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REVIEW

Ecotoxicity of Petrogenic Plastic Particles in Fish: Implication for Human Health and Environmental Risk Assessment

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ABSTRACT

Petrogenic plastics might fragment within the ecosystems into progressively smaller fragments classified by size as “macroplastics”, “mesoplastics”, “microplastics”, and “nanoplastics”. Petrogenic micro and nano plastics (MNPs) are ubiquitous in the ecosystems and form as a result of the ageing or the action of prevailing bio-environmental factors on the plastic materials or direct release of MNPs in the environment. Fish and other aquatic organisms may ingest MNPs from their polluted environment. This review aims to explore the multifaceted interactions between MNPs, other pollutants, and the potential threats to human health. MNPs can translocate from the digestive tract to the kidney, liver, and other body tissues, causing several toxicological effects in fish and other organisms in the food chain. MNPs can induce hepatic and renal toxicity, causing the generation of reactive oxygen species (ROS), as well as carcinogenic, teratogenic, and mutagenic potentials in organisms. MNPs can also act as channels via which contaminants and pollutants such as heavy metals, endocrine disrupting chemicals (EDCs), polycyclic aromatic hydrocarbons (PAHs),

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organophosphate and organochlorine pesticides, etc, might pass to the organisms from different environmental media to organisms in their environment. The ingestion of fish and other contaminated aquatic bio-resources might affect human health via cancer or non-cancer risk effects. MNPs can also impact negatively on the human genetic makeup, inhibit cell viability, induce inflammatory responses, and cause minor morphological alterations. Different equipment is used to detect and characterize MNPs from the environmental matrix.

Keywords: Microplastics; Nanoplastics; Sampling Microplastics; Health Risk; Aquatic Pollution

1. Introduction

The discovery of plastic materials, their potential uses, and subsequent introduction into the anthrosphere in the 1800s [1] has made it an indispensable material that is used in all sectors of human activities, and it affects all areas of daily lives [2-4]. The word “plastics” originates from the Greek words, “πλαστικός” “plastikos” which mean “fit for moulding” and “πλαστός”, “plastos” which simply mean “moulded” [1]. Plastics can be manufactured in different sizes for industrial, agricultural, clinical, or domestic uses [2]. The term plastic is used in regard to the material’s ability to be molded and shaped during manufacturing processes, as well as its capacity to deform without breaking under stress during usage [1,3,4]. Plastics are generally a group of synthetic and semi-synthetic polymers that either originate from fossil fuels (coal, crude oil, natural gas), known as petrogenic plastics, and/or organic products or renewable resources such as starch, grain, cellulose, corn, sugar cane, and vegetable oils, etc., known as biogenic plastics. Currently, in a bid to move from conventional

fossil fuels, technological advancements have enabled the creation of hydrocarbon-based plastics from renewable sources, giving rise to bioplastics [1,4]. Petrogenic plastics are reported to account for over 90% of the total plastic materials in circulation globally, and the aquatic ecosystem is reported to have become the universal disposal site for end-of-life to most of these materials [1,5,6].

Petrogenic plastics are non-biodegradable but can fragment into smaller sizes of different shapes in the environment. The terms “macroplastics, mesoplastics, microplastics, and nanoplastics” are used in relation to the size of the plastic pollutants in the ecosystem. The different size ranges are shown in **Table 1**. Micro and nano plastics (MNPs) are ubiquitous in the ecosystems and form as a result of the ageing or the action of prevailing bio-environmental factors on the plastic materials, which form the secondary source of plastic particles. Plastic materials in micro and nano sizes can also be manufactured for different purposes, and they are a primary source of plastic particles in the ecosystem [1,5].

Table 1. Size Ranges of Plastic Pollutants in the Environment.

Types of Plastic Pollutants	Sizes Range in Nanometre (nm)	Sizes Range in Micrometre (µm)	Size Range in Millimetre (mm)	Size Range in Centimetre (cm)
Macroplastics	>25,000,000	>25,000	>25	>2.5
Mesoplastics	5,000,000–25,000,000	5,000–25,000	5–25	0.5–2.5
Microplastics	100–5,000,000	0.1–5,000	0.0001–5	10 ⁻⁵ –0.5
Nanoplastics	1–100	0.001–0.1	0.000001–0.0001	10 ⁻⁷ –10 ⁻⁵

Source: UNEP [5]; Graham et al. [7].

The pervasive presence of MNPs in aquatic ecosystems has emerged as a significant environmental concern, necessitating a thorough ecotoxicological assessment of their sources, distribution, and implications. Once introduced into surface waters from either the primary or secondary sources, these particles can accumulate and pollute the water and sediments, affecting not only the ecological

balance but also the health of aquatic organisms, particularly fish species that serve as crucial links in the food chain [8-10]. These particles might exert toxicological effects on aquatic organisms, which could ultimately translate to human health risks through bioconcentration via the consumption of contaminated fish and other aquatic bio-resources [11-13]. This review therefore seeks to explore the

multifaceted interactions between MNPs, other pollutants, and the potential threats to human health.

2. Methodology

Peer-reviewed articles were searched from open access repositories platforms (Research Gate, PubMed, and

Google Scholar) using keywords such as microplastics, nanoplastics, health effects of micro and nano plastics, MNPs in surface water, sediments, and fish, and interactions between MNPs and other pollutants. The study excluded non-peer-reviewed reviews and other irrelevant articles. A total of 92 articles were used, as summarized in **Table 2**.

Table 2. Sources, Sampling and Analytical Methods, Ecological Impacts and Human Health Risk of MNPs.

Experimentation/Study Location	Source of MNPs	Sampling and Analytical Technique Employed	Analyzed Bio-Environmental Media	Ecological Impacts	Human Health Risk	References
Global (reviews & policy guidance)	Primary & secondary MPs from fisheries, aquaculture, consumer/litter inputs	Evidence syntheses; collation of monitoring protocols; risk appraisal	Marine & freshwater biota, water, sediments, seafood	Ecosystem-level exposure across trophic levels; food-web transfer; habitat contamination; persistence	Potential exposure via seafood and water; data gaps highlighted for dose-response	Lusher et al. ^[1] ; UNEP ^[5] ; Triebkorn et al. ^[6] ; GESAMP ^[14] ; Andradý ^[15]
Freshwater systems & Great Lakes (reviews/monitoring strategy)	Urban runoff, WWTP effluent, tire wear, fibers	Literature reviews; basin-scale monitoring/QA proposals	Rivers, lakes, sediments, biota	MPs widespread in inland waters; hotspots near population centres	Pathways to drinking water and fish consumption identified; call for health-relevant metrics	Horton et al. ^[3] ; McIlwraith et al. ^[4] ; Dris et al. ^[16] ; Driedger et al. ^[17] ; Eerkes-Medrano et al. ^[18] ; Besseling et al. ^[19]
Modeling transport / source mapping	Floating litter from coasts, shipping, rivers; watershed loads	Oceanographic particle-tracking; geospatial source assessment	Surface waters; catchments	Predicts accumulation zones; informs monitoring design	—	Politikos et al. ^[20] ; Tasneem ^[12]
Inland waters & sediments (occurrence)	Urban/industrial inputs, recreation, rivers	Shore/bed sediments; density separation; stereomicroscopy; FTIR/Raman	River/lake shore sediments; water column	High spatial heterogeneity; proximity to urban areas increases loads	—	Klein et al. ^[21] ; Free et al. ^[22] ; Dai et al. ^[23] ; Zhang et al. ^[9]
Urban/coastal interfaces (mangroves, canals, ports, lagoons)	Urban runoff, boating, ports	Sediment grabs/cores; density separation; microscopy; polymer ID (FTIR/Raman)	Mangrove/lagoon sediments; canal water/biota	Sensitive nursery habitats accumulate MPs; altered benthic conditions	Possible indirect effects via seafood harvested near cities	Mohamed and Obbard ^[24] ; Leslie et al. ^[25] ; Vianello et al. ^[26]
Beaches & strandlines (distribution studies)	Coastal litter inputs & fragmentation	Belt/line transects; sieving; visual counts; particle sizing	Beach surface & high-strandline debris	Size-selective accumulation; indicators for coastal inputs	—	Heo et al. ^[27] ; Lee et al. ^[28]
Fish ingestion—marine & freshwater (field)	Ambient MPs (fibers/fragments) from coastal/oceanic systems	GI tract dissection; density separation; visual sorting; FTIR/Raman confirmation	Wild fish (pelagic/demersal; larvae to adults)	Widespread ingestion; retention varies by ecology/gut morphology; potential sublethal effects	Dietary exposure route to humans via seafood noted	Markic et al. ^[29] ; Kılıç and Yücel ^[30] ; Reboa et al. ^[31] ; Ferreira et al. ^[32] ; Rummel et al. ^[33] ; Foekema et al. ^[34] ; Jabeen et al. ^[35] ; Güven et al. ^[36] ; Biginagwa et al. ^[37] ; Sutton et al. ^[38] ; Steer et al. ^[39] ; Sanchez et al. ^[40] ; Welden and Cowie ^[41] ; Atamanalp et al. ^[10] ; Paul and Ramesh ^[42]

Table 2. Cont.

Experimentation/Study Location	Source of MNPs	Sampling and Analytical Technique Employed	Analyzed Bio-Environmental Media	Ecological Impacts	Human Health Risk	References
Bivalves/mussels & targeted taxa (field + lab behavior)	Ambient MNPs; experimental nanoplastics	Field: digestion + FTIR/Raman; Lab: exposure assays, feeding metrics	Marine mussels & clams; feeding behavior endpoints	Reduced feeding efficiency; tissue accumulation; biomarker responses	Seafood vector highlighted; need for human-relevant doses	Avio et al. ^[111] ; Davidson and Dudas ^[43] ; Wegner et al. ^[44]
Laboratory toxicity—fish and other biota	Polystyrene MNPs/NPs; chemical-loaded MNPs	Controlled exposures; histology; oxidative stress; transcriptomics; enzyme assays	Zebrafish, sea bass, goby; trophic transfer via Artemia	Liver toxicity, intestinal alterations, behavioral changes; trophic transfer of PAHs; prey confusion and reduced predation	Mechanistic evidence (but higher lab doses than environment); relevance to human risk via comparable pathways (oxidative stress, inflammation)	Lu et al. ^[45] ; Batel et al. ^[46] ; Mattsson et al. ^[47] ; Pedà et al. ^[48] ; De Sá et al. ^[49] ; Oliveira et al. ^[50] ; Yin et al. ^[51] ; Iheanacho and Odo ^[52]
Human exposure & effects (reviews, foods, cells)	MNPs/NPs in salt/seafood; airborne deposition; dietary microparticles	Food digestion & filtration; FTIR/Raman; in-vitro cell uptake; narrative reviews	Table salt; seafood; human gastric cell lines	—	Potential ingestion/inhalation; cell internalization; immune/gut-microbiome interactions; uncertain dose–response in humans	Prata et al. ^[53] ; Lai et al. ^[13] ; Karami et al. ^[54] ; Ensign et al. ^[55] ; Salim et al. ^[56] ; Powell et al. ^[57] ; Forte et al. ^[58] ; Rochman et al. ^[59]
Analytical methods & standardization	Environmental MNPs/NPs (method development)	Visual sorting, FTIR, μ -FTIR, Raman/ μ -Raman, Py-GC/MS; SRS microscopy; QA/QC guidance; staining	Particles from water/sediment/biota	Method choice affects ecological inference; need harmonized QA/QC	Accurate exposure assessment underpins health risk evaluation	Hidalgo-Ruz et al. ^[60] ; Wirnkör et al. ^[61] ; Shim et al. ^[62] ; Zada et al. ^[63]
Contaminant vector (POPs & metals on plastics)	MNPs as carriers of POPs (PCBs, PAHs, DDTs) and trace metals	Sorption/desorption experiments; pellet monitoring; GC-MS; metals assays	Plastic pellets, environmental MNPs; ingested plastics (seabirds)	Enhanced bio-availability of hydrophobics; potential point sources to biota and sediments	Indirect risk via contaminated seafood; metals/POPs co-exposure	Frias et al. ^[64] ; Rios et al. ^[65] ; Teuten et al. ^[66] ; Karapanagioti et al. ^[67] ; Hirai et al. ^[68] ; Fisner et al. ^[69] ; Mato et al. ^[70] ; Ogata et al. ^[71] ; Colabuono et al. ^[72] ; Mohsen et al. ^[73] ; Munier and Bendell ^[74]
River-basin scale, Africa (multi-media field study)	Mixed urban, agricultural, industrial sources	Coordinated sampling of water, sediment, fish; density separation; microscopy + polymer ID	River water, sediments, multiple fish species	Basin-wide distribution; differing polymer profiles by compartment	Food-web exposure plausible; local dietary relevance	Graham et al. ^[7]
General ocean–ecosystem interactions & management	Global marine litter (gear, packaging, textiles)	Synthesis of pathways and interventions	Water column, biota, habitats	Interactions across trophic levels; ecosystem function impacts	Source reduction improves seafood safety; management portfolios needed	Galloway et al. ^[75] ; Rochman ^[76]

3. Methods of Sampling, Identification and Characterization of MNPs from the Aquatic Environment

Petrogenic plastics are isolated from bio-environmental media using a variety of methods depending on the targeted size of the plastic pollutant. Nanoplastics might require a combination of density separation, ultracentrifugation, and nano-filtration techniques.

3.1. Methods of Sampling MNPs in Freshwater Environment

Hidalgo-Ruz et al. ^[60] suggest that sampling petrogenic plastic particles within aquatic ecosystems, specifically concerning sediments and the water's surface, can be divided into three categories: selective, bulk, and volume-reduced sampling techniques.

The selective sampling technique entails the direct extraction of plastic materials from the environment. This method is applicable when the particles, such as macro and mesoplastics, are visible to the naked eye. It is particularly effective for collecting sediments found along the shoreline of freshwater bodies ^[60]. The bulk sampling technique involves collecting the entire sample volume without any reduction methods, such as sieving. The bulk sampling technique is utilized in locations where the visual identification of MNPs is challenging and when the sample contains a high concentration of small-sized MNPs, providing a representative understanding of contamination levels ^[60]. Volume-reduced sampling, on the other hand, is a focused approach that targets specific MNPs while discarding other elements present in the environment. This sampling method is advantageous in extensive study areas where bulk sampling may not yield optimal outcomes ^[60].

In bulk water sampling, containers like buckets, drums, or bottles are utilized. In contrast, volume-reduced sampling often involves trawling with nets such as manta nets and plankton nets, as well as using sieves of various sizes either during or after sampling. Primarily, trawling with different types of nets—including manta, neuston, plankton, and bongo nets—is employed in volume-reduced

water sampling. Additionally, some researchers have used pumps combined with sieves featuring mesh sizes ranging from 50–100 μm ^[60]. In bulk water, samples are usually collected using stainless steel buckets, bottles, and various other containers, accompanied by a mesh that has an upper size limit of 2000–5000 μm to prevent larger particles from contaminating the sample. In certain studies, volume reduction has been achieved through the use of sieves of varying sizes following the bulk water sampling; this approach serves a dual purpose: reducing volume and facilitating particle size distribution. The volume of water collected for bulk sampling within freshwater systems lacks standardization, ranging from 5–100 L, and larger volumes yielding more robust and dependable results might be obtained ^[60].

3.2. Methods of Identification and Characterization of MNPs

The process of identifying and characterizing MNPs involves the use of various types of instruments to facilitate the identification and visualization of their shapes, colors, polymers, and other characteristics. For effective visualization of their morphology, such as the shapes and colours of MNPs, different microscopy tools such as standard optical microscopes, fluorescent microscopes, stereomicroscopes, and scanning electron microscopes (SEM) are utilized ^[20,77].

Additionally, the characterization of the polymers is performed through spectroscopic methods such as Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, and pyrolysis-gas chromatography linked with mass spectrometry (Pyr-GC-MS) ^[60–61,64,78]. The polymer types are usually identified by comparing the FT-IR spectra with known spectra. Fourier transform infrared spectroscopy (FT-IR) can only identify MPs with a minimum particle size of 20 μm , while Raman spectroscopy identifies MNPs of particle size smaller than 20 μm ^[61,64,77–79]. Micro-spectroscopy FTIR (μ -FTIR) can detect smaller MPs (20–300 μm) as opposed to just FT-IR alone, which usually has a detection limit of 50–300 μm ^[77]; attenuated total reflectance-FTIR (ATR-FTIR) is capable of identifying thick or opaque MNPs ^[24,62]. Stimulated Raman scattering (SRS) is suitable to characterize MNPs on a low Raman background filter membrane when no pretreatment processes are con-

ducted [63,77] but it is highly cost-effective. As Raman spectroscopy (including micro-Raman spectroscopy (μ -Raman)) can identify extremely small-sized MNPs.

Pyrolysis-gas chromatography linked with mass spectrometry (Pyr-GC-MS) is also used in analyzing the chemical composition and structural properties of higher molecular weight polymers via detecting their thermal degradation products [77]. This can be used to detect both the MNPs polymers, other additives in the MNPs, including the chemicals that might have sorbed or absorbed on their surfaces from the environment [77,79].

4. Sources and Ecological Impacts of MNPs in the Aquatic Ecosystems

The level of concentrations of MNPs in the ecosystem is mainly induced by either fragmentation and weathering of large plastic waste or direct release of primary sourced MNPs into the environment [5,14,15,42]. The occurrence of MNPs in the aquatic ecosystems and in the environment generally, is reported to originate primarily from secondary sources [9,23,42] as shown in Figures 1 and 2.

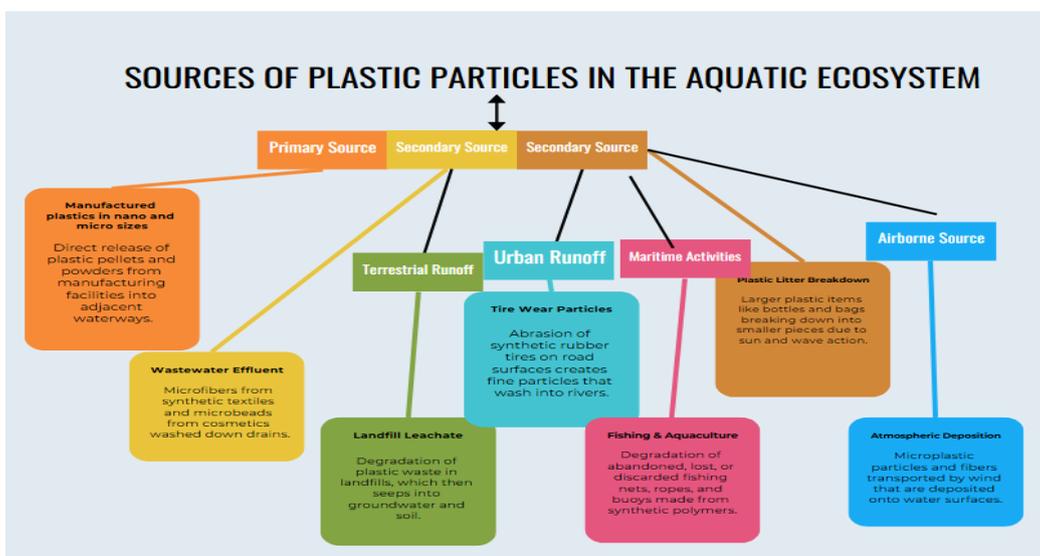


Figure 1. Sources of MNPs in the Aquatic Ecosystems.

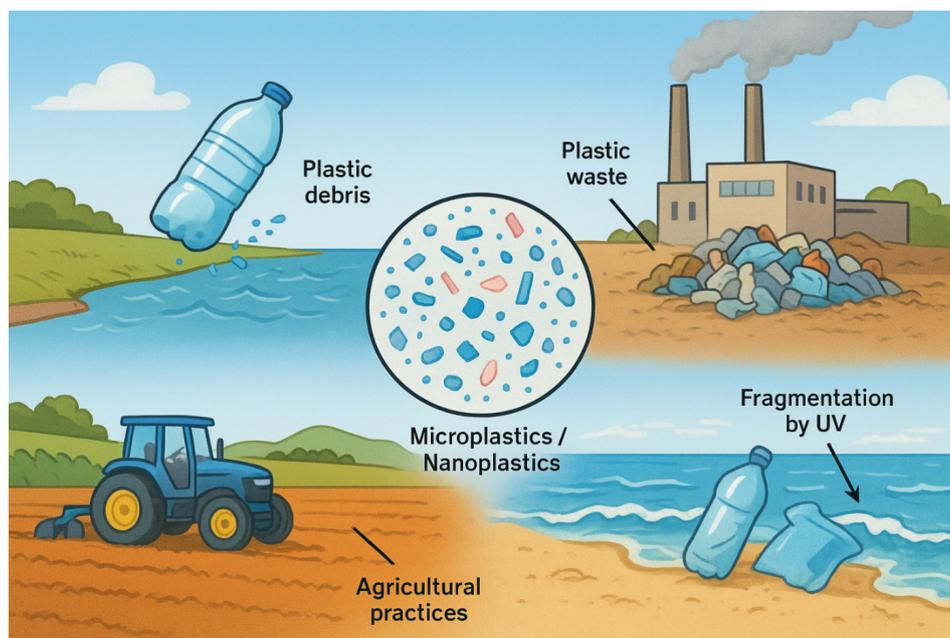


Figure 2. Secondary Source of MNPs in the Environment.

MNPs in the aquatic ecosystems are reported to stay longer in the hydrographic columns, interact more with other pollutants and travel to a more longer distance simply because of their size and their density independent qualities, additionally their behaviour and toxicity do not depend exclusively on their size as other properties of in their bio-environmental factors might also influence their risk ability to exert toxic effect in the environment^[13,15].

MNPs exhibit diverse morphological and chemical characteristics. They might occur in diverse shapes (spheres, fragments, film, fiber, etc.), colour (white, black, red, green, etc.), and polymers compositions (polyethylene—PE, polystyrene—PS, polyamide—PA, polypropylene—PP, polyvinyl chloride—PVC, polyethylene terephthalate—PET, etc.) in the aquatic ecosystems^[12].

The distribution of MNPs in freshwater ecosystems exhibits significant spatial heterogeneity, which leads to the large discrepancies, spanning multiple orders of magnitude, both within and between studies conducted by scholars^[16–19,21,23,24]. Most studies suggest that the sediments show higher concentrations of MNPs than water samples. Surprisingly, in lacustrine environments, MNPs tend to show higher abundance in areas close to urban and industrial centers, but in some riverine ecosystems, this was not always the case, as the river flow dynamics and flooding might affect their abundance^[21]. Furthermore, inadequate waste management, wind action, and effluent discharges from effluent treatment plants (ETP) and water treatment plants (WTP) might also contribute to the abundance of MNPs in relatively isolated freshwater environments^[22]. Paul and Ramesh^[42] reported that the fishing industry itself might also contribute to the global increase in MNPs pollution, as several studies revealed that MNPs analyzed are of similar polymers with the polymers from fishing gears^[9,27,28,43]. Similarly, high concentrations of MNPs were found in sediments at Chioggia in the Venice Lagoon, a major Adriatic Sea fishing hub^[26].

4.1. MNPs Ingestion by Aquatic Organisms

Fish and other aquatic organisms may ingest MNPs from their polluted environment for several reasons; they may mistake these particles as prey or ingest them during filter feeding^[8,10]. Atamanalp et al.^[10] found that levels of MNPs contamination in their analyzed fish are influenced

by multiple bio-ecological factors such as age, ecological niche, and feeding behavior, along with the extent of MNPs contamination in the environment. Markic et al.^[29], on the other hand, particularly reported a higher level of concentration of MNPs and a corresponding higher levels of ingestion rate in the gyre regions, Kılıç and Yücel^[30] reported similar situation in freshwater drainage areas whereas Naidoo et al.^[8] and Reboa et al.^[31] reported a relatively similar trends in a heavily industrialized or urbanized regions porting areas, all these studies revealed a higher levels of concentrations of MNPs compared to a more relatively environmental green areas where there are less anthropogenic activities.

MNPs have been reported to translocate from the gastrointestinal tract to the hepatic tissues of the Flathead grey mullet (*Mugil cephalus*)^[11]. Nevertheless, the concentration of these MNPs within the liver was found to be two orders of magnitude lower than in the associated gastrointestinal tract^[11]. Additionally, MNPs were identified within the gills, liver, and gastrointestinal tract of the Zebra danio (*Danio rerio*), resulting in inflammation, oxidative stress, and disturbances in energy metabolism^[45].

The transfer of MNPs within the food chain refers to the phenomenon whereby a prey organism that harbors MNPs is ingested by a predatory species. Such dietary exposure could potentially account for the presence of petrogenic MNPs in predatory fish species^[46,47]. Mattsson et al.^[47] observed that the behavioral and metabolic repercussions on predatory Crucian carps (*Carassius carassius*) following exposure to pre-contaminated prey, noting a significant decline in their feeding activity. The physiological and behavioural effects of MNPs exposure were manifested in alterations to the gastrointestinal tract, with compromised intestinal functionality being observed in the European seabass (*Dicentrarchus labrax*) after a 90-day exposure period^[48]. The behavior of fish is likewise influenced by exposure to MNPs: the common goby (*Pomatoschistus microps*) exhibited diminished predatory efficacy, atypical swimming patterns, and increased lethargy^[32,49,50]. Rochman et al.^[76,80] and Rochman^[59] used environmentally pertinent levels of MNPs and their related pollutants, revealing that they caused liver damage, hepatic stress, altered endocrine function, and affected gene expression in Japanese medaka (*Oryzias latipes*). Interest-

ingly, a comparable study by Rummel et al. [33] found no negative health impacts associated with MNPs exposure in rainbow trout (*Oncorhynchus mykiss*).

4.1.1. MNPs in Fish Gastrointestinal Tract

Numerous studies have detected MNPs in the gastrointestinal tracts of wild-caught fishes. Most studies are focusing on commercially important species because of the potential effects of these petrogenic plastic particles on the market and risks to human health. Field studies have confirmed the ingestion of MNPs by many commercial fish species from both pelagic and benthic zones [1,33–36,59]. Interestingly, MNPs are detected in fish brought from markets [59], including wild-caught freshwater Nile Tilapia (*Oreochromis niloticus*) from Tanzania's Lake Victoria [37]. Jabeen et al. [35] discovered that all the 27 fish species collected from fish markets in Shanghai exhibited varying levels of MNP contamination. MNPs may be expelled along with feces or may remain in the digestive tract [38,39]. MNPs have been found in the gastrointestinal systems of fish, and smaller freshwater species are sometimes consumed whole, including their digestive tracts, which may pose a health risk to the consuming human population [14,40].

4.1.2. MNPs Bioaccumulation Through Trophic Transfer

A prevalent worry regarding numerous persistent pollutants, particularly petrogenic plastic particles, is the potential for trophic transfer and bioaccumulation. Most ingested environmental pollutants can accumulate in the tissues of organisms and increase in concentration throughout the food chain, resulting in heightened body burdens in organisms at higher trophic levels [41]. MNPs not only translocate into the tissues of their hosts but can also be retained and amplified at higher trophic levels [3,18]. If trophic transfer occurs frequently, animals higher in the food chain may face a greater risk of adverse effects, such as harm to and irritation of the gut lining, as well as decreased nutrient absorption [45,51]. MNPs have been found in large pelagic fish, and it has been suggested that the MNPs present in these species might have originated from the prey they consume rather than from other sources [36,39].

4.1.3. Toxicological Effects of MNPs on Fish

MNPs that accumulate in the gastrointestinal tracts of fish after consumption lead to digestive system blockages and diminished feeding due to a feeling of fullness in the gut [1,27,50]. This situation further results in both structural and functional impairments in the gastrointestinal tracts, subsequently causing nutritional deficiencies and growth issues in fish [48,80]. Once MNPs translocate to other organs of the fish, such as the liver and gills, they may inflict damage on these organs [39,51]. Yin et al. [51] reported that experimental fish after exposure to MNPs show a loss of weight, reduced growth, and gross energy rate. Ingestion of MNPs might trigger inflammatory reactions in fish [45], disrupt metabolic processes [47], and compromise the immune functions in the fish [36]. MNPs can also induce a variety of adverse effects in fish, including decreased energy reserves, hindered reproduction and growth, oxidative harm, disruption of metabolism, and cellular damage [3,18].

The harmful effects of MNPs in fish are defined by the production of reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), superoxide anion ($O_2^{\cdot-}$), peroxy (RO_2^{\cdot}), alkoxy (RO^{\cdot}) and hydroxyl ($\cdot OH$), radicals which induce the oxidation of lipid, protein, Deoxyribonucleic Acid (DNA) and other cellular component [49,52,81]. Iheanacho and Odo [52] reported that MNPs cause the alterations in hematological metrics, with considerable decreases noted in mean cell volume and mean cell hemoglobin levels. Moreover, neutrophil counts were found to be lower, along with significant modifications in glutathione peroxidase activity observed in both the brain and gill. In addition, the activity of superoxide dismutase was suppressed in these tissues, catalase activity in the brain showed a significant decline, and there was a notable rise in lipid peroxidation levels in the brain, which was influenced by both the quantity and duration of exposure.

4.2. Ecological Impact of MNPs in Surface Water Bodies

MNPs have significant ecological impacts on surface water bodies. These impacts are multifaceted, affecting aquatic organisms, ecosystem dynamics, and subsequently human health [82,83]. The ecological impacts and ecotoxicity of MNPs in surface water bodies increase largely due to

their ability to sorb, absorb, and leach heavy metals and other pollutants in the aquatic environment. Their overall ecological impact is as follows:

Ingestion and Toxicity: MNPs are easily ingested by aquatic organisms due to their small size, leading to the accumulation of toxic substances and disruption of physiological functions in these organisms^[78,84]. This ingestion can cause physical damage, suffocation, and starvation in marine life^[78,84].

Ecosystem Disruption: MNPs might disrupt the structure and function of the ecosystems. They might interfere with nutrient cycling and biogeochemical processes, affecting primary producers like phytoplankton, which are crucial for photosynthesis and primary productivity^[16,84]. This disruption can lead to altered food web interactions and may lead to biodiversity loss^[16,84].

Pollutant Transport: MNPs can sorb and absorb harmful pollutants from their environment and act as vectors, transporting these pollutants and other disease vectors through the aquatic systems^[25,85]. They can also leach chemicals, further contaminating water bodies^[25,85].

Habitat Alteration: The presence of MNPs can provide new habitats for invasive species and alter the microbial community structure, leading to changes in ecosystem dynamics^[78,84].

Socio-Economic Effects: The ecological impacts of MNPs may extend to the socio-economic aspects of the environment, affecting fisheries, tourism, and human health due to the contamination of the water and aquatic bio-resource^[16,78,82].

4.3. MNPs Interactions with Other Chemicals in the Ecosystem

4.3.1. Interaction of MNPs with Heavy Metals in the Aquatic Ecosystems

Heavy metals are naturally occurring elements found in the earth's lithosphere and have been recognized and utilized by humans for hundreds of years. They exist in varying concentrations across all ecosystems^[86]. They are defined and characterized as metallic substances that have a density considerably greater than that of water^[87-90]. The presumption that heaviness and toxicity are strongly correlated made metalloids, such as cadmium, chromium, ar-

senic, lead, and mercury, also be regarded as heavy metals, in that they can induce toxicity even at low levels of exposure in the ecosystem^[87,88,91]. Humans can be exposed to heavy metals both from natural and anthropogenic sources. Regardless of the mode and routes of exposure, heavy metals are all toxic in a sufficient concentration to biota in the ecosystem^[88-90].

Heavy metals are sometimes used as additives in the manufacturing processes of plastics for many reasons, such as pigmentation, stabilizers, and resistors^[15]. MNPs additionally interact with heavy metals while in the environment by absorbing, sorbing, or attaching these metals to their surfaces, thereby increasing their bioavailability and their subsequent chances of intake by biota^[73,74,92].

Rochman et al.^[80] studied heavy metal accumulation on MNPs polymers such as PS, PET, PE, PVC, and PP in different locations in the United States of America (USA), and reported relatively high concentrations of heavy metals (Zn, Cd, and Pb) on all the detected polymers. Similarly, Munier and Bendell^[74] studied the different heavy metals sorption and absorption on different MNPs in Canada. They discovered that different polymers of the MNPs had a strong positive affinity with Cd, Cu, Zn, and Pb. Mohsen et al.^[73] studied eight different heavy metals in association with isolated plastic particles from some selected farms in China and discovered different levels of heavy metals (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) associated with MNPs.

4.3.2. Interaction of MNPs with Other Pollutants in the Aquatic Ecosystems

Micro and nano plastics (MNPs) have a large surface area-to-volume ratio, enhancing their sorbent ability for toxic chemicals on their surface. These chemicals may include polycyclic aromatic hydrocarbons (PAHs), endocrine-disrupting chemicals (EDCs), etc. MNPs can act as a medium or channels via which contaminants might pass to organisms from different environmental media, including the aquatic environment^[61]. MNPs can both be hydrophilic and hydrophobic depending on their chemical characteristics. MNPs tend to be hydrophobic in most cases, and their surfaces exhibit minimal polarity. This allows for the hydrophobic (repellent to water or immiscible in water) adsorption of various chemicals from the water column onto their surfaces^[61].

Several studies discovered different concentrations of polycyclic aromatic hydrocarbons (PAHs) associated with MNPs in the aquatic environment^[20,58,60,64,65,77]. These studies further indicate that the petroleum industry might have impacted the availability and concentration of both PAHs and MNPs, and reaffirm that MNPs have a strong positive association with PAHs in the aquatic environment.

Studies further indicate that MNPs also have a relationship with organophosphate (OP) and organochlorine (OC) pesticides, which are synthetic pesticides that belong to the group of chlorinated hydrocarbon derivatives^[67,70–72]. Different concentrations of dichloro-diphenyl-trichloroethane (DDT) and dichlorodiphenyldichloroethane (DDD) were indicated in association with MNPs^[71,77].

4.4. Potential Human Health Risk from the Consumption of MNPs Contaminated Aquatic Bio-Resource

The presence of MNPs in fish and other aquatic bio-resources complicates human exposure, as millions of individuals source their protein from the aquatic bio-resources. The ingestion of fish and other contaminated aquatic bio-resources might affect human health via cancer or non-cancer health risk effects.

Human exposure to MNPs might result in different degrees of toxicity, such as oxidative stress, inflammatory lesions, and increased uptake, which might result in translocation to other body parts like the liver, kidney, etc, which might cause damage to the immune system, and chronic inflammation might result in the risk of neoplasia^[53,77].

The human route of exposure to MNPs is mainly via ingestion of contaminated food sources^[74,77]. Studies reveal that MNPs were detected in some wild-caught and even home-grown fish species, indicating a high possibility of human exposure via consumption of contaminated fish^[1–3,8,9,42,54]. Once ingested, petrogenic MNPs within the human digestive system may be absorbed by specialized M-cells that line the intestinal lymphoid tissues, together with the chemical additives and other absorbed chemicals from the environment. This interaction can lead to an inflammatory response and alter the composition and metabolism of gut microbiota^[55,56,77]. MNPs are also reported to impact negatively on the human genetic makeup, inhibit

cell viability, induce inflammatory responses, and minor morphological alterations^[56,57,77].

The increase in bio-availability of MNPs and other associated environmental persistent pollutants in the aquatic environment might increase the bio-magnification, bio-accumulation, and bio-concentration potentials of both pollutants, thereby increasing their potential health risks. MNPs are associated with chemicals that are known to possess carcinogenic, mutagenic, and teratogenic properties; they act as a vehicle for their movement from their contaminated environment into the body of living organisms^[54–56,77]. MNPs not only absorb or sorb different pollutants onto their surfaces but also desorb and dissociate native inherent chemicals of different degrees into the environment and possibly in the body of living organisms, including humans.

5. Conclusions

Micro- and nanoplastics (MNPs) have emerged as pervasive and persistent contaminants in aquatic ecosystems, originating from both the fragmentation of larger plastic materials and the deliberate production of primary micro- and nano sized plastics for industrial and domestic applications. Their widespread distribution, physicochemical stability, and ability to travel long distances in water bodies highlight their environmental importance and growing global concern. Evidence from multiple studies demonstrates that MNPs occur in various shapes, colours, and polymer compositions, with significant spatial variability influenced by anthropogenic activities, hydrodynamic conditions, waste management practices, and industrial discharges.

The ecological consequences of MNPs are profound. Aquatic organisms, particularly fish, readily ingest MNPs through filter feeding, mistaken identity, or trophic transfer. Once ingested, these particles may accumulate in the gastrointestinal tract, translocate into vital organs such as the liver and gills, and induce numerous physiological and biochemical disturbances. These include inflammation, oxidative stress, reduced feeding efficiency, metabolic disruption, intestinal damage, compromised immunity, and altered behavioural patterns. The generation of reactive oxygen species (ROS) is a major mechanism underlying

MNP-induced cellular toxicity, contributing to lipid peroxidation, DNA damage, enzyme alterations, and disturbances in hematological parameters.

Additionally, MNPs serve as vectors for various environmental pollutants. Their hydrophobic surfaces facilitate the sorption, absorption, and transport of heavy metals, polycyclic aromatic hydrocarbons (PAHs), organophosphate pesticides, and endocrine-disrupting chemicals (EDCs). These interactions not only enhance the environmental persistence of such contaminants but also increase their bioavailability, thereby intensifying ecological and toxicological risks. Heavy metals such as cadmium, lead, chromium, arsenic, and mercury have been documented on different MNP polymers, while PAHs and chlorinated pesticides adhere strongly to plastic surfaces, potentially magnifying the pollutant burden in exposed organisms.

The human health implications of MNP contamination are equally concerning. With numerous studies confirming MNP presence in commercial fish species and fish sold in markets, humans are increasingly exposed to both plastic particles and their associated pollutants through dietary pathways. The ingestion of MNP-contaminated aquatic foods may lead to cancer and non-cancer health risks, endocrine disruption, inflammatory responses, genetic alterations, and compromised cellular viability. While the full extent of human health consequences remains under active scientific investigation, existing evidence underscores a clear cause for precaution and urgent intervention.

The cumulative scientific evidence indicates that MNPs represent a complex, multidimensional environmental threat with significant ecological, toxicological, and public health implications. Addressing this challenge requires a combination of improved waste management practices, stricter regulations on plastic production and disposal, advanced monitoring and detection technologies, and strengthened global policies aimed at minimizing plastic pollution. Continued research is essential to refine our understanding of MNPs behaviour, pollutant interactions, exposure pathways, and long-term risks. Without comprehensive mitigation efforts, the persistence and bioaccumulative potential of MNPs will continue to pose escalating risks to aquatic ecosystems and human populations.

Author Contributions

B.M.N.: writing, original draft preparation, methodology, formal investigation and analysis in the project; G.A.E.: Conceptualization, validation, editing, project administration and supervision; N.A.J.: Conceptualization, validation and supervision; B.T.: Conceptualization, editing, validation and supervision. All authors have read and agreed to the published version of the manuscript.

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References

- [1] Lusher, A., Hollman, P., Mendoza-Hill, J., 2017. Microplastics in Fisheries and Aquaculture: Status of Knowledge on Their Occurrence and Implications for Aquatic Organisms and Food Safety. Food and Agriculture Organization (FAO): Rome, Italy. Available from: <https://openknowledge.fao.org/server/api/core/bitstreams/a9a298e0-9db6-4769-beac-37325be3e280/content>
- [2] Barnes, D.K.A., Galgani, F., Thompson, R.C., et al., 2009. Accumulation and Fragmentation of Plastic Debris in Global Environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 364(1526), 1985–1998. DOI: <https://doi.org/10.1098/rstb.2008.0205>

- [3] Horton, A.A., Walton, A., Spurgeon, D.J., et al., 2017. Microplastics in Freshwater and Terrestrial Environments: Evaluating the Current Understanding to Identify the Knowledge Gaps and Future Research Priorities. *Science of The Total Environment*. 586, 127–141. DOI: <https://doi.org/10.1016/j.scitotenv.2017.01.190>
- [4] McIlwraith, H.K., Hataley, E., Rochman, C.M., 2021. Towards a Management Strategy for Microplastic Pollution in the Laurentian Great Lakes - Monitoring (Part 1). *Canadian Journal of Fisheries and Aquatic Sciences*. 80(10), cjfas-2023-0022. DOI: <https://doi.org/10.1139/cjfas-2023-0022>
- [5] The United Nations Environment Programme (UNEP), 2016. Marine Plastic Debris and Microplastics: Global Lessons and Research to Inspire Action and Guide Policy Change. UNEP: Nairobi, Kenya. Available from: <https://www.unep.org/resources/publication/marine-plastic-debris-and-microplastics-global-lessons-and-research-inspire>
- [6] Triebkorn, R., Braunbeck, T., Grummt, T., et al., 2019. Relevance of Nano- and Microplastics for Freshwater Ecosystems: A Critical Review. *TrAC Trends in Analytical Chemistry*. 110, 375–392. DOI: <https://doi.org/10.1016/j.trac.2018.11.023>
- [7] Graham, P.M., Pattinson, N.B., Bakir, A., et al., 2024. Determination of Microplastics in Sediment, Water, and Fish Across the Orange-Senqu River Basin. *Water Research*. 266, 122394. DOI: <https://doi.org/10.1016/j.watres.2024.122394>
- [8] Naidoo, T., Smit, A., Glassom, D., 2016. Plastic Ingestion by Estuarine Mullet Mugil Cephalus (Mugilidae) in an Urban Harbour, KwaZulu-Natal, South Africa. *African Journal of Marine Science*. 38(1), 145–149. DOI: <https://doi.org/10.2989/1814232X.2016.1159616>
- [9] Zhang, K., Shi, H., Peng, J., et al., 2018. Microplastic Pollution in China's Inland Water Systems: A Review of Findings, Methods, Characteristics, Effects, and Management. *Science of The Total Environment*. 630, 1641–1653. DOI: <https://doi.org/10.1016/j.scitotenv.2018.02.300>
- [10] Atamanalp, M., Köktürk, M., Parlak, V., et al., 2022. A New Record for the Presence of Microplastics in Dominant Fish Species of the Karasu River Erzurum, Turkey. *Environmental Science and Pollution Research*. 29(5), 7866–7876. DOI: <https://doi.org/10.1007/s11356-021-16243-w>
- [11] Avio, C.G., Gorbi, S., Milan, M., et al., 2015. Pollutants Bioavailability and Toxicological Risk from Microplastics to Marine Mussels. *Environmental Pollution*. 198, 211–222. DOI: <https://doi.org/10.1016/j.envpol.2014.12.021>
- [12] Tasneem, A.T., 2021. Assessing the Sources of Microplastic Pollution in the Maumee Watershed: A Geospatial Approach [Master's Thesis]. University of Toledo: Toledo, OH, USA. Available from: https://etd.ohiolink.edu/acprod/odb_etd/ws/send_file/send?accession=toledo1628538423149272&disposition=inline
- [13] Lai, H., Liu, X., Qu, M., 2022. Nanoplastics and Human Health: Hazard Identification and Biointerface. *Nanomaterials*. 12(8), 1298. DOI: <https://doi.org/10.3390/nano12081298>
- [14] The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), 2016. Sources, Fate and Effects of Microplastics in the Marine Environment: Part Two of a Global Assessment. GESAMP: London, UK. Available from: <http://www.gesamp.org/site/assets/files/1275/sources-fate-and-effects-of-microplastics-in-the-marine-environment-part-2-of-a-global-assessment-en.pdf>
- [15] Andrady, A.L., 2015. Persistence of Plastic Litter in the Oceans. In: Bergmann, M., Gutow, L., Klages, M. (Eds.). *Marine Anthropogenic Litter*. Springer International Publishing: Cham, Switzerland. pp. 57–72. DOI: https://doi.org/10.1007/978-3-319-16510-3_3
- [16] Dris, R., Imhof, H., Sanchez, W., et al., 2015. Beyond the Ocean: Contamination of Freshwater Ecosystems with (micro-)plastic Particles. *Environmental Chemistry*. 12(5), 539–550. DOI: <https://doi.org/10.1071/EN14172>
- [17] Driedger, A.G.J., Dürr, H.H., Mitchell, K., et al., 2015. Plastic Debris in the Laurentian Great Lakes: A Review. *Journal of Great Lakes Research*. 41(1), 9–19. DOI: <https://doi.org/10.1016/j.jglr.2014.12.020>
- [18] Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in Freshwater Systems: A Review of the Emerging Threats, Identification of Knowledge Gaps and Prioritisation of Research Needs. *Water Research*. 75, 63–82. DOI: <https://doi.org/10.1016/j.watres.2015.02.012>
- [19] Besseling, E., Quik, J.T.K., Sun, M., et al., 2017. Fate of Nano- and Microplastic in Freshwater Systems: A Modeling Study. *Environmental Pollution*. 220, 540–548. DOI: <https://doi.org/10.1016/j.envpol.2016.10.001>
- [20] Politikos, D.V., Ioakeimidis, C., Papatheodorou, G., et al., 2017. Modeling the Fate and Distribution of Floating Litter Particles in the Aegean Sea (E. Mediterranean). *Frontiers in Marine Science*. 4, 191. DOI: <https://doi.org/10.3389/fmars.2017.00191>
- [21] Klein, S., Worch, E., Knepper, T.P., 2015. Occurrence

- and Spatial Distribution of Microplastics in River Shore Sediments of the Rhine-Main Area in Germany. *Environmental Science & Technology*. 49(10), 6070–6076. DOI: <https://doi.org/10.1021/acs.est.5b00492>
- [22] Free, C.M., Jensen, O.P., Mason, S.A., et al., 2014. High-Levels of Microplastic Pollution in a Large, Remote, Mountain Lake. *Marine Pollution Bulletin*. 85(1), 156–163. DOI: <https://doi.org/10.1016/j.marpolbul.2014.06.001>
- [23] Dai, Z., Zhang, H., Zhou, Q., et al., 2018. Occurrence of Microplastics in the Water Column and Sediment in an Inland Sea Affected by Intensive Anthropogenic Activities. *Environmental Pollution*. 242, 1557–1565. DOI: <https://doi.org/10.1016/j.envpol.2018.07.131>
- [24] Mohamed, N.H.N., Obbard, J.P., 2014. Microplastics in Singapore’s Coastal Mangrove Ecosystems. *Marine Pollution Bulletin*. 79(1–2), 278–283. DOI: <https://doi.org/10.1016/j.marpolbul.2013.11.025>
- [25] Leslie, H.A., Brandsma, S.H., Van Velzen, M.J.M., et al., 2017. Microplastics En Route: Field Measurements in the Dutch River Delta and Amsterdam Canals, Wastewater Treatment Plants, North Sea Sediments and Biota. *Environment International*. 101, 133–142. DOI: <https://doi.org/10.1016/j.envint.2017.01.018>
- [26] Vianello, A., Boldrin, A., Guerriero, P., et al., 2013. Microplastic Particles in Sediments of Lagoon of Venice, Italy: First Observations on Occurrence, Spatial Patterns and Identification. *Estuarine, Coastal and Shelf Science*. 130, 54–61. DOI: <https://doi.org/10.1016/j.ecss.2013.03.022>
- [27] Heo, N.W., Hong, S.H., Han, G.M., et al., 2013. Distribution of Small Plastic Debris in Cross-Section and High Strandline on Heungnam Beach, South Korea. *Ocean Science Journal*. 48(2), 225–233. DOI: <https://doi.org/10.1007/s12601-013-0019-9>
- [28] Lee, J., Lee, J.S., Jang, Y.C., et al., 2015. Distribution and Size Relationships of Plastic Marine Debris on Beaches in South Korea. *Archives of Environmental Contamination and Toxicology*. 69(3), 288–298. DOI: <https://doi.org/10.1007/s00244-015-0208-x>
- [29] Markic, A., Niemand, C., Bridson, J.H., et al., 2018. Double Trouble in the South Pacific Subtropical Gyre: Increased Plastic Ingestion by Fish in the Oceanic Accumulation Zone. *Marine Pollution Bulletin*. 136, 547–564. DOI: <https://doi.org/10.1016/j.marpolbul.2018.09.031>
- [30] Kılıç, E., Yücel, N., 2022. Microplastic Occurrence in the Gastrointestinal Tract and Gill of Bioindicator Fish Species in the Northeastern Mediterranean. *Marine Pollution Bulletin*. 177, 113556. DOI: <https://doi.org/10.1016/j.marpolbul.2022.113556>
- [31] Reboa, A., Cutroneo, L., Consani, S., et al., 2022. Mugilidae Fish as Bioindicator for Monitoring Plastic Pollution: Comparison Between a Commercial Port and a Fishpond (north-Western Mediterranean Sea). *Marine Pollution Bulletin*. 177, 113531. DOI: <https://doi.org/10.1016/j.marpolbul.2022.113531>
- [32] Ferreira, G.V.B., Barletta, M., Lima, A.R.A., et al., 2016. Plastic debris contamination in the life cycle of Acoupa weakfish (*Cynoscion acoupa*) in a tropical estuary. *ICES Journal of Marine Science: Journal du Conseil*. 73(10), 2695–2707. DOI: <https://doi.org/10.1093/icesjms/fsw108>
- [33] Rummel, C.D., Löder, M.G.J., Fricke, N.F., et al., 2016. Plastic Ingestion by Pelagic and Demersal Fish from the North Sea and Baltic Sea. *Marine Pollution Bulletin*. 102(1), 134–141. DOI: <https://doi.org/10.1016/j.marpolbul.2015.11.043>
- [34] Foekema, E.M., De Gruijter, C., Mergia, M.T., et al., 2013. Plastic in North Sea Fish. *Environmental Science & Technology*. 47(15), 8818–8824. DOI: <https://doi.org/10.1021/es400931b>
- [35] Jabeen, K., Su, L., Li, J., et al., 2017. Microplastics and Mesoplastics in Fish from Coastal and Fresh Waters of China. *Environmental Pollution*. 221, 141–149. DOI: <https://doi.org/10.1016/j.envpol.2016.11.055>
- [36] Güven, O., Gökdağ, K., Jovanović, B., et al., 2017. Microplastic Litter Composition of the Turkish Territorial Waters of the Mediterranean Sea, and Its Occurrence in the Gastrointestinal Tract of Fish. *Environmental Pollution*. 223, 286–294. DOI: <https://doi.org/10.1016/j.envpol.2017.01.025>
- [37] Biginagwa, F.J., Mayoma, B.S., Shashoua, Y., et al., 2016. First Evidence of Microplastics in the African Great Lakes: Recovery from Lake Victoria Nile Perch and Nile Tilapia. *Journal of Great Lakes Research*. 42(1), 146–149. DOI: <https://doi.org/10.1016/j.jglr.2015.10.012>
- [38] Sutton, R., Mason, S.A., Stanek, S.K., et al., 2016. Microplastic Contamination in the San Francisco Bay, California, USA. *Marine Pollution Bulletin*. 109(1), 230–235. DOI: <https://doi.org/10.1016/j.marpolbul.2016.05.077>
- [39] Steer, M., Cole, M., Thompson, R.C., et al., 2017. Microplastic Ingestion in Fish Larvae in the Western English Channel. *Environmental Pollution*. 226, 250–259. DOI: <https://doi.org/10.1016/j.envpol.2017.03.062>
- [40] Sanchez, W., Bender, C., Porcher, J.-M., 2014. Wild Gudgeons (*Gobio Gobio*) from French Rivers Are Contaminated by Microplastics: Preliminary

- Study and First Evidence. *Environmental Research*. 128, 98–100. DOI: <https://doi.org/10.1016/j.envres.2013.11.004>
- [41] Welden, N.A.C., Cowie, P.R., 2016. Environment and Gut Morphology Influence Microplastic Retention in Langoustine, *Nephrops Norvegicus*. *Environmental Pollution*. 214, 859–865. DOI: <https://doi.org/10.1016/j.envpol.2016.03.067>
- [42] Paul, D.K., Ramesh, Y., 2022. Microplastic in Inland Water Fish in India: Presence and Fate. *Techno World*. 37–53. Available from: https://www.socialresearchfoundation.com/upoadreserchpapers/4/491/220112044646microplastic%20in%20inland%20water%20fish%20in%20india_%20presence%20and%20fate.docx.pdf
- [43] Davidson, K., Dudas, S.E., 2016. Microplastic Ingestion by Wild and Cultured Manila Clams (*Venerupis Philippinarum*) from Baynes Sound, British Columbia. *Archives of Environmental Contamination and Toxicology*. 71(2), 147–156. DOI: <https://doi.org/10.1007/s00244-016-0286-4>
- [44] Wegner, A., Besseling, E., Foekema, E.M., et al., 2012. Effects of Nanopolystyrene on the Feeding Behavior of the Blue Mussel (*Mytilus Edulis* L.). *Environmental Toxicology and Chemistry*. 31(11), 2490–2497. DOI: <https://doi.org/10.1002/etc.1984>
- [45] Lu, Y., Zhang, Y., Deng, Y., et al., 2016. Uptake and Accumulation of Polystyrene Microplastics in Zebrafish (*Danio Rerio*) and Toxic Effects in Liver. *Environmental Science & Technology*. 50(7), 4054–4060. DOI: <https://doi.org/10.1021/acs.est.6b00183>
- [46] Batel, A., Linti, F., Scherer, M., et al., 2016. Transfer of Benzo[a]pyrene from Microplastics to *Artemia Nauplii* and Further to Zebrafish Via a Trophic Food Web Experiment: CYP1A Induction and Visual Tracking of Persistent Organic Pollutants. *Environmental Toxicology and Chemistry*. 35(7), 1656–1666. DOI: <https://doi.org/10.1002/etc.3361>
- [47] Mattsson, K., Hansson, L.-A., Cedervall, T., 2015. Nano-Plastics in the Aquatic Environment. *Environmental Science: Processes & Impacts*. 17(10), 1712–1721. DOI: <https://doi.org/10.1039/C5EM00227C>
- [48] Pedà, C., Caccamo, L., Fossi, M.C., et al., 2016. Intestinal Alterations in European Sea Bass *Dicentrarchus Labrax* (Linnaeus, 1758) Exposed to Microplastics: Preliminary Results. *Environmental Pollution*. 212, 251–256. DOI: <https://doi.org/10.1016/j.envpol.2016.01.083>
- [49] De Sá, L.C., Luís, L.G., Guilhermino, L., 2015. Effects of Microplastics on Juveniles of the Common Goby (*Pomatoschistus Microps*): Confusion with Prey, Reduction of the Predatory Performance and Efficiency, and Possible Influence of Developmental Conditions. *Environmental Pollution*. 196, 359–362. DOI: <https://doi.org/10.1016/j.envpol.2014.10.026>
- [50] Oliveira, M., Ribeiro, A., Hylland, K., et al., 2013. Single and Combined Effects of Microplastics and Pyrene on Juveniles (0+ Group) of the Common Goby *Pomatoschistus Microps* (Teleostei, Gobiidae). *Ecological Indicators*. 34, 641–647. DOI: <https://doi.org/10.1016/j.ecolind.2013.06.019>
- [51] Yin, L., Chen, B., Xia, B., et al., 2018. Polystyrene Microplastics Alter the Behavior, Energy Reserve and Nutritional Composition of Marine *Jacopever* (*Sebastes Schlegelii*). *Journal of Hazardous Materials*. 360, 97–105. DOI: <https://doi.org/10.1016/j.jhazmat.2018.07.110>
- [52] Iheanacho, S.C., Odo, G.E., 2020. Neurotoxicity, Oxidative Stress Biomarkers and Haematological Responses in African Catfish (*Clarias Gariepinus*) Exposed to Polyvinyl Chloride Microparticles. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*. 232, 108741. DOI: <https://doi.org/10.1016/j.cbpc.2020.108741>
- [53] Prata, J.C., Da Costa, J.P., Lopes, I., et al., 2020. Environmental Exposure to Microplastics: An Overview on Possible Human Health Effects. *Science of The Total Environment*. 702, 134455. DOI: <https://doi.org/10.1016/j.scitotenv.2019.134455>
- [54] Karami, A., Golieskardi, A., Keong Choo, C., et al., 2017. The Presence of Microplastics in Commercial Salts from Different Countries. *Scientific Reports*. 7(1), 46173. DOI: <https://doi.org/10.1038/srep46173>
- [55] Ensign, L.M., Cone, R., Hanes, J., 2012. Oral Drug Delivery with Polymeric Nanoparticles: The Gastrointestinal Mucus Barriers. *Advanced Drug Delivery Reviews*. 64(6), 557–570. DOI: <https://doi.org/10.1016/j.addr.2011.12.009>
- [56] Salim, S.Y., Kaplan, G.G., Madsen, K.L., 2014. Air Pollution Effects on the Gut Microbiota: A Link Between Exposure and Inflammatory Disease. *Gut Microbes*. 5(2), 215–219. DOI: <https://doi.org/10.4161/gmic.27251>
- [57] Powell, J.J., Thoree, V., Pele, L.C., 2007. Dietary Microparticles and Their Impact on Tolerance and Immune Responsiveness of the Gastrointestinal Tract. *British Journal of Nutrition*. 98(S1), S59–S63. DOI: <https://doi.org/10.1017/S0007114507832922>
- [58] Forte, M., Iachetta, G., Tussellino, M., et al., 2016. Polystyrene Nanoparticles Internalization in Human Gastric Adenocarcinoma Cells. *Toxicology in Vitro*. 31, 126–136. DOI: <https://doi.org/10.1016/>

- j.tiv.2015.11.006
- [59] Rochman, C.M., Tahir, A., Williams, S.L., et al., 2015. Anthropogenic Debris in Seafood: Plastic Debris and Fibers from Textiles in Fish and Bivalves Sold for Human Consumption. *Scientific Reports*. 5(1), 14340. DOI: <https://doi.org/10.1038/srep14340>
- [60] Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., et al., 2012. Microplastics in the Marine Environment: A Review of the Methods Used for Identification and Quantification. *Environmental Science & Technology*. 46(6), 3060–3075. DOI: <https://doi.org/10.1021/es2031505>
- [61] Wirnkör, V.A., Ebere, E.C., Ngozi, V.E., 2019. Microplastics, an Emerging Concern: A Review of Analytical Techniques for Detecting and Quantifying Microplastics. *Analytical Methods in Environmental Chemistry Journal*. 2(2), 13–30. DOI: <https://doi.org/10.24200/amecj.v2.i2.57>
- [62] Shim, W.J., Hong, S.H., Eo, S.E., 2017. Identification Methods in Microplastic Analysis: A Review. *Analytical Methods*. 9(9), 1384–1391. DOI: <https://doi.org/10.1039/C6AY02558G>
- [63] Zada, L., Leslie, H.A., Vethaak, A.D., et al., 2018. Fast Microplastics Identification with Stimulated Raman Scattering Microscopy. *Journal of Raman Spectroscopy*. 49(7), 1136–1144. DOI: <https://doi.org/10.1002/jrs.5367>
- [64] Frias, J.P.G.L., Sobral, P., Ferreira, A.M., 2010. Organic Pollutants in Microplastics from Two Beaches of the Portuguese Coast. *Marine Pollution Bulletin*. 60(11), 1988–1992. DOI: <https://doi.org/10.1016/j.marpolbul.2010.07.030>
- [65] Rios, L.M., Moore, C., Jones, P.R., 2007. Persistent Organic Pollutants Carried by Synthetic Polymers in the Ocean Environment. *Marine Pollution Bulletin*. 54(8), 1230–1237. DOI: <https://doi.org/10.1016/j.marpolbul.2007.03.022>
- [66] Teuten, E.L., Rowland, S.J., Galloway, T.S., et al., 2007. Potential for Plastics to Transport Hydrophobic Contaminants. *Environmental Science & Technology*. 41(22), 7759–7764. DOI: <https://doi.org/10.1021/es071737s>
- [67] Karapanagioti, H.K., Siavalas, G., Kalaitzidis, S., et al., 2009. Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in the Gulf of Aliveri. In *Proceedings of the 9th National Greek Symposium on Oceanography and Fishery*, Athens, Greece, 16 April 2009; pp. 251–255.
- [68] Hirai, H., Takada, H., Ogata, Y., et al., 2011. Organic Micropollutants in Marine Plastics Debris from the Open Ocean and Remote and Urban Beaches. *Marine Pollution Bulletin*. 62(8), 1683–1692. DOI: <https://doi.org/10.1016/j.marpolbul.2011.06.004>
- [69] Fisner, M., Taniguchi, S., Moreira, F., et al., 2013. Polycyclic Aromatic Hydrocarbons (PAHs) in Plastic Pellets: Variability in the Concentration and Composition at Different Sediment Depths in a Sandy Beach. *Marine Pollution Bulletin*. 70(1–2), 219–226. DOI: <https://doi.org/10.1016/j.marpolbul.2013.03.008>
- [70] Mato, Y., Isobe, T., Takada, H., et al., 2001. Plastic Resin Pellets as a Transport Medium for Toxic Chemicals in the Marine Environment. *Environmental Science & Technology*. 35(2), 318–324. DOI: <https://doi.org/10.1021/es0010498>
- [71] Ogata, Y., Takada, H., Mizukawa, K., et al., 2009. International Pellet Watch: Global Monitoring of Persistent Organic Pollutants (POPs) in Coastal Waters. 1. Initial Phase Data on PCBs, DDTs, and HCHs. *Marine Pollution Bulletin*. 58(10), 1437–1446. DOI: <https://doi.org/10.1016/j.marpolbul.2009.06.014>
- [72] Colabuono, F.I., Taniguchi, S., Montone, R.C., 2010. Polychlorinated Biphenyls and Organochlorine Pesticides in Plastics Ingested by Seabirds. *Marine Pollution Bulletin*. 60(4), 630–634. DOI: <https://doi.org/10.1016/j.marpolbul.2010.01.018>
- [73] Mohsen, M., Wang, Q., Zhang, L., et al., 2019. Heavy Metals in Sediment, Microplastic and Sea Cucumber *Apostichopus Japonicus* from Farms in China. *Marine Pollution Bulletin*. 143, 42–49. DOI: <https://doi.org/10.1016/j.marpolbul.2019.04.025>
- [74] Munier, B., Bendell, L.I., 2018. Macro and Micro Plastics Sorb and Desorb Metals and Act as a Point Source of Trace Metals to Coastal Ecosystems. *PLOS ONE*. 13(2), e0191759. DOI: <https://doi.org/10.1371/journal.pone.0191759>
- [75] Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of Microplastic Debris Throughout the Marine Ecosystem. *Nature Ecology & Evolution*. 1(5), 0116. DOI: <https://doi.org/10.1038/s41559-017-0116>
- [76] Rochman, C.M., 2016. Strategies for Reducing Ocean Plastic Debris Should Be Diverse and Guided by Science. *Environmental Research Letters*. 11(4), 041001. DOI: <https://doi.org/10.1088/1748-9326/11/4/041001>
- [77] Wu, M., Yang, C., Du, C., et al., 2020. Microplastics in Waters and Soils: Occurrence, Analytical Methods and Ecotoxicological Effects. *Ecotoxicology and Environmental Safety*. 202, 110910. DOI: <https://doi.org/10.1016/j.ecoenv.2020.110910>
- [78] Thushari, G.G.N., Senevirathna, J.D.M., 2020. Plastic Pollution in the Marine Environment. *Heliyon*. 6(8), e04709. DOI: <https://doi.org/10.1016/j.heliyon.2020.e04709>

- [79] Li, J., Song, Y., Cai, Y., 2020. Focus Topics on Microplastics in Soil: Analytical Methods, Occurrence, Transport, and Ecological Risks. *Environmental Pollution*. 257, 113570. DOI: <https://doi.org/10.1016/j.envpol.2019.113570>
- [80] Rochman, C.M., Kurobe, T., Flores, I., et al., 2014. Early Warning Signs of Endocrine Disruption in Adult Fish from the Ingestion of Polyethylene with and Without Sorbed Chemical Pollutants from the Marine Environment. *Science of The Total Environment*. 493, 656–661. DOI: <https://doi.org/10.1016/j.scitotenv.2014.06.051>
- [81] AshaRani, P.V., Low Kah Mun, G., Hande, M.P., et al., 2009. Cytotoxicity and Genotoxicity of Silver Nanoparticles in Human Cells. *ACS Nano*. 3(2), 279–290. DOI: <https://doi.org/10.1021/nn800596w>
- [82] Collard, F., Gilbert, B., Eppe, G., et al., 2015. Detection of Anthropogenic Particles in Fish Stomachs: An Isolation Method Adapted to Identification by Raman Spectroscopy. *Archives of Environmental Contamination and Toxicology*. 69(3), 331–339. DOI: <https://doi.org/10.1007/s00244-015-0221-0>
- [83] Campbell, S.H., Williamson, P.R., Hall, B.D., 2017. Microplastics in the Gastrointestinal Tracts of Fish and the Water from an Urban Prairie Creek. *FACETS*. 2, 395–409. DOI: <https://doi.org/10.1139/facets-2017-0008>
- [84] Amaneesh, C., Balan, S.A., Silpa, P.S., et al., 2023. Gross Negligence: Impacts of Microplastics and Plastic Leachates on Phytoplankton Community and Ecosystem Dynamics. *Environmental Science & Technology*. 57(1), 5–24. DOI: <https://doi.org/10.1021/acs.est.2c05817>
- [85] Issac, M.N., Kandasubramanian, B., 2021. Effect of Microplastics in Water and Aquatic Systems. *Environmental Science and Pollution Research*. 28(16), 19544–19562. DOI: <https://doi.org/10.1007/s11356-021-13184-2>
- [86] Ibrahim, D., Froberg, B., Wolf, A., et al., 2006. Heavy Metal Poisoning: Clinical Presentations and Pathophysiology. *Clinics in Laboratory Medicine*. 26(1), 67–97. DOI: <https://doi.org/10.1016/j.cll.2006.02.003>
- [87] Fergusson, J.E., 1990. *The Heavy Elements: Chemistry, Environmental Impact and Health Effects*. Pergamon Press: Oxford, UK.
- [88] Bwala, M.N., Imam, T.S., 2021. Fish Smoking, Preservation and Socio-Economic Characteristics of Fish Smokers and Traders in Selected Fish Markets in Borno State, Nigeria. *Nigerian Journal of Fisheries*. 18 (2), 2346–2354. Available from: https://www.researchgate.net/publication/359894475_FISH_SMOKING_PRESERVATION_AND_SOCIO-ECONOMIC_CHARACTERISTICS_OF_FISH_SMOKERS_AND_TRADERS_IN_SELECTED_FISH_MARKETS_IN_BORNO_STATE_NIGERIA
- [89] Bwala, M.N., 2021. The Impact of Irrigational Activities on the Abundance and Distribution of Cat Fish (*Clarias gariepinus*) in River Ngadda, Maiduguri, Borno State. *Nigerian Journal of Science & Research*. 2(1), 7–12. Available from: https://www.researchgate.net/publication/353759908_The_Impact_of_Irrigational_Activities_on_the_Abundance_and_Distribution_of_Cat_Fish_Clarias_gariepinus_in_River_Ngadda_Maiduguri_Borno_State
- [90] Bwala, M.N., 2021. Impact of Nonpoint Source Pollutant on Fish Biodiversity in River Ngadda, Maiduguri – Borno State. *Nigerian Journal of Pure & Applied Sciences*. 34(1), 3631–3640. Available from: <https://njpas.com.ng/wp-content/uploads/2021/05/NJPAS-20-B04.pdf>
- [91] Duffus, J.H., 2002. “Heavy metals” a meaningless term? (IUPAC Technical Report). *Pure and Applied Chemistry*. 74(5), 793–807. DOI: <https://doi.org/10.1351/pac200274050793>
- [92] Andrady, A.L., 2011. Microplastics in the Marine Environment. *Marine Pollution Bulletin*. 62(8), 1596–1605. DOI: <https://doi.org/10.1016/j.marpolbul.2011.05.030>