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5. The Silent Crisis of Microplastic Pollution in Our Environment and Its Impact on Living Organisms

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5.1 Introduction:

Plastics have become essential components of our daily life and find extensive applications across various industries owing to their distinctive characteristics, including exceptional durability, portability, ease of manufacturing, cost-effectiveness, as well as their utility in thermal/electrical insulation (Jambeck et al. 2015). Moreover, plastics exhibit resistance to corrosion, shock, water, and chemicals. Plastic consumption has increased four times over the past 30 years, owing to growth in emerging markets. Recently in 2019, 6.1 million tonnes (Mt) of plastic waste entered into aquatic environments and more specifically 1.7 Mt flowed into oceans. Approximately 30 million metric tons of plastic wastes are currently present in seas and oceans, with an additional 109 million metric tons accumulating in rivers (OECD 2023). Deposition and accumulation of plastics in the natural environment has become a global concern of environmental urgency (Ašmonaitė 2019).

Plastics have been recognized as emerging pollutants worldwide and pose a serious threat to our ecosystem due to their ability to accumulate in living organisms causing adverse physiological effects (Wright et al. 2013). Plastic pollutants are found in different sizes in the environment and are classified as macroplastics (>2.5 cm), mesoplastics (2.5 cm to 5 mm) and microplastics (1 μm to 5mm) (Pannetier et al. 2020). Among all the plastic materials of different size ranges, microplastics (MP) research has attracted widespread attention due to their ubiquitous nature, abundance and potential impact on ecosystem (Andrady 2011). MPs are a heterogeneous mixture of particles of various shapes, colours, forms and polymers and have been widely detected in seawater (Peng et al. 2017), freshwater lakes (Anderson et al. 2017) and soils (Zhang and Liu 2018). MPs exposure is a matter of great concern because their ingestion causes physical effects to biota such as mechanical damage and blockage of digestive tract and act as potential vectors for entry of hazardous substances into the aquatic food web including hazardous chemicals, plastic additives and pathogenic microorganisms due to the ability of MPs to attach to other toxic pollutants (Rochman et al. 2013; Wright and Kelly 2017). Furthermore, the properties such as reduced size, hydrophobicity and increased specific surface area/volume ratio also enhance the adsorption capacity of MPs (Wagner et al. 2014). MPs are mistaken as food by many aquatic organisms because their size and colours resemble some algae and microorganisms. Benthic biota also uptake MPs unintentionally while feeding in sediments or ingesting resuspended MPs during bioturbation in sediments.

Due to their smaller size, MPs are ingested and translocated to the circulatory system and accumulated in different tissues of organisms (Browne et al. 2008). MPs have been isolated from the viscera of over 300 species extending from invertebrates to vertebrates including copepods, turtles, fish, mice and birds (Zhao et al. 2018). In recent years, many studies have focused on microplastic debris in coastal areas and marine environment, the studies found that polyethylene, polystyrene and polypropylene, polyvinyl alcohol, polyvinyl chloride are the most abundant MPs and all of these accumulate hydrophobic organic chemicals from sea water (Hermabessiere et al. 2017).

Advances in monitoring and detection methods for microplastics have facilitated a better understanding of their distribution. Techniques such as spectroscopy, microscopy, and chemical analysis are used to identify and quantify microplastics in environmental samples. This chapter delves into the sources, distribution, and effects of microplastics on various organisms, shedding light on the intricate web of interactions between these minuscule particles and the environment.

5.2 Sources, Types and Degradation of Microplastics:

MPs have ability to travel through large distances throughout the world because of their properties such as lightweight, buoyancy, durability, colour and shape. It is also commonly found in the terrestrial environments as a result of daily human activities. Terrestrial ecosystems are regarded as chief sources and transport pathways of MPs into the marine ecosystems (Horton et al. 2017). About 80% of MPs arise from land-based sources and remaining 20% from sea-based sources (Barboza et al. 2019). Majority of the literature has examined the existence of MPs in marine environments and acknowledged that MP pollution in marine environment is derived primarily from inland areas, mostly via rivers and runoff following rain events (Lebreton et al. 2017). High levels of MP discharge in rivers have been detected in areas with intensive anthropogenic activities (such as urban and industrial areas) due to poor waste management (Eriksen et al. 2013, Browne et al. 2011; Wagner et al. 2014). Direct sources of MP pollution involve discharge from wastewater treatment plants, weathering and degradation of plastic debris in water bodies (Medrano et al. 2015), and land input from soil erosion or surface runoff (Horton et al. 2017).

MPs are classified into two categories as primary MPs and secondary MPs on the basis of their origin. Primary MPs are specially produced micro-sized beads and pellets for medical usage (as vectors for various drugs), industrial use (as plastic resins and for air-blasting equipment) and personal-care products (as emulsion stabilizers in cosmetics and cleansers and exfoliating materials) (Cheung and Fok 2017, Horton et al. 2017). After usage, primary MPs are discharged into the aquatic bodies or wastewater treatment plants. Although treatment plants remove 98.41% of MPs and only 0.25 MPs L^{-1} remains in the final effluent, significant number of MPs are still released into freshwater due to a large quantity of effluent discharge daily (Murphy et al. 2016). Approximately 5 kg of primary MPs from personal hygiene and health care products enter into the waste streams that finally make their way in marine environment each year (Alimba and Faggio 2019). Secondary MPs are formed due to breakdown of larger plastic items both at sea and on land (Thompson et al. 2004) due to different degradation or weathering processes occurring in the environment, including mechanical (erosion, wind abrasion, wave action), chemical (photooxidation, corrosion, temperature) and biodegradation activities (microorganisms) which lead to fragmentation of these items into MPs (Andrady 2011; Zettler et al. 2013). Breakdown of MPs may occur before they enter the environment, e.g. synthetic fibres formed by washing of clothes (Browne et al. 2011). Secondary MPs include disposable plastic textiles and microfibers from clothing released during washing processes (Horton et al. 2017). Secondary MPs, which arise as fibres by washing clothes are generally acrylic, polyester, and polyamide may reach above 100 fibres/litre of effluent (Browne et al. 2011). It is considered that the fragmentation of plastic litter in coastal areas is more rapid than in water because plastic degrades mainly by photooxidation which is caused by ultraviolet (UV) radiations coming from the sun and this degradation rate can be accelerated by the elevated temperature and UV radiation on the coastal land as compared to that of the sea surface. Moreover, mechanical and chemical breakdown of plastic litter is increased during saltation in the coastal environment (Corcoran et al. 2009).

Changing degrees of physical forces, such as waves in oceans; environmental conditions, such as sunlight, temperature and pH; and both physical and chemical properties of plastics itself are considered to play a role in degradation of plastics. Plastics present in freshwater ecosystems also undergo physical and environmental degradation regardless of milder physical forces than in marine ecosystems (Andrady 2011). Surface features can explain whether plastic litter undergo mechanical degradation, such as from the wave action; sand friction; oxidative weathering, such as from the exposure to UV-B (Zbyszewski et al. 2014); or biological degradation, such as by the action of microorganisms that degrade hydrocarbons (Zettler et al. 2013). Recognizing the degradation patterns of plastics in various environments is essential as this can disclose how particles interrelate with the environment and how different factors influence their stability, transport, fate, and specify potential effects to organisms (Ballent et al. 2016). The polymer type and its concentration can be used to relate MPs with their origin. For instance, MPs found in the Great Lakes of North America were similar in shape, size, colour, and basic composition to those found in facial cleansers (Eriksen et al. 2013).

Simultaneously, MP particles present in the effluent of a wastewater treatment plant were identical in shape, size, and colour, to those found in toothpaste formulations, indicating that the plastic particles present in personal care products may be amongst the sources of MP pollution in freshwater environments (Carr et al. 2016). MPs greatly differ in shape: from identical microspheres to roughly shaped plastic fragments, microscopic films, fibres and filaments. Primary MPs are regular in shape and have comparatively consistent morphology, whereas secondary MPs are usually uneven and varied in shape. Primary MPs represent a small part of all MPs found in the natural environment and their global importance in context to plastic pollution is low as it is overshadowed by the occurrence of secondary MPs.

5.3 Ecological and Health Risks Associated with Microplastics:

This section delves into the broader ecological and health risks associated with microplastic pollution. Discussions include the persistence of microplastics in the environment, their potential to act as vectors for pollutants, and the cascading effects on biodiversity and ecosystem services.

5.3.1 Effects on Aquatic Organisms:

Aquatic organisms, being living in extensive water environments, are exposed to MPs, either directly or indirectly. Direct exposure is when contaminants (like MPs) come in direct contact with organisms by means of air, soil, or water. On the other hand, indirect exposure is when contaminants (like MPs) are toxic to organisms via food chain or in combination with other compounds. In general, direct exposure can bring about short-range acute toxicity, while indirect exposure can bring about chronic organ toxicity. MPs are exposed to aquatic organisms by different processes (subcutaneous, transdermal, intravenous, intraperitoneal, inhalation and oral) and finally accumulate in their tissues and organs. The detrimental effects of microplastics on marine life are highlighted, covering various species from plankton to large marine mammals.

The initial examination by Peda et al. (2016) delved into the intestinal reactions resulting from prolonged ingestion of microplastics (MPs) for 90 days, in European sea bass (*Dicentrarchus labrax*). Fish were exposed to three distinct diets: a control diet containing 0% PVC, a diet with native PVC, and a diet with polluted PVC pellets, each comprising 0.1% (w/w) PVC. Histopathological assessments of intestinal samples revealed that the presence of MPs led to both structural and functional alterations like weakening of intestine, mainly in the distal part, with regular pathological changes varying from moderate to critical associated to exposure times. The severe histological picture and decrease in the perivisceral fat was observed in some fish of both PVC-exposed groups mainly after 90 days of exposure, suggesting reduced and totally compromised intestinal functions in some cases. Choi et al. (2018) compared the effects of spherical and irregular shaped MPs on changes in swimming behaviours, organ distribution, enzyme activities and gene expression in marine teleost, sheepshead minnow (*Cyprino donvariegatus*) larvae exposed to 50mg/L and

250mg/L of both types of MPs for 4 days. Both types of MPs were accumulated in the digestive tract, causing distention of intestine. However, irregular MPs caused decrease in swimming behaviour of fish as compared to spherical MPs and produced cellular reactive oxygen species (ROS), though molecular changes. Study of Jacob et al. (2019), for the first time, discovered the effects of exposure of polystyrene on the foraging activity and survival of post-larvae of coral-reef fish (*Acanthurus triostegus*). They found that larvae under metamorphosis, when exposed to PS MPs in concentration of 5 MP particles per mL for 3, 5 and 8 days did not have any effect on their foraging activity and their vulnerability to predation even ingestion of 1.7 ± 1.33 MP per fish was confirmed after 8 days exposure.

Espinosa et al. (2019) found that dietary exposure to 100 or 500 mg/kg diet of 40-150 μm PE- or PVC-MPs for 3 weeks affected European sea bass, suggesting histopathological changes in the intestine and liver ranging from medium to severe depending upon the kind and concentration of MPs, while altering the immune parameters and the redox status. PE-MPs, but not PVC-MPs, reduced the activity of antioxidant enzymes (SOD and CAT), at a functional level, which suggests a particular level of oxidative stress. However, activity of GR was not affected by exposure to both MPs. Considering immunity, the ingestion of PVC-MPs enhanced the phagocytic and respiratory burst activities of head-kidney leucocytes while the ingestion of PE-MPs enhanced the immunoglobulin M levels of skin mucus and respiratory burst activity of leucocytes.

These results propose that the short-medium term ingestion of PE- or PVC MPs by fish reduces their immunity to some extent and produces oxidative stress. Karami et al. (2017) designed a study to evaluate the effects of MPs on the total length, body weight, condition factor, antioxidant transcriptional level, anti and pro-apoptotic, and neurotransmitter genes, and histopathology of the brain, gill, intestine, liver and kidney in the zebrafish (*Danio rerio*) larvae.

They exposed fish larvae to virgin low-density polyethylene (LDPE) fragments in concentrations of 5, 50, or 500 mg/L for 10 and 20 days. Alterations in any of the selected biomarkers were not observed across all MPs concentrations at 10 or 20 days. Thus, this study indicated that short-term exposure to virgin LDPE fragments has negligible impact on biomarker responses in zebrafish larvae.

Jabeen et al. (2018) showed that uptake and ingestion of MPs by fish depends on the size and shape of MPs. They conducted experiments in which goldfish (*Carassius auratus*) were exposed through diet to three types of virgin MPs with shapes including fragments, fibers and pellets for six weeks. No mortality was observed after exposure period. MP fibers were found in the gills, alimentary canal, and faeces of fish. Fibers caused breakage of gill filaments due to their direct contact with gills of fish and remarkable changes in liver and intestine were also noticed indicating the oral and respiratory route of MP entry. Chisada et al. (2019) designed their study to explain the effects of PE microbeads on the growth and fecundity of medaka fish after long-term exposure of 12 weeks. Fish exposed to PE microbeads at dose of 0.065 mg/L and 0.65 mg/L showed that low dose did not affect growth of fish but high dose did. Exposure to both doses decreased the egg number and hatching rate in fish. Differences in growth were first identified at 7 weeks, and differences in the egg number at 12 weeks.

Mak et al. (2019) studied the acute toxic effects caused due to exposure of HDPE MPs in adult zebrafish. Fish were exposed via feed to a concentration of 2mg/L of individual HDPE MPs in five size ranges i.e. 10–22 μm, 45–53 μm, 90–106 μm, 212–250 μm, and 500–600 μm for 96 hours. In parallel, a mixture of MPs (made as plastic stock solution) of three size ranges (45–53 μm [blue], 90–106 μm [green], and 212–250 μm [clear] in diameter) at high (1,100 particles/L), moderate (110 particles/L) and effluent-related (11particles/L) concentrations were applied via feed to separate fish groups for 96 hours to study the behavioural changes and targeted gene expression profiles. The results indicated that the higher and lower size boundaries for MPs to be ingested by fish were 558.4 ± 26.2 μm and 19.7 ± 3.1 μm respectively. In addition, 61 ± 10% of fish, each in moderate and in high concentration treatments were found to ingest MPs which remained in their intestine, some amount was egested out also. Also, 28 ± 10% of fish in high concentration treatments were found with MPs retained in their gills. Finally, abnormal behaviour (including tightening of pectoral and caudal fins, seizures, erratic movement, and tail bent upward or downward) was observed indicating neurotoxicity in fish exposed to moderate and high concentrations of MPs. Malafaia et al. (2019) conducted a study with the aim to assess the toxicity of PE MPs during the development of *Danio rerio* by exposing the fish embryos and larvae to different concentrations of MPs i.e. 6.2, 12.5, 25, 50 and 100 mg/L under static and semi-static conditions. PE MPs had harmful effect on hatching rate of embryos in both exposure systems. Conversely, larvae exposed to PE MPs, mainly in groups of 50 and 100 mg/L MPs concentrations, represented more significant changes in various morphometric parameters and higher rates of teratogenic abnormality, and this result suggested the sublethal effect of MPs exposure.

Hamed et al. (2019) conducted experiments to study the effect of MPs on blood biomarkers of early juveniles of Nile Tilapia (*Oreochromis niloticus*). They divided fish into four groups: first served as control with no MPs and rest three groups contained fish exposed to 1 mg/L, 10 mg/L and 100 mg/L of MPs respectively for 15 days after which recovery of fish was allowed for next 15 days. After exposure period, MPs in higher amounts were found in the body of fish. Significant increase in biochemical parameters (uric acid, creatinine, ALT, AST, ALP, cholesterol, glucose, total protein, albumin, globulin and A/G ratio) was observed in dose dependent manner after exposure to MPs. The hematological indices (Hb, Ht, MCHC, RBC's count, WBC's count, monocytes and platelets) showed a significant drop after exposure to MPs, whereas MCH and MCV showed a significant rise after exposure to MPs. Study conducted by Hoang and Felix-Kim (2020) investigated that consumption and excretion of MPs by fish depends on particle size of MPs and body shape of fish. In their experiment, larval fathead minnow (*Pimephales promelas*) exposed to PE microbeads of two size ranges i.e. 63-75 µm and 125-150 µm consumed considerable amount of both sized MPs after 1 hour. For the first time, this study demonstrated that fish with bent bodies, took longer time to excrete PE microbeads than fish with regular straight bodies. Naidoo and Glassom (2019) took Glassfish (*Ambassis dussumieri*) to explore the effects caused by ingestion of MPs at environmentally relevant concentrations on growth and survival of juvenile fish. Small juvenile fish were fed daily with virgin plastic and plastic gathered from an urban harbour along with tropical flake food for 95 days. The growth of body length and body depth of fish was less in both plastic treatments as compared to those of control treatments. The survival probability of fish was lower in both plastic treatments as compared to fish in controls.

Zhu et al. (2019) investigated the effects of PS-MPs on develoing stages of outbred and see-through Japanese medaka (*Oryziaslatipes*) fish. During their maturation, fish were provided with food containing 500, 1000 or 2000 µg/g of 10µm fluorescent spherical PS-MPs for 10 weeks. No mortalities, change in behaviour and growth was observed. But histological analysis revealed changes in buccal cavity, spleen and kidney. In head gut and pharynx, thickening and roughening ofepithelium was observed. In spleen, alterations at cellular level occurred. Head kidney was found to be the main site of alteration. Nephrogenesis and glomerulopathy were observed in exposed fish but these became more severe with increase in exposure level of MPs. Zhao et al. (2020) performed experiments in which adult male zebrafish were exposed to 5 μm PS MPs in concentrations of 20 and 100 μg/L for 21 days. A significant decrease in the transcription levels of main genes linked to glycolipid metabolism was observed in the liver. Correspondingly, decrease in the levels of main biochemical parameters, including pyruvic acid, α-ketoglutaric acid, Glu, and IDH, was also observed in the livers of exposed fish, mainly in group exposed to 100 μg/L MPs. Overall data confirmed that exposure to PS-MPs for 21 days caused glycolipid metabolism disorder in the liver of zebrafish at the physiological, biochemical, and transcriptomic levels.

Yang et al. (2020) compared the toxicity of micron-sized MPs and nano-sized MPs to Goldfish larvae by exposing fish to 70 nm and 5 μm PS-MPs at concentrations of 10, 100 and 1000 μg/L for 1, 3 and 7 days. Results showed accumulation of both types in the alimentary canal of larvae and further high concentrations of MPs induced oxidative stress, damage gills, intestine and liver tissues, elevate heart rate, and reduce growth and swimming speed of fish larvae. Nano-sized MPs were found to be more toxic to larval movement as they penetrate into the muscle tissue via epidermis layer and cause damage to muscle tissue, nerve fibres, reduce acetylcholinase activity. Pannetier et al. (2020) investigated the behavioral and physiological effects caused due to consumption of environmental MPs by Japanese Medaka fish at different life stages. MP samples gathered from beaches on three islands (Guam, Hawaii and Easter Island) were given to larvae and juveniles of fish at three doses i.e. 0.01, 0.1 and 1% w/w in fish feed for 30 days near to the concentrations measured in moderately and heavily contaminated ocean areas. The results indicated that MPs ingestion caused death, decreased head to body ratios and changed the swimming behaviour in larvae of fish. Other harmful effects such as damage to DNA may be due to bioavailability of sorbed pollutants and/or plastic additives to fish larvae after ingestion of MPs. The authors conclude that the toxic effect of MPs differs from one sample to another, depending on composition, contamination and life story of the plastic polymer.

To evaluate the possible toxic effects of PVC-MPs in fish larvae of *Cyprinus carpio* var., Xia et al. (2020) conducted a chronic 30 and 60-day dietary exposure experiment in which fish larvae were exposed to different concentrations of MPs (10%, 20% and 30% by weight) in their diet. Results showed that MPs reduced the gain in body weight and growth of body length in all treatments of MPs exposure. An inverse relationship between activities of SOD (superoxide dismutase) and CAT (catalase) was observed.

The activities of GPx (glutathione peroxidase) seemed to be first increasing then decreasing with the increase in concentration of MPs after 30-day exposure and it displayed a fall after 60 days of exposure in a dose-dependent manner. The levels of MDA (malondialdehyde) were significantly decreased in various tissues on exposure to different concentrations of MPs. In liver, change in antioxidant-related gene expression was detected. Initially, transcription of CYP1A and GSTa increased and then decreased with the increasing concentration of MPs after 30-day exposure. Additionally, histological examination of the liver revealed inflammatory cell infiltration, cytoplasmic vacuolation and nuclear disappearance by exposure of 20% and 30% PVC-MPs.

Hamed et al. (2020) conducted a study to evaluate the effects of MPs on response to oxidative stress, DNA damage and protein profile of Nile Tilapia (*Oreochromis niloticus*) early juveniles. The fishes were divided into four groups: one served as control (no MPs) and other three as MPs-treated groups of concentrations- 1 mg/L, 10 mg/L and 100 mg/L of MPs respectively for 15 days and 15 days of recovery. The activities of oxidative stress enzymes such as catalase, superoxide dismutase, total peroxides, oxidative stress index, lipid peroxidation and DNA damage increased in a dose-dependent manner in all MPs-treated groups as compared to control group. In contrary, the activity of total antioxidant capacity decreased in a dose-dependent manner in all MPs-treated groups as compared to control group. The electrophoretic pattern of the muscle proteins also showed variation in the proteinogram of the MPs-treated groups as compared to control group. After the recovery period, the activities of catalase, superoxide dismutase, total peroxides, lipid peroxidation, total antioxidant capacity, DNA damage and the electrophoretic pattern of the muscle proteins restored to normal levels only in 1 mg/L of MPs-treated group. The results suggest that MPs cause the excess production of reactive oxygen species and changes the antioxidants parameters which results in oxidative stress and DNA damage.

5.3.2 Effect on Terrestrial Organisms:

While microplastics are often associated with aquatic environments, their influence on terrestrial ecosystems is increasingly recognized. A number of reports highlight the effects on soil-dwelling organisms, invertebrates and potential implications for human health. Microplastics can accumulate in soils through various sources, including the breakdown of larger plastic debris and the application of plastic-based mulches in agriculture. Microplastics are more abundant in topsoils than in deep soil which constitutes that habitat of the earthworms which are the primary soil fauna. Research by Huerta Lwanga et al. (2016) demonstrated that microplastics are ingested by earthworms, a crucial component of soil ecosystems, leading to alterations in their physiology and behaviour. The presence of microplastics in soil also raises concerns about their potential transfer through the food chain. Recent studies have investigated the impact of microplastics on plant health and growth. Hu et al (2020) found that the presence of microplastics in soil can interfere with the germination of seeds and affect the overall growth of several plant species. The mechanisms behind these effects include altered nutrient availability and microbial communities in the rhizosphere. Terrestrial wildlife, including insects and small mammals, may be exposed to microplastics through ingestion or contact with contaminated environments. A study by Rillig et al. (2017) demonstrated that microplastics alter the behaviour of soil-dwelling insects, affecting their feeding patterns and overall ecological interactions. The potential for microplastics to accumulate toxic substances and act as vectors for chemical pollutants has raised concerns about their impact on higher trophic levels. A study by de Souza Machado et al. (2018) found evidence of biomagnification of microplastics and associated contaminants in the tissues of soil invertebrates, emphasizing the potential for widespread ecological consequences.

Studies on rats have demonstrated the ingestion of microplastics and their subsequent accumulation in various tissues. Jin et al. (2018) found that ingested microplastics could translocate to the liver and negatively influence lipid metabolism in rats, suggesting potential metabolic disruptions. Research by Li et al. (2019) indicated that the presence of microplastics in the gastrointestinal tract of rats could lead to inflammation and alterations in gut microbiota composition, highlighting potential implications for digestive health. Some studies have raised concerns about the potential toxicity of microplastics and their additives. Bouwmeester et al. (2015) explored the release of additives from microplastics and their potential impact on human health, emphasizing the need for comprehensive risk assessments. Human exposure to microplastics has been primarily linked to the ingestion of contaminated food and water. Catarino et al. (2018) reviewed the presence of microplastics in various food items, emphasizing the need for further research to assess the potential health risks associated with human consumption. Emerging research has focused on the detection of microplastics in human tissues. Schwabl et al. (2019) identified microplastic particles in human stool samples, raising questions about the extent of microplastic translocation and accumulation within the human body.

In conclusion, the growing body of research on the impact of microplastics on living organisms highlights the need for comprehensive strategies to mitigate their effects. Understanding the mechanisms of microplastic interactions with soil, plants, invertebrates, vertebrates and wildlife is crucial for developing informed policies and practices that safeguard our ecosystems from the detrimental consequences of microplastic pollution. Further interdisciplinary research is warranted to unravel the complexities of microplastic dynamics in the environment and their broader implications for ecosystem health and biodiversity. This chapter aims to contribute to the growing body of knowledge surrounding microplastic pollution and fostering a deeper understanding of its multifaceted impact on living beings and the environment.

5.4 References:

1. Alimba CG, Faggio C (2019) Microplastics in the marine environment: current trends in environmental pollution and mechanisms of toxicological profile. Environ Toxicol Pharmacol 68: 61-74.
2. Anderson PJ, Warrack S, Langen V et al (2017) Microplastic contamination in Lake Winnipeg, Canada. Environ Pollut 225: 223-231.
3. Andrady AL (2011) Microplastics in the marine environment. Marine Pollution Bulletin 62 (8): 1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030
4. Ašmonaitė G (2019) Microplastics in the Aquatic Environment: Insights into Biological Fate and Effects in Fish. Ph. D dissertation, University of Gothenburg, Sweden.

5. Ballent A, Corcoran PL, Madden O, Helm PA, Longstaffe FJ (2016) Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. Mar Pollut Bull 110.1: 383-395.
6. Barboza LGA, Cózar A, Gimenez BCG, Lima Barros T, Kershaw PJ, Guilhermino L (2019) Macroplastics pollution in the marine environment. In: C. Sheppard (ed.). World Seas: An environmental evaluation. Volume III: Ecological issues and environmental impacts. Second edition. Academic Press. pp. 305-328. doi: 10.1016/B978-0-12-805052-1.00019-X
7. Bouwmeester H, Hollman PC, Peters RJ (2015) Potential health impact of environmentally released micro-and nanoplastics in the human food production chain: Experiences from nanotoxicology. Env Sci Tech 49(15): 8932–8947.
8. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, Thompson R (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ SciTechnol 45: 9175-9179.
9. Browne MA, Dissanayake A, Galloway TS, Lowe DM, Thompson RC (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilusedulis* (L.). Environ SciTechnol 42: 5026-5031.
10. Carr SA, Liu J, Tesoro A G (2016) Transport and fate of microplastic particles in wastewater treatment plants. Water Res 91: 174-182.
11. Catarino AI, Macchia V, Sanderson WG, Thompson RC (2018) Ingestion of microplastics by natural zooplankton groups in the northern South China Sea. Mar Pollut Bull 136: 334–341.
12. Cheung PK, Fok L (2016) Evidence of microbeads from personal care product contaminating the sea. Mar Pollut Bull 109(1): 582-585.
13. Chisada S, Yoshida M, Karita K (2019) Ingestion of polyethylene microbeads affects the growth and reproduction of medaka, *Oryzia slatipes*. Environ Pollut 254 (Part B): 113094.
14. Choi JS, Jung Y, Hong N, Hong SH, Park J (2018) Toxicological effects of irregularly shaped and spherical microplastics in a marine teleost, the sheepshead minnow (*Cyprino donvariegatus*). Mar Pollut Bull 129: 231-240.
15. Corcoran PL, Biesinger MC, Grifi M (2009) Plastics and beaches: a degrading relationship. Mar Pollut Bull 58: 80-84.

16. de Souza Machado AA, Kloas W, Zarfl C, Hempel S, Rillig MC (2018) Microplastics as an emerging threat to terrestrial ecosystems. Glob Change Biol 24(4): 1405–1416.
17. Eriksen M, Mason S, Wilson S, Box C, Zellers A, Edwards W, Farley H, Amato S (2013) Microplastic pollution in the surface waters of the Laurentian great lakes. Mar Pollut Bull 77(1-2): 177-82.
18. Espinosa C, Esteban MÁ, Cuesta A (2019) Dietary administration of PVC and PE microplastics produces histological damage, oxidative stress and immunoregulation in European sea bass (*Dicentrarchuslabrax* L.). Fish Shellfish Immuno 95: 574-583. https://doi.org/10.1016/j.fsi.2019.10.072
19. Hamed M, Soliman HAM, Osman AGM, Sayed AEH (2019) Assessment the effect of exposure to microplastics in Nile Tilapia (*Oreochromis niloticus*) early juvenile: I. blood biomarkers. Chemosphere 228: 345-350.
20. Hamed M, Soliman HAM, Osman AGM, Sayed AEH (2020) Antioxidants and molecular damage in Nile Tilapia (*Oreochromis niloticus*) after exposure to microplastics. Environ Sci Pollut Res 27: 14581-14588.
21. Hermabessiere L, Dehaut A, Paul-Pont I, Lacroix C, Jezequel R, Soudant P, Duflos G (2017) Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 128: 781-793.
22. Hoang TC, Felix-Kim M (2020) Microplastic consumption and excretion by fathead minnows (*Pimephales promelas*): Influence of particles size and body shape of fish. Sci Total Environ 704: 135433.
23. Horton AA, Waltona A, Spurgeon D J, Lahive E, Svendsen C (2017) Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci Total Environ 586:127-141.
24. Hu L, Li D, Chen J (2020) Effects of microplastics on growth and photosynthetic pigment content of three wetland plants in northeastern China. Environ Poll 262: 114301.
25. Huerta Lwanga E, Gertsen H, Gooren H, Peters P, Salánki T, van der Ploeg M, Besselings E, Koelmans AA, Geissen V (2016) Microplastics in the Terrestrial Ecosystem: Implications for *Lumbricus terrestris* (Oligochaeta, Lumbricidae). Env Sci Tech 50(5): 2685–2691.

26. Jabeen K, Li B, Chen Q, Su L, Wu C, holler H, Shi H (2018) Effects of virgin microplastics on goldfish (*Carassius auratus*). Chemosphere 213: 323-332.
27. Jacob H, Gilson A, Lanctot C, BessonM, Metian M, Lecchini D (2019) No effect of polystyrene microplastics on foraging activity and survival in a post-larvae coral-reef fish, *Acanthurus triostegus*. Bull Environ Contam Toxicol 102(4): 457-461.
28. Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, Narayan R, Law KL (2015) Plastic waste inputs from land into the ocean. Science 347(6223): 768–771. https://www.science.org/doi/10.1126/science.1260352
29. Jin Y, Lu L, Tu W, Luo T, Fu Z, Jin F (2018) Microplastics in the atmosphere and deposition in the rat lung. Env Sci Tech 52(21): 12841–12850.
30. Karami A, Groman DB, Wilson SP, Ismail P, Neela VK (2017) Biomarker responses in zebrafish (*Danio rerio*) larvae exposed to pristine low-density polyethylene fragments. Environ Pollut 223: 466-475.
31. Lebreton LCM, Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J (2017) River plastic emissions to the world's oceans. Nat Commun 8: 15611.
32. Li J, Yang D, Li L, Jabeen K, Shi H (2019) Microplastics in commercial bivalves from China. Env Pollut 244: 675–684.
33. Mak CW, Ching-Fong Yeung K, Chan KM (2019) Acute toxic effects of polyethylene microplasticon adult zebrafish. Ecotoxicol Environ Saf 182: 109442.
34. Malafaia G, de Souza AM, Pereira AC, Gonçalves S, da Costa Araújo AP, Ribeiro RX, Rocha TL (2020) Developmental toxicity in zebrafish exposed to polyethylene microplastics under static and semi-static aquatic systems. Sci Total Environ 700: 134867. https://doi.org/10.1016/j.scitotenv.2019.134867
35. Medrano DE, Thompson RC, Aldridge DC (2015) Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res 75: 63-82.
36. Murphy F, Ewins C, Carbonnier F, Quinn B (2016) Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ Sci Technol 50(11):5800-5808. https://doi.org/10.1021/acs. est.5b05416
37. Naidoo T, Glassom D (2019) Decreased growth and survival in small juvenile fish, after chronic exposure to environmentally relevant concentrations of microplastic. Mar Pollut Bull 145: 254-259.

38. OECD (2023) https://www.oecd.org/environment/plastics
39. Pannetier P, Morin B, Le Bihanic F, Dubreil L, Clérandeau C, Chouvellon F, Van Arkel K, Danion M, Cachot J (2020) Environmental samples of microplastics induce significant toxic effects in fish larvae. Environ Internation 134: 105047. https://doi.org/10.1016/j.envint.2019.105047
40. Peda C, Caccamo L, Fossi MC, Gai F, Andaloro F, Genovese L, Perdichizzi A, Romeo T, Maricchiolo G (2016) Intestinal alterations in European sea bass *Dicentrarchuslabrax* (Linnaeus, 1758) exposed to microplastics: Preliminary results. Environ Pollut 212: 251-256. https://doi.org/10.1016/j.envpol.2016.01.083
41. Peng G, Zhu B, Yang D, et al (2017) Microplastics in sediments of the Chingjiang Estuary, China. Environ Pollut 225: 283-290.
42. Rillig MC, Ziersch L, Hempel S, Velbert MV (2017) Microplastic transport in soil by earthworms. Sci Total Env 572: 1547–1555.
43. Rochman CM, Browne MA, Halpern BS, Hentschel BT, Hoh E, Karapanagioti HK, Rios-Mendoza LM, Takada H, Teh S, Thompson RC (2013) Classify plastic waste as hazardous. Nature 494:169-171. https://doi. org/10.1038/494169a
44. Schwabl P, Köppel S, Königshofer P, Bucsics T, Trauner M, Reiberger T, Leibman B (2019) Detection of various microplastics in human stool: A prospective case series. Ann Intl Med 171(7): 453–457.
45. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE (2004) Lost at sea: where is all the plastic? Sci 304 (5672): 838. https://www.science.org/doi/10.1126/science.1094559
46. Wagner M, Scherer C, Alvarez-Muñoz D, Brennholt N, Bourrain X, Buchinger S, Fries E, Grosbois C, Klasmeier J, Marti T, Rodriguez-Mozaz S, Urbatzka R, Vethaak A, Winther-Nielsen M, Reifferscheid G (2014) Microplastics in freshwater ecosystems: what we know and what we need to know. Environ SciEur 26(1):12. https://doi.org/10.1186/s12302-014-0012-7
47. Wright SL and Kelly FJ (2017) Plastic and Human Health: A Micro Issue? Environ SciTechnol 51 (12): 6634-6647.
48. Xia X, Sun M, Zhou M, Chang Z, Li L. (2020) Polyvinyl chloride microplastics induce growth inhibition and oxidative stress in *Cyprinuscarpio* var. larvae. Sci Total Environ 716: 136479.

49. Yang W, Gao X, Wu Y, Wan L, Tan L, Yuan S, Ding H, Zhang W (2020) The combined toxicity influence of microplastics and nonylphenol on microalgae *Chlorella pyrenoidosa*. *Ecotoxicol Environ Saf* 195: 110484.
50. Zbyszewski M, Corcoran PL, HockinA (2014) Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. J Great Lakes Res 40: 288-299.
51. Zbyszewski M, Corcoran PL, HockinA (2014) Comparison of the distribution and degradation of plastic debris along shorelines of the Great Lakes, North America. J Great Lakes Res 40: 288-299.
52. Zettler ER, Mincer TJ and Zettler LAA (2013) Life in the "Plastisphere": Microbial communities on plastic marine debris. Environ Sci Technol 47(13): 7137-7146.
53. Zhang G, Liu Y (2018) The distribution of microplastics in soil aggregate fractions in southwestern China. Sci Total Environ 642: 12-20.
54. Zhao S, Zhu L, Gao L, Li D (2018) Microplastic Contamination in Aquatic Environments, pp. 27-49, Elsevier.
55. Zhao Y, Bao Z, Wan Z, Fu Z, Jin Y (2020) Polystyrene microplastic exposure disturbs hepatic glycolipid metabolism at the physiological, biochemical, and transcriptomic levels in adult zebrafish. Sci Total Environ 710: 136279.
56. Zhu M, Chernick M, Rittschof D, Hinton DE (2020) Chronic dietary exposure to polystyrene microplastics in maturing Japanese medaka (*Oryzia slatipes*). Aquat Toxicol 220: 105396.