate in their tissues and disrupt overall physiological health [70]. It is also worth noting that further studies on the impact of microplastics on mammalian species have mostly been conducted using laboratory mice. These studies reveal serious consequences, including reduced body weight, chronic respiratory problems, increased neonatal mortality, metabolic imbalances, and altered gut microbiota [71]. Research on mice has also shown that microplastics combined with the marine toxin okadaic acid can intensify oxidative stress, inflammation, and gut damage, highlighting potential health risks for humans through the food chain [72]. A recent study further demonstrated that short-term exposure to microplastics in mice causes age-dependent behavioral and immune changes, highlighting the urgent need for deeper research into their health impacts [73].

Beyond ingestion, inhalation is another significant pathway of exposure posing major risks, particularly for marine mammals exposed to airborne or waterborne microplastics. A review found microplastics in the respiratory systems of small cetaceans, raising concerns about long-term respiratory health effects [74]. Apart from that, smaller microplastic particles are particularly concerning due to their abundance and ability to infiltrate tissues, leading to long-term damage [75]. One of the most concerning long-term consequences of microplastic pollution is reproductive toxicity. Microplastics disrupt critical aspects of the reproductive cycle such as gametogenesis, gamete quality, egg production, fertility, and sperm motility [51]. The concentration of microplastics has been shown to be positively correlated with growth inhibition. This is primarily due to physical damage and intestinal blockage caused by ingested particles, which can induce a false sense of satiety, reduce food intake, and impair nutrient digestion and absorption. These disruptions may ultimately lead to malnutrition, stunted growth, and diminished reproductive capacity in affected animals [76]. For instance, studies on zebrafish (*Danio rerio*) and water fleas (*Daphnia magna*) show that exposure to microplastics results in reduced offspring numbers, fewer eggs per clutch, and lower fertility rates [77]. Research on marine tubeworms and barnacles has revealed species-specific differences in how nanoplastics are transferred from parents to offspring, potentially affecting development [78]. This highlights the risk of widespread reproductive failure, especially in aquatic organisms. Beyond physiological effects, microplastics also threaten essential ecosystem services, including pollination, nutrient cycling, and habitat stability. For example, they interfere with bee foraging behavior, reducing pollination success and negatively impacting food production [79]. Fig. 5 summarizes the impacts of microplastics on wildlife and their exposure pathways.

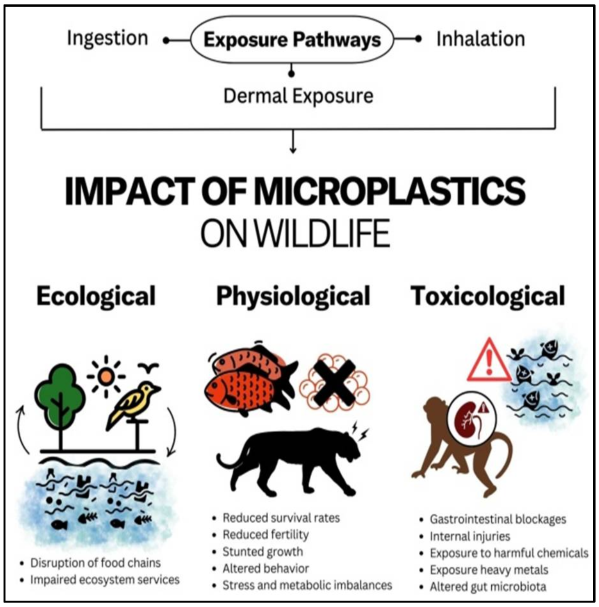


Figure 5. **Summary on impact of microplastics on wildlife and its exposure pathways**

The ingestion and inhalation of microplastics are well-documented exposure routes, but the dermal pathway, where organisms absorb microplastics through their skin or outer integument, requires further exploration, particularly regarding its implications for wildlife health and biodiversity [80]. This pathway is especially relevant for species with permeable skin or those inhabiting microplastic-contaminated environments. For instance, amphibians that rely on their skin for respiration and osmoregulation are particularly vulnerable to contaminants in their aquatic habitats [81]. Studies have shown that toxic additives in plastics, such as flame retardants, can leach out and be absorbed through the skin [82]. Research using 3D human skin models has demonstrated that up to 8% of such chemicals can be absorbed within 24 hours, with higher absorption rates in more hydrated (sweaty) skin conditions [83]. Although this study was conducted on human skin models, it suggests potential similar mechanisms in wildlife species with comparable skin properties.

Emerging evidence also suggests that mosquito bites may serve as a novel vector for microplastic transmission, potentially exposing other organisms to these particles through saliva or other fluids [84]. A study by Simakova et al. [85] found that bloodsucking *Anopheles* mosquitoes, known disease vectors can ingest and transfer microplastics from larvae to adults. While this process does not affect mosquito survival, it slightly increases metamorphosis rates raising concerns about the movement of microplastics through aquatic ecosystems and their potential broader impact. Microplastics and their associated chemicals can interact with the skin through several mechanisms [86]. One primary route is direct contact with contaminated water, particularly for aquatic organisms like fish and amphibians that remain in continuous contact with microplastic-laden water [87]. Another mechanism involves the adherence of microplastics to the skin surface, leading to prolonged exposure. This is especially concerning for species with mucous-covered skin as trapped particles may increase the likelihood of dermal absorption [80]. Additionally, smaller microplastics and nanoplastics may penetrate the skin through appendages such as hair follicles or sweat glands [88]. Research suggests that factors such as particle size, shape, and surface chemistry influence their ability to breach the skin barrier [89]. Overall, the literature highlights the pervasive nature of microplastic pollution, underscoring its threat not only to individual organisms but also to entire food webs and overall ecosystem stability.

Methodological Approaches in Microplastic Analysis

As a newly emerging contaminant, microplastics require standardized methods and protocols for data collection, which are still in the development phase. This ongoing refinement presents opportunities for the application of various techniques, while establishing best practices remains a primary focus [90]. Standard operating procedures include ISO 24187:2023 (*Principles for the Analysis of Microplastics Present in the Environment*) and ASTM D8401-24 (*Standard Test Method for Identification of Polymer Type and Quantity of Microplastic Particles and Fibers in Waters with High to Low Suspended Solids Using Pyrolysis-Gas Chromatography/Mass Spectrometry*). These standards provide guidelines for sampling procedures, sample preparation, and analysis of microplastic contamination. ISO 24187:2023 outlines protocols for analyzing microplastics in environmental matrices such as water, soil, air, sludge, biota, and minerals. It includes methods for size classification to distinguish microplastics from natural debris, details sampling and identification procedures, and emphasizes quality assurance to ensure accurate results [91]. ASTM D8401-24 complements ISO 24187:2023 by focusing on detecting and quantifying microplastics in water with varying suspended solid levels using Pyrolysis-Gas Chromatography/Mass Spectrometry (Py-GC/MS). Together, these standards aid in the analysis of microplastics in environmental water samples.

The choice of analytical method depends on the study's specific objectives, such as identifying polymer types, measuring particle size, quantifying mass or characterizing the morphological features of microplastics. Several techniques have been identified for analyzing microplastics in wildlife and environmental studies, including: 1) Microscopy, 2) Laser Direct Infrared (LDIR), 3) Attenuated Total Reflectance Fourier-Transform Infrared Spectroscopy (ATR-FTIR), 4) Micro-Fourier Transform Infrared spectroscopy (Micro-FTIR), 5) Pyrolysis-GC-MS, and 6) Raman Spectroscopy. Each microplastic analysis method has been used across various animal taxa to evaluate the effects of microplastic pollution in different ecosystems. The microscopy technique can characterize the physical properties of microplastics through visual identification. It is primarily used to analyze microplastics in fish [92-96], invertebrates [97-101], and mammals [24, 102-105]. With minimum particle damage and great precision, LDIR is used to analyse microplastics in complicated matrices such as soil, water, and sediment therefore, this method is typically employed for smaller organisms such as plankton, zooplankton, and benthic organisms [6,106].

ATR-FTIR is used to determine the types of polymers present in microplastics by performing chemical identification, aiding in pollution source tracking, and assessing polymers with significant ecological consequences. Micro-FTIR facilitates extensive monitoring of microplastic pollution across ecosystems. Both techniques have been widely applied in studies on fish [107-112], seabirds [6,113-116], and marine mammals [117-121]. Py-GC/MS is particularly effective in assessing the bioaccumulation and persistence of microplastics and their long-term effects on wildlife populations.

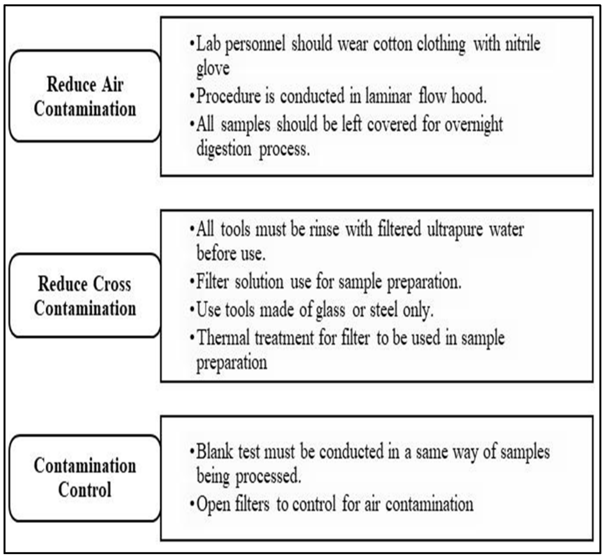
Table 4. **Advantages and Limitations of Various Microplastic Detection Techniques [136].**

Technique	Advantages	Limitations
Microscopy	• Able to determine morphological characteristics such as size, shape and colour	• Lack of chemical identification • Absence of polymer • Subject to bias and inaccuracies
LDIR	• Fast and high-precision • Non-invasive	• Lacks sufficient infrared spectral data
ATR-FTIR	• Non-invasive • Manual analysis • Able to identify chemical composition	• Absence of polymer • Limited to relatively big particles (approx. > 100 µm)
Micro-FTIR	• Non-invasive • Able to identify chemical composition • Able to identify and quantify particle counting • Automatic analysis	• Limited to a particle size of 10 µm and above • Absence of polymer • Time-consuming
Pyrolysis-GCMS	• High sensitivity • No size limitation (depending on the filter pore size) • Able to identify chemical composition • Able to determine polymer mass quantification	• Invasive • Not able to identify and quantify particles in counting
Raman Spectroscopy	• Detection down to 1 µm • Able to tolerate the presence of water	• Costly • Time-consuming • Interpreting data may be difficult without standards. • Can be affected by additives, dyes, or impurities, sample fluorescence background

This technique has been extensively used in studies on marine mammals [122-125] and fish [123,126-128]. Raman Spectroscopy is particularly valuable for detecting contamination in sensitive environments, such as coral reefs and deep-sea ecosystems. This technique provides insights into the effects of microplastics on microscopic organisms across diverse taxa, including invertebrates, fish, birds, and mammals [25,125,129-135]. Understanding the strengths and limitations of each technique is crucial for selecting the most appropriate approach based on the study's objectives. Table 4 provides a summary of key features of commonly used microplastic analysis techniques, highlighting their advantages, limitations, and applications.

When selecting instruments for microplastic analysis, understanding the type of sample matrix is crucial, as no single isolation method is universally applicable across all matrices. The presence of organic and inorganic materials, as well as the sample's condition and origin, influences the choice of isolation method. The selected approach must effectively separate microplastic particles from the sample while preserving their integrity. Isolation methods range from simple filtration to enzymatic digestion, depending on the sample composition, to ensure accurate results.

Quality control in microplastic analysis consists of two main components: the sampling component and the analysis component. In the sampling component, the use of plastic materials should be avoided not only in sampling equipment but also in the clothing worn by the sampler. Additionally, the use of field blanks is recommended due to the ubiquitous nature of microplastics [90]. For the analysis component, rigorous precautions are necessary in the laboratory, including proper handling of apparatus, the use of spikes (internal standards), and blank controls to minimize contamination. Prata et al. [137] emphasize three key aspects of quality control in the analytical component: airborne contamination, cross-contamination, and contamination control, as illustrated in Fig. 6.



Reduce Air Contamination
- Lab personnel should wear cotton clothing with nitrile glove
- Procedure is conducted in laminar flow hood.
- All samples should be left covered for overnight digestion process.

Reduce Cross Contamination
- All tools must be rinse with filtered ultrapure water before use.
- Filter solution use for sample preparation.
- Use tools made of glass or steel only.
- Thermal treatment for filter to be used in sample preparation

Contamination Control
- Blank test must be conducted in a same way of samples being processed.
- Open filters to control for air contamination

Figure 6. **Measures to Minimize Contamination in Microplastic Analysis [137]**

Challenges in Assessing Microplastic Effects

The long-term impacts of microplastics on wildlife remain poorly understood, as many effects take years to manifest and require extensive research for a comprehensive assessment. Understanding these impacts involves identifying the diverse range of microplastic types, shapes, and compositions [138]. A key challenge in microplastic research is their diversity, which far exceeds that of other pollutants such as pesticides or polychlorinated biphenyls (PCBs), both of which can be analyzed using well-established techniques like FTIR spectroscopy and Raman spectroscopy [139]. Microplastics exist in various shapes, including fragments, granules, and fibers, and they vary in size and chemical composition. They are further classified as primary or secondary, making their categorization and analysis more complex, which in turn hinders assessments of their impact on biodiversity [140,141].

Another significant challenge is the lack of standardized definitions and methodologies for studying microplastics, leading to inconsistent findings and limiting cross-study comparisons [142,143]. For instance, relying on a single analytical method may produce false positives or negatives, requiring researchers to combine multiple techniques, such as physical and chemical characterization to enhance detection accuracy [144]. Furthermore, smaller particles like nanoplastics are often excluded from studies due to analytical limitations, despite their ability to penetrate biological membranes, accumulate in tissues, and disrupt cellular processes. These effects could cascade across populations and trophic levels, amplifying their ecological consequences [37]. Methodological discrepancies create inconsistencies in data interpretation and hinder progress in understanding microplastic pollution. Additionally, variations in research methodologies complicate assessments of microplastic toxicity and prevalence in wildlife ecosystems. Differences in sampling and extraction techniques, where some studies quantify microplastics by particle count and others by weight, further contribute to inconsistencies in exposure assessments [145].

Despite advancements in analytical methods, the absence of standardized protocols for assessing the ecological and physiological impacts of microplastics makes it difficult to establish cause-and-effect relationships [146]. Developing universal protocols for microplastic analysis would enhance the reproducibility and reliability of research findings. In biodiversity studies, standardized methodologies are essential not only for quantifying microplastics but also for evaluating their ecological effects across different habitats and species. Such protocols would allow researchers to identify vulnerable species, monitor population dynamics, and assess the long-term implications of microplastic pollution on ecosystem stability and biodiversity conservation.

Future Directions in Microplastic Research

Future research on microplastics should address critical knowledge gaps, particularly regarding their effects across different habitats. According to Jeong et al. [47], interspecies differences in ingestion, accumulation, and responses to microplastics emerge as key areas of study, influenced by factors such as feeding behavior, physiology, and ecological niches. Greater attention is needed to understand how various species respond to microplastic exposure, particularly aerial and terrestrial species which have been largely overlooked [147,148]. Additionally, the chemical, physical, and behavioral interactions between microplastics and wildlife require further investigation, as these interactions can lead to health issues and toxicological effects. While previous studies have primarily focused on the short-term effects of microplastics, their long-term accumulation and degradation in the environment remain poorly understood. Most studies provide only snapshot data, focusing on specific regions or short-term observations [149]. This approach fails to capture the temporal and spatial dynamics of microplastic pollution, including seasonal and geographical variations, which are critical for understanding their effects on different species and ecosystems over time. For instance, long-term studies are necessary to explore potential links between microplastic exposure and zoonotic diseases [47,150]. Prolonged exposure to microplastics may alter wildlife microbiomes through mechanical disruption, chemical disturbances, and pathogen transmission [151].

Geographical coverage in microplastic research also remains uneven, with studies predominantly conducted in developed regions such as Europe and North America [152]. In contrast, biodiversity-rich areas in the Global South, where microplastic pollution may be more severe due to inadequate waste management are underrepresented [153]. The lack of data from ecologically sensitive regions limits our ability to assess the global impact of microplastics comprehensively. Addressing these gaps is crucial for understanding how microplastic pollution contributes to biodiversity loss and ecosystem degradation, particularly in vulnerable habitats. Stronger policies and legislation are also urgently needed to mitigate the effects of microplastics on biodiversity and prevent cascading ecological consequences. International standards such as ISO 24187 and regulations like the EU's REACH Regulation (Registration, Evaluation, Authorization, and Restriction of Chemicals) enforced by the European Chemicals Agency (ECHA), aim to limit primary microplastic pollution, including through bans on microbeads in personal care products [154]. Countries such as the United States, South Korea, China, Canada, and several European nations have implemented similar measures to reduce microplastic pollution from cosmetics. Policymakers must carefully evaluate whether incentives for replacing microplastics could stimulate the development of innovative, eco-friendly materials. Establishing global standardization is crucial for effective microplastic management. Additionally, urgent action is needed to address the emerging risks of microplastics to food safety, particularly their potential impact on microbiomes, which remains poorly understood. Further research is essential to improve our understanding of the ecological, physiological, and toxicological effects of microplastics on wildlife, ecosystems, and human health.

Conclusion

This review highlights the detrimental effects of microplastics on wildlife, emphasizing their toxicological and ecological consequences. Besides, there is an urgent need for more research and focus on terrestrial and aerial wildlife, which remain underexplored in microplastic studies. While the harmful effects of microplastics are evident, it is crucial to recognize that their toxicity primarily stems from their chemical composition and physical characteristics.

Although standardized protocols for microplastic analysis have yet to be fully established, researchers can refer to the minimum requirements outlined in ISO 24187 as a baseline for analysis. Additionally, it is important to recognize that different wildlife species vary in their exposure to and ability to ingest microplastics. Therefore, both researchers and policymakers must take immediate action by implementing stricter regulations and policies to mitigate the growing threat of microplastics. The long-term impacts of microplastic pollution on wildlife may not be immediately apparent, but these microscopic particles exist in diverse forms and can easily infiltrate natural habitats. Without prompt intervention, their widespread presence could have irreversible effects on biodiversity and ecosystem stability.

Acknowledgement

This project is supported by UTHM-W033, Southeast Asia Program (Research and Conservation Division), Copenhagen Zoo, Denmark, and UTHM-GPPS-J018-2025 postgraduate grant by Universiti Tun Hussein Onn Malaysia. We are deeply indebted to Faculty of Applied Science and Technology (FAST), Universiti Tun Hussein Onn Malaysia, Copenhagen Zoo, and Department of Wildlife and National Parks (DWNP) for providing necessary funding, facilities, and assistance.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. J. P. G. L. Frias and R. Nash, *Mar. Pollut. Bull.,* 138 (2019) 145. doi: 10.1016/j.marpolbul.2018.11.022
2. F. Galgani, G. Hanke and T. Maes, Global Distribution, Composition and Abundance of Marine Litter, In: *Marine Litter* (M. Bergmann, L. Gutow, M. Klages, Eds) Springer, Cham (2015) pp. 29-56. doi: 10.1007/978-3-319-16510-3_2
3. R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle and A. E. Russell, *Science,* 304 (2004) 838. doi: 10.1126/science.1094559
4. A. Kärrman, C. Schönlau and M. Engwall, Exposure and Effects of Microplastics on Wildlife, MTM Research Centre, Orebro, Sweden, Tech. Report (2016). www.diva-portal.org
5. S. B. Kurniawan, N. S. M. Said, M. F. Imron and S. R. S. Abdullah, *Environ. Technol. Innov*., 23 (2021) 101790. doi: 10.1016/j.eti.2021.101790
6. S. Sarkar, H. Diab and J. Thompson, *Int. J. Environ. Res. Public Health*, 20 (2023) 1745. doi: 10.3390/ijerph20031745
7. M. Pirsaheb, H. Hossini, P. Makhdoumi, *Process Saf. Environ. Prot.,* 142 (2020) 1. doi: 10.1016/j.psep.2020.05.050
8. M. Cole, P. Lindeque, C. Halsband and T. S. Galloway, *Mar. Pollut. Bull.,* 62 (2011) 2588. doi: 10.1016/j.marpolbul.2011.09.025

9. I. Järlskog, A.-M. Strömvall, K. Magnusson, M. Gustafsson, M. Polukarova, H. Galfi, M. Aronsson and Y. Andersson-Sköld, *Sci. Total. Environ.,* 729 (2020) 138950. doi: 10.1016/j.scitotenv.2020.138950.
10. P. Byrley, W. K. Boyes, K. Rogers and A. M. Jarabek, *J. Aerosol Sci.,* 154 (2021) 105765. doi: 10.1016/j.jaerosci.2021.105765
11. L. An, Q. Liu, Y. Deng, W. Wu, Y. Gao and W. Ling, Sources of Microplastic in the Environment. In: D. He and Y. Luo (Eds) Microplastics in Terrestrial Environments: Emerging Contaminants. The Handbook of Environmental Chemistry, vol 95 (Springer, Cham) (2020) 143. doi: 10.1007/698_2020_449
12. A. M. Rochman, C. Brookson, J. Bikker, N. Djuric, A. Earn, K. Bucci, S. Athey, A. Huntington, H. McIlwraith, K. Munno, H. De Frond, A. Kolomijeca, L. Erdle, J. Grbic, M. Bayoumi, S. B. Borrelle, T. Wu, S. Santoro, L. M. Werbowski and X. Zhu, *Environ. Toxicol. Chem.,* 38 (2019) 703. doi: 10.1002/etc.4371
13. N. K. Y. Susanti, A. Mardiastuti and Y. Wardiatno, *IOP Conf. Ser.: Earth Environ. Sci.,* 528 (2020) 012013. doi: 10.1088/1755-1315/528/1/012013
14. A. I. Osman, M. Hosny, A. S. Eltaweil, S. Omar, A. M. Elgarahy, M. Farghali, P.-S. Yap, Y.-S. Wu, S. Nagandran, K. Batumalaie, S. C. B. Gopinath, O. D. John, M. Sekar, T. Saikia, P. Karunanithi, M. H. M. Hatta and K. A. Akinyede, *Environ. Chem. Lett.,* 21 (2023) 1-41. doi: 10.1007/s10311-023-01593-3
15. H. Deng, R. Wei, W. Luo, L. Hu, B. Li, Y. Di and H. Shi, *Environ. Pollut.,* 258 (2020) 113658. doi: 10.1016/j.envpol.2019.113658
16. Z. Long, W. Wang, X. Yu, Z. Lin and J. Chen, *Front. Environ. Sci.,* 9 (2021) 770634. doi: 10.3389/fenvs.2021.770634
17. N. A. S. M. Rahim, F. Islahudin, N. Abu Tahrim and M. Jasamai, *Sains Malaysiana,* 51 (2021) 2495. doi: 10.17576/jsm-2022-5108-12
18. A. Kukkola, A. J. Chetwynd, S. Krause and I. Lynch, *J. Hazard. Mater.,* 476 (2024) 135053. doi: 10.1016/j.jhazmat.2024.135053
19. P. J. Kershaw and C. M. Rochman. (2015). *Sources, Fate and Effects of Microplastics in the Marine Environment: Part 2 of A Global Assessment*. London, UK: GESAMP. doi: 10.13140/RG.2.1.3803.7925
20. Z. M. Wang, J. Wagner, S. Ghosal, G. Bedi and S. Wall, *Sci. Total Environ.,* 603 (2017) 616. doi: 10.1016/j.scitotenv.2017.06.047
21. C. Guerranti, T. Martellini, G. Perra, C. Scopetani and A. Cincinelli, *Environ. Toxicol. Pharmacol.,* 68 (2019) 75. doi: 10.1016/j.etap.2019.03.007
22. D. A. Herrera, T. R. Ault, J. T. Fasullo, S. J. Coats, C. M. Carrillo, B. I. Cook, and A. P. Williams, *Geophys. Res. Lett.*, 45 (2018) 19. doi: 10.1029/2018gl079408
23. S. S. Sadri and R. C. Thompson, *Mar. Pollut. Bull.,* 81 (1)(2014) 55. doi: 10.1016/j.marpolbul.2014.02.020
24. E. Besseling, E.M. Foekema, J.A. Van Franeker, M.F. Leopold, S. Kühn, E.L. Bravo Rebolledo, E. Heße, L. Mielke, J. I. Jzer, P. Kamminga and A.A. Koelmans, *Mar. Pollut. Bull.,* 95 (2015) 248. doi: 10.1016/j.marpolbul.2015.04.007
25. M. Dong, Q. Zhang, X. Xing, W. Chen, Z. She and Z. Luo, *Sci. Total Environ.,* 739 (2020) 139990. doi: 10.1016/j.scitotenv.2020.139990

26. S. Allen, D. Allen, V. R. Phoenix, G. Le Roux, P. Durántez Jiménez, A. Simonneau and D. Galop, *Nat. Geosci.,* 12 (2019) 339. doi: 10.1038/s41561-019-0335-5
27. M. Trainic, J. M. Flores, I. Pinkas, M. L. Pedrotti, F. Lombard, G. Bourdin, G. Gorsky, E. Boss, Y. Rudich, A. Vardi and I. Koren, Commun. *Earth Environ.,* 1 (2020) 64. doi: 10.1038/s43247-020-00061-y
28. Z. Huang, B. Hu and H. Wang, *Environ. Chem. Lett.,* 21 (2022) 383. doi: 10.1039/C6AY02558G
29. L. An, Q. Liu, Y. Deng, W. Wu, Y. Gao and W. Ling, In: Microplastics in Terrestrial Environments: Emerging Contaminants and Major Challenges (Springer, Cham) (2020) 143-159. doi: 10.1007/698_2020_449
30. S. H. Hong, W. J. Shim and L. Hong, *Anal. Methods,* 9 (2017) 1361. doi: 10.1039/C6AY02971J
31. S. Pignattelli, A. Broccoli and M. Renzi, *Sci. Total Environ.,* 727 (2020) 138609. doi: 10.1016/j.scitotenv.2020.138609
32. J. Meng, B. Xu, F. Liu, W. Li, N. Sy, X. Zhou and B. Yan, *Chemosphere,* 283 (2021) 131274. doi:10.1016/j.chemosphere.2021.131274
33. C. M. Free, O. P. Jensen, S. A. Mason, M. Eriksen, N. J. Williamson and B. Boldgiv, *Mar. Pollut. Bul.,* 85 (2014) 156. doi: 10.1016/j.marpolbul.2014.06.001
34. C. Campanale, C. Massarelli, I. Savino, V. Locaputo and V. F. Uricchio, *Int. J. Environ. Res. Public Health.,* 17 (2020) 1212. doi: 10.3390/ijerph17041212
35. A. Moher, A. Liberati, J. Tetzlaff, D. G. Altman and PRISMA Group, *Ann. Intern. Med.,* 151 (2009) 264. doi: 10.1371/journal.pmed.1000097
36. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady and K. L. Law, *Science,* 347 (2015) 768. doi: 10.1126/science.1260352
37. A. A. Koelmans, M. Kooi, K. L. Law and E. Van Sebille, *Environ. Res. Lett.,* 14 (2019) 124021. doi: 10.1088/1748-9326/aa9500
38. A. L. Lusher, P. C. Hollman and J. J. Mendoza-Hill, FAO Fisheries and Aquaculture Technical Paper No. 615 (2017).
39. M. C. Rillig, L. Ziersch and S. Hempel, *Sci. Rep.,* 7 (2017) 1362. doi: 10.1038/s41598-017-01594-7
40. B. Boots, C. W. Russell and D. S. Green, *Environ. Sci. Technol.,* 53 (2019) 11496. doi: 10.1021/acs.est.9b03304
41. J. Shen, B. Liang and H. Jin, *Trends Anal. Chem.,* 165 (2023) 117130. doi: 10.1016/j.trac.2023.117130
42. J. C. Prata, J. P. da Costa, I. Lopes, A. C. Duarte and T. Rocha-Santos, *Sci. Total Environ.,* 702 (2020) 134455. doi: 10.1016/j.scitotenv.2019.134455
43. A. Khan, A. Qadeer, A. Wahid, Q. Ullah, S. Ur Rahman, K. Ullah, S. Z. Safi, L. Ticha, S. Skalickova, P. Chilala, S. Bernatova, O. Samek and P. Horky, *J. Agric. Food Res.,* 17 (2024) 101258. doi: 10.1016/j.jafr.2024.101258
44. F. Gallo, C. Fossi, R. Weber, D. Santillo, J. Sousa, I. Ingram and D. Romano, *Environ. Sci. Eur.,* 30 (2018) 13. doi: 10.1186/s12302-018-0139-z
45. W. C. Li, H. F. Tse and L. Fok, *Sci. Total Environ.,* 536 (2020) 144. doi: 10.1016/j.scitotenv.2015.05.001
46. M. A. Browne, A. Dissanayake, T. S. Galloway, D. M. Lowe and R. C. Thompson, *Environ. Sci. Tech.,* 42 (2008) 5026-5031. doi: 10.1021/es800249a
47. E. Jeong, J. Y. Lee and M. Redwan, *Emerg. Contam.,* 100369 (2024) 100369. doi: 10.1016/j.emcon.2024.100369
48. M. Lackner and M. Branka, *J. Environ. Prot.,* 3 (2024) 559.

doi: 10.3390/microplastics3040035

49. A. Altunışık, M. Z. Yildiz and H. H. Tatli, Environ. Pollut., 359 (2024) 124754. doi: 10.1016/j.envpol.2024.124754
50. L. Wang, G. Nabi, L. Yin, Y. Wang, S. Li, Z. Hao and D. Li, *Avian Res.,* 59 (2021) 59. doi: 10.1186/s40657-021-00293-2
51. M. Bilal, H. Ul Hassan, M. Taj, N. Rafiq, G. Nabi, A. Ali, K. Gabol, M. I. A. Shah, R. A. Ghaffar, M. Sohail and T. Arai, *Water,* 15 (2023) 2831. doi: 10.3390/w15152831
52. L. Carrasco, E. Jiménez-Mora, M. J. Utrilla, I. T. Pizarro, M. M. Reglero, L. R. Roman and B. Martin-Maldonado, *Birds.,* 6 (1) (2025) 10. doi: 10.3390/birds6010010
53. A. Navarro, O. P. Luzardo, M. Gómez, A. Acosta-Dacal, I. Martínez, J. F. de la Rosa, A. Macías-Montes, A. Suárez-Pérez and A. Herrera, *Mar. Pollut. Bull.,* 186 (2023) 114434. doi: 10.1016/j.marpolbul.2022.114434
54. K. Kadac-Czapska, J. Osko. E. Knez and M. Grembecka, *Antioxidants (Basel),* 4 (2024) 490. doi: 10.3390/pollutants4040033
55. A. Garcês and I. Pires, *Res. Ecol.,* 6 (2024) 42. doi: 10.30564/re.v6i2.6294
56. E. L. Teuten, J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, A. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. H. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong and Y. Ogata, *Philos. Trans. R. Soc. B: Biol. Sci.,* 364 (2009) 2027. doi: 10.1098/rstb.2008.0284
57. S. Messinetti, S. Mercurio, M. Parolini, M. Sugni and R. Pennati, *Environ. Pollut.,* 237 (2018) 1080. doi: 10.1016/j.envpol.2017.11.030
58. N. Casagrande, C. O. Silva, F. Verones, P. Sobral and G. Martinho, *Environ. Pollut.,* 341 (2024) 122935. doi: 10.1016/j.envpol.2023.122935
59. J. Teampanpong and P. Duengkae, *PeerJ.,* 12 (2024) e17384. doi: 10.7717/peerj.17384
60. C. Chagnon, M. Thiel, J. Antunes, J. L. Ferreira, P. Sobral and N. C. Ory, *Environ. Pollut.,* 243 (2018) 127. doi: 10.1016/j.envpol.2018.08.042
61. P. Farrel and K. Nelson, *Environ. Pollut.,* 177 (2013) 1. doi: 10.1016/j.envpol.2013.01.046
62. O. Setälä, V. Fleming-Lehtinen and M. Lehtiniemi, *Environ. Pollut.,* 185 (2014) 77. doi: 10.1016/j.envpol.2013.10.013
63. D. Hou and D. Rao, *Pak. J. Zool.,* 54 (2022) 2931-2951. doi: 10.17582/journal.pjz/20210820080823
64. R. Sussarellu, M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M. E. J. Pernet, N. Le Goïc, V. Quillien, C. Mingant, Y. Epelboin, C. Corporeau, J. Guyomarch, J. Robbens, I. Paul-Pont, P. Soudant and A. Huvet, *Proc. Natl. Acad. Sci. USA,* 113 (2016) 2430. doi: 10.1073/pnas.1519019113
65. P. Burkhardt-Holm and A. N'Guyen, *Mar. Pollut. Bull.,* 144 (2019) 224. doi: 10.1016/j.marpolbul.2019.04.068
66. A. Werth, S. Kahane-Rapport, J. Potvin, J. Goldbogen and M. Savoca, *Oceans,* 5 (2024) 48. doi: 10.3390/oceans5010004
67. M. Smith, D. C. Love, C. M. Rochman and R. A. Neff, *Environ. Anal. Health Toxicol.,* 35 (2018) e2020004. doi: 10.1007/s40572-018-0206-z
68. E. Thrift, A. Porter, T. S. Galloway, F. G. Coomber and F. Mathews, *Sci. Total Environ.,* 842 (2022) 156679. doi: 10.1016/j.scitotenv.2022.156679
69. T. Wu, X. Shu, C. Wang, W. Li, D. Zhu, J. Wang, Y. Zhang, X. Yang and X. Wang, *Glob. Ecol. Conserv.,* 51 (2024) e02865. doi: 10.1016/j.gecco.2024.e02865

70. A. Bhowmik, G. Saha and S. C. Saha, *Pollutants,* 4 (2024) 490. doi: 10.3390/pollutants4040033
71. N. Zolotova, A. Kosyreva, D. Dzhalilova, N. Fokichev and O. Makarova, *PeerJ.,* 10 (2022) 10. doi: doi.org/10.7717/peerj.13503
72. H.J. Huang, Y. Liu, X. Wang, L. Huang, D. Li, H.-Y. Li and W. Yang, *Ecotoxicol. Environ. Saf.,* 281 (2024) 116628. doi: 10.1016/j.ecoenv.2024.116628
73. L. Gaspar, S. Bartman, G. Coppotelli and J. M. Ross, *Int. J. Mol. Sci.,* 24 (2023) 12308. doi: 10.3390/ijms241512308
74. M. K. Dziobak, A. Fahlman, R. S. Wells, R. Takeshita, C. Smith, A. Gray, J. Weinstein, L. B. Hart, *Plos One,* 19 (2024) 10. doi: 10.1371/journal.pone.0309377
75. A. Moledo, R. Nascimento, M. Ueda, N. Spanghero, N. Sales, M. Fornari, F. C. Perina and A. Carolina, *Marit. Technol. Res.,* 6 (2024). doi: 10.33175/mtr.2024.270722
76. M. Su, S. Gan, R. Gao, C. Du, C. Wei, A. M. Shah and J. Ma, *Biomolecules,* 15 (4) (2025) 462. doi: 10.3390/biom15040462
77. M. Tanveer, N. Mansha, A. Nimra, M. B. Khawar, A. Afzal, H. Afzal, M. Farooq, S. Ehsan, R. Rana and S. Shahzaman, *Environ. Sci. Pollut. Res.,* 30 (2023) 95077. doi: 10.1007/s11356-023-29273-3
78. S. Bhargava, S. S. Chen Lee, L. S. Min Ying, M. L. Neo, S. Lay-Ming Teo and S. Valiyaveettil, *ACS Sustainable Chem. Eng.,* 6(5) (2018) 6932. doi: 10.1021/acssuschemeng.8b00766
79. G.L. Pardee, K.M. Ballare, J.L. Neff, L.Q. Do, D. Ojeda, E.J. Bienenstock, B.J. Brosi, T.H. Grubesic, J.A. Miller, D. Tong and S. Jha, *Land.,* 12 (2023) 362. doi: 10.3390/land12020362
80. C. E. Enyoh, L. Shafea, A. W. Verla, E. N. Verla, Q. Wang, T. Chowdhury and M. Paredes, *Environ. Anal. Health Toxicol.,* 35 (2020) e2020004. doi: 10.5620/eaht.e2020004
81. E. Akat Çömden, M. Yenmiş and B. Çakır, *J. Dev. Biol.,* 11 (2023) 6. doi: 10.3390/jdb11010006
82. M. Wensing, E. Uhde and T. Salthammer*, Sci. Total Environ.,* 339 (2005) 19. doi: 10.1016/j.scitotenv.2004.10.028
83. O. A. Abafe, S. Harrad and M. A.-E. Abdallah, *Environ. Int.,* 186 (2024) 108635. doi: 10.1016/j.envint.2024.108635
84. J.-H. Li, X.-H. Liu, G.-R. Liang, H.-T. Gao, S.-H. Guo, X.-Y. Zhou, D. Xing, T. Zhao and C.-X. Li, *Sci. Total Environ.,* 917 (2024) 170547. doi: 10.1016/j.scitotenv.2024.170547
85. A. Simakova, A. Varenitsina, I. Babkina, Y. Andreeva and Y. Frank, *Entomol. Exp. Appl.,* 172 (2024) 1046-1053. doi: 10.1111/eea.13509
86. A. Sun and W.-X. Wang, *Environ. Health*, 1 (2023) 139. doi: 10.1021/envhealth.3c00053
87. I. Bashir, F. A. Lone, R. A. Bhat, S. A. Mir, Z. A. Dar and S. A. Dar, Concerns and Threats of Contamination on Aquatic Ecosystems, In: *Bioremediat. Biotech*. (K. Hakeem, R. Bhat, H. Qadri, Eds) Springer, Cham (2020) pp. 1-26. doi: 10.1007/978-3-030-35691-0_1
88. M. S. Yee, L. W. Hii, C. K. Looi, W. M. Lim, S. F. Wong, Y. Y. Kok, B. K. Tan, C. Y. Wong and C. O. Leong, *Nanomaterials,* 11 (2021) 496. doi: 10.3390/nano11020496
89. M. Schneider, F. Stracke, S. Hansen and U. F. Schaefer, *Dermatoendocrinol.,* 1 (2009) 197. doi: 10.4161/derm.1.4.9501
90. S. M. Brander, V. C. Renick, M. M. Foley, C. Steele, M. Woo, A. Lusher, S.

Carr, P. Helm, C. Box, S. Cherniak, R. C. Andrews and C. M. Rochman, *Appl. Spectrosc.,* 74 (2020) 1099. doi: 10.1177/0003702820945713

91. W. Cowger, A. Gray, S. H. Christiansen, H. DeFrond, A. D. Deshpande, L. Hemabessiere, E. Lee, L. Mill, K. Munno, B. E. Ossmann, M. Pittroff, C. Rochman, G. Sarau, S. Tarby and S. Primpke, *Appl. Spectrosc.,* 74 (2020) 989. doi: 10.1177/0003702820929064
92. Z. T. R. Abadi, B. Abtahi, H. P. Grossart and S. Khodabandeh, *Sci. Total Environ.,* 752 (2021) 141542. doi: 10.1016/j.scitotenv.2020.141542
93. N. Wootton, P. Reis-Santos and B. M. Gillanders, *Rev. Fish Biol. Fish.,* 31 (2021) 1. doi: 10.1007/s11160-021-09684-6
94. C. De Sales-Ribeiro, Y. Brito-Casillas, A. Fernandez and M. J. Caballero, *Sci. Rep.,* 10 (2020) 12434. doi: 10.1038/s41598-020-69062-3
95. J. Wagner, Z. M. Wang, S. Ghosal, C. Rochman, M. Gassel and S. Wall, *Anal. Methods,* 9 (2017) 1479. doi: 10.1039/c6ay02396g
96. Z. M. Wang, J. Wagner, S. Ghosal, G. Bedi and S. Wall, *Sci. Total Environ.,* 603 (2017) 616. doi: 10.1016/j.scitotenv.2017.06.047
97. F. Hierl, H. C. Wu and H. Westphal, *Environ. Sci. Pollut. Res.,* 28 (2021) 37882. doi: 10.1007/s11356-021-13240-x
98. S. H. Maxwell, K. F. Melinda and G. Matthew, *Environ. Sci. Technol.,* 54 (2020) 5580. doi: 10.1021/acs.est.0c00711
99. J. Li, A. L. Lusher, J. M. Rotchell, S. Deudero, A. Turra, I. L. N. Bråte, C. Sun, M. Shahadat Hossain, Q. Li, P. Kolandhasamy and H. Shi, *Environ. Pollut.,* 244 (2019) 522. doi: 10.1016/j.envpol.2018.10.032
100. J. Reichert, J. Schellenberg, P. Schubert and T. Wilke, *Environ. Pollut.,* 237 (2018) 955. doi: 10.1016/j.envpol.2017.11.006
101. A. Khoironi, S. Anggoro and Sudarno, *IOP Conf. Ser.: Earth Environ. Sci.,* 131 (2018) 012050. doi: 10.1088/1755-1315/131/1/012050
102. M. Haave, A. Gomiero, J. Schönheit, H. Nilsen and A. B. Olsen, *Front. Environ. Sci.,* 9 (2021) 575058. doi: 10.3389/fenvs.2021.575058
103. R. C. Marcelino, R. M. Cardoso, E. L. Domingues, R. V. Gonçalves, G. D. Lima and R. D. Novaes, *Life Sci.,* 295 (2022) 120404. doi: 10.1016/j.lfs.2022.120404
104. S. E. Nelms, J. Barnett, A. Brownlow, N. J. Davison, R. Deaville, T. S. Galloway, P. K. Lindeque, D. Santillo and B. J. Godley, *Sci. Rep.,* 9 (2019) 1075. doi: 10.1038/s41598-018-37428-3
105. S. E. Nelms, T. S. Galloway, B. J. Godley, D. S. Jarvis and P. K. Lindeque, Environ. *Pollut.,* 238 (2018) 999. doi: 10.1016/j.envpol.2018.02.016
106. G. V. B. Ferreira, A. K. S. Justino, L. N. Eduardo, V. Lenoble, V. Fauvelle, N. Schmidt, T. V. Junior, T. Frédou and F. Lucena-Frédou, *Mar. Pollut. Bull.,* 174 (2022) 113309. doi: 10.1016/j.marpolbul.2021.113309
107. K. Schmid, K. O. Winemiller, D. Chelazzi, A. Cincinelli, L. Dei and T. Giarrizzo, *Mar. Pollut. Bull.,* 133 (2018) 814. doi: 10.1016/j.marpolbul.2018.06.035
108. A. M. Wieczorek, L. Morrison, P. L. Croot, A. L. Allcock, E. MacLoughlin, O. Savard, H. Brownlow and T. K. Doyle, *Front. Mar. Sci.,* 5 (2018) 39. doi: 10.3389/fmars.2018.00039
109. J. E. Halstead, J. A. Smith, E. A. Carter, P. A. Lay and E. L. Johnston, *Environ. Pollut.,* 234 (2018) 552.

doi: 10.1016/j.envpol.2017.11.085
110. N. Rianda, F. Armin and A. Djamaan, *IOSR J. Pharm. Biol. Sci.,* 15 (2020) 15. doi: 10.9790/3008-1503051522
111. J. S. Huang, J. B. Koongolla, H. X. Li, L. Lin, Y. F. Pan, S. Liu and X. R. Xu, *Sci. Total Environ.,* 708 (2020) 134839. doi: 10.1016/j.scitotenv.2019.134839
112. E. Uurasjärvi, E. Sainio, O. Setälä, M. Lehtiniemi and A. Koistinen, *Environ. Pollut.,* 288 (2021) 117780. doi: 10.1016/j.envpol.2021.117780
113. A. Winkler, A. Nessi, D. Antonioli, M. Laus, N. Santo, M. Parolini and P. Tremolada, *Environ. Sci. Pollut. Res.,* 27 (2020) 41731. doi: 10.1007/s11356-020-10163-x
114. J. Carlin, C. Craig, S. Little, M. Donnelly, D. Fox, L. Zhai and L. Walters, *Environ. Pollut.,* 264 (2020) 114633. doi: 10.1016/j.envpol.2020.114633
115. A. Teboul, D. M. Orihel, J. F. Provencher, M. C. Drever, L. Wilson and A. L. Harrison, *Mar. Pollut. Bull.,* 171 (2021) 112640. doi: 10.1016/j.marpolbul.2021.112640
116. A. Dilshad, M. Taneez, F. Younas, A. Jabeen, M. T. Rafiq and H. Fatimah, *Environ. Monit. Assess.,* 194 (2022) 511. doi: 10.1007/s10661-022-10171-z
117. M. R. Jung, F. D. Horgen, S. V. Orski, C. V. Rodriguez, K. L. Beers, G. H. Balazs, T. T. Jones, T. M. Work, K. C. Brignac, S.-J. Royer, K. D. Hyrenbach, B. A. Jensen and J. M. Lynch, *Mar. Pollut. Bull.,* 127 (2018) 704. doi: 10.1016/j.marpolbul.2017.12.061
118. L. Di Renzo, G. Mascilongo, M. Berti, T. Bogdanović, E. Listeš, M. Brkljaca, V. Notarstefano, G. Gioacchini, E. Giorgini, V. Olivieri, C. Silvestri, M. Matiddi, N. D'Alterio, N. Ferri and F. Giacinto, *Water Air Soil Pollut.,* 232 (2021) 98. doi: 10.1007/s11270-021-04994-8
119. J. D. Cebuhar, J. Negrete, L. S. R. Pirani, A. L. Picone, M. Proietti, R. M. Romano and S. Botta, *Sci. Total Environ.,* 922 (2024) 171273. doi: 10.1016/j.scitotenv.2024.171273
120. J. J. Samson, Characterization of Microplastics Using Fourier Infrared Spectroscopy, In: *Microplast. Pollut.,* (V. Sivasankar, T. G. Sunitha, Eds) Springer, Cham (2024) pp.129-148. doi: 10.1007/978-3-031-54565-8_6
121. R. Aierken, Y. Zhang, Q. Zeng, L. Yong, J. Qu, H. Tong and L. Zhao, *Animals,* 14 (2024) 641. doi: 10.3390/ani14040641
122. P. Kusch, *Compr. Anal. Chem.,* 75 (2017) 169. doi: 10.1016/bs.coac.2016.10.003
123. K. Matsui, T. Ishimura, M. Mattonai, I. Iwai, A. Watanabe, N. Teramae, H. Ohtani and C. Watanabe, *J. Anal. Appl. Pyrolysis,* 149 (2020) 104834. doi: 10.1016/j.jaap.2020.104834
124. M. Albignac, J. F. Ghiglione, C. Labrune and A. Ter Halle, *Mar. Pollut. Bull.,* 181 (2022) 113882. doi: 10.1016/j.marpolbul.2022.113882
125. G. B. Merrill, L. Hermabessiere, C. M. Rochman and D. P. Nowacek, *Environ. Pollut.,* 335 (2023) 122252. doi: 10.1016/j.envpol.2023.122252
126. S. K. Pal, G. Garcés-Sánchez, M. Kranert and R. Vinu, *J. Anal. Appl. Pyrol.,* 172 (2023) 105996. doi: 10.1016/j.jaap.2023.105996
127. T. N. Falkenhaug (2024). *Effects of microplastic mixture on hatching, mortality and morphometry in early life-stages of Atlantic cod* (Master's Thesis in Environmental Toxicology and Chemistry, NTNU, Trondheim. Norway). doi: 10.1016/j.scitotenv.2021.151909
128. F. Sefiloglu, M. Brits, A. König Kardgar, M.J.M. Velzen, E. Kaldenbach, A. Vethaak, D. Doyle, B. Almroth and

M. Lamoree, *Environ. Sci. Eur.,* 36 (2024) 172.
doi: 10.1186/s12302-024-00987-6

129. S. A. Naidu, V. Ranga Rao and K. J. E. G. Ramu, *Environ. Geochem. Health,* 40 (2018) 1377.
doi: 10.1007/s10653-017-0062-z

130. A. L. Lusher, N. A. Welden, P. Sobral and M. Cole, *Anal. Methods,* 9 (2016) 1346-1360.
doi: 10.1039/C6AY02415G

131. V. Nava, M. L. Frezzotti and B. Leoni, *Appl. Spectrosc.,* 75 (2021) 1341.
doi: 10.1177/00037028211043119

132. W. Huang, M. Chen, B. Song, J. Deng, M. Shen, Q. Chen and J. Liang, *Sci. Total Environ.,* 762 (2021) 143112.
doi: 10.1016/j.scitotenv.2020.143112

133. J. C. Prata, A. L. P. Silva, J. P. da Costa, P. Dias-Pereira, A. Carvalho, A. J. S. Fernandes, F. M. da Costa, A. C. Duarte and T. Rocha-Santos, *Animals,* 12 (2022) 1979.
doi: 10.3390/ani12151979

134. A. Sherlock, K. J. Fernie, K. Munno, J. Provencher and C. Rochman, *Sci. Total Environ.,* 807 (2022) 150453.
doi: 10.1016/j.scitotenv.2021.150453

135. J. R. Hollis, J. L. Lavers and A. L. Bond, *J. Hazard. Mater.,* 476 (2024) 134996.
doi: 10.1016/j.jhazmat.2024.134996

136. S. Upadhyay, P. K. Sharma, K. Dogra, P. Bhattacharya, M. Kumar, V. Tripathi and R. Karmakar, *Groundw. Sustain. Dev.,* 101185 (2024) ??.
doi: 10.1016/j.gsd.2024.101185

137. J. C. Prata, V. Reis, J. P. da Costa, C. Mouneyrac, A. C. Duarte and T. Rocha-Santos, *J. Hazard. Mater.,* 403 (2021) 123660.
doi: 10.1016/j.jhazmat.2020.123660

138. A. C. Vivekanand, S. Mohapatra and V. K. Tyagi, *Chemosphere,* 282 (2021) 131151.
doi: 10.1016/j.chemosphere.2021.131151

139. R. C. Hale, *Anal. Methods,* 9 (2017) 1326.
doi: 10.1039/C7AY90015E

140. Y. Huang, Y. Zhao, J. Wang, M. Zhang, W. Jia and X. Qin, *Environ. Pollut.,* 254 (2019) 112983.
doi: 10.1016/j.envpol.2019.112983

141. J. J. Guo, X. P. Huang, L. Xiang, Y. Z. Wang, Y. W. Li, H. Li, Q. Y. Cai, C. H. Mo and M. H. Wong, *Environ. Int.,* 137 (2020) 105263.
doi: 10.1016/j.envint.2019.105263

142. N. B. Hartmann, T. Hüffer, R. C. Thompson, M. Hassellöv, A. Verschoor and A. E. Daugaard, *Environ. Sci. Technol.,* 53 (2019) 1039.
doi: 10.1021/acs.est.8b05297

143. Z. Huang, B. Hu and H. Wang, *Environ. Chem. Lett.,* 21 (2022) 383.
doi: 10.1039/C6AY02558G

144. W. J. Shim, S. H. Hong and S. E. Eo, *Anal. Methods,* 9 (2017) 1384.
doi: 10.1039/c6ay02558g

145. S. L. Wright, R. C. Thompson and T. S. Galloway, *Environ. Pollut.,* 178 (2013) 483.
doi: 10.1016/j.envpol.2013.02.031

146. L. C. de Sá, M. Oliveira, F. Ribeiro, T. L. Rocha and M. N. Futter, *Sci. Total Environ.,* 645 (2018) 1029.
doi: 10.1016/j.scitotenv.2018.07.207

147. J. D. O'Connor, H. T. Lally, A. M. Mahon, I. O'Connor, R. Nash, J. J. O'Sullivan, M. Bruen, L. Heerey, A. A. Koelmans, F. Marnell and S. Murphy, *Ecosphere,* 13 (2022) e3955.
doi: 10.1002/ecs2.3955

148. P. E. Charles, M. Sathya, R. Rajaram, M. K. Al-Sadoon, A. Gulnaz and B. A. Paray, *Int. J. Environ. Sci. Technol.,* 21 (2024) 4013.
doi: 10.1007/s13762-023-05207-x

149. L. C. Woodall, A. Sanchez-Vidal, M. Canals, G. L. J. Paterson, R. Coppock, V. Sleight, A. Calafat, A. D. Rogers, B. E. Narayanaswamy and R. C. Thompson, *R. Soc. Open Sci.,* 1 (2014) 140317.
doi: 10.1098/rsos.140317

150. O. Bajt, FEBS Open Bio, 11 (2021) 954. doi: 10.1002/2211-5463.13120
151. G. Fackelmann and S. Sommer, *Mar. Pollut. Bull.,* 143 (2019) 193. doi: 10.1016/j.marpolbul.2019.04.030
152. J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady and K. L. Law, *Science,* 347 (2015) 768. doi: 10.1126/science.1260352
153. W. C. Li, H. F. Tse and L. Fok, *Sci. Total Environ.,* 536 (2020) 144. doi: 10.1016/j.scitotenv.2015.05.001
154. D. M. Mitrano and W. Wohlleben, *Nat. Commun.,* 11(1) (2020) 5324. doi: 10.1038/s41467-020-19069-1