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Vivek Singh Bisht
M.F.Sc, Department of Aquatic Environment Management, College of Fisheries, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, Uttarakhand, India

Deepti Negi
M.F.Sc, Department of Fisheries Resource Management, College of Fisheries, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, Uttarakhand, India

Corresponding Author:
Vivek Singh Bisht
M.F.Sc, Department of Aquatic Environment Management, College of Fisheries, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, Uttarakhand, India

Microplastics in aquatic ecosystem: Sources, trophic transfer and implications

Vivek Singh Bisht and Deepti Negi

Abstract
Plastics have been sporadically reported in the aquatic ecosystem by scientists as early as 1950s. Every year about 8 million tonnes of plastic waste enters the sea which is the result of its exponential production growth. The different sources of this plastic debris include packaging materials, utensils, cosmetics, plastic materials used in nets, lost nets, cages, and waste from fishing vessels. Defragmentation of this plastic debris by physical or biological (including plastic degrading bacteria) process results in the formation of smaller particles (<5mm) termed as 'microplastics', includes much smaller nanoplastics (<150µm). These omnipresent particles, when ingested directly or indirectly by the aquatic organisms, enters the diverse food web. These contaminated fishes, when consumed by humans, results in trophic transfer of microplastics to human which can cause adverse health effects. Microplastics also act as a vector of several contaminants, harmful additives, heavy metals, chemicals and pathogens.

Keywords: Microplastics, ingestion, trophic transfer, human health, vector

1. Introduction
1.1 Microplastics
Microplastics are commonly classified into primary and secondary types. These are widely defined as synthetic polymers with a maximum size limit of 5mm and without a specified minimum limit [82]. They can be separated into primary microplastics and secondary microplastics. Interpretation of microplastics is, plastics originally manufactured in sizes less than 5 mm and found primarily in clothing, medicines and personal care products such as face and body scrubs [22, 14]. These primary microplastics can be transported by rivers, from water sources, air and land flow into freshwater and seawater [37]. Secondary microplastics are formed by the defragmentation of large plastic debris due to processes such as degradation, physical, chemical and biological interactions [84, 36]. Slow degradation of plastics polymers is done by microorganisms (e.g., *Bacillus cereus*, *Micrococcus* sp., or *Corynebacterium*), heat, oxidation, light or hydrolysis. The origins of secondary microplastics include fishing nets, industrial resin pellets, household items and other disposable plastic waste [27]. Significantly, it was found that the majority of microplastics are secondary microplastics [30] and that the amount of water will increase with the increase of plastic waste inclusion from different sources, leading to the continued conversion of secondary microplastics [22]. When microplastics are exposed to the environment, there is a higher chance of dissolution of microplastics into nanoplastics that may have a higher environmental risk due to the nano-size. Up to 10% of plastic produced annually worldwide ends up in aquatic ecosystems, where it is persistent and accumulates [83, 85, 45]. By 2025, the ratio of plastic to marine fish is expected to be 1 to 3, as marine plastic stocks are projected to grow to at least 250 million MT by 2025. By 2050, plastic will be equal again and likely to pass through fish stocks at sea by weight, as current production is expected to continue. Plastic does not last forever, and the marine environment is suitable for its degradation. The physical, chemical and biological processes splinter the original plastic pieces, turning the ocean into microplastics soup. The quantity of plastic in some parts of the ocean has even exceeded the quantity of plankton [61], and soon, if the plastic pollution process continues at the same pace, the quantity of micro and nanoparticles will be greater than the number of plankton.

1.2 Microplastics in the aquatic ecosystem

Scientists have occasionally reported the presence of small plastic particles in the marine ecosystem in the early 1950s, but research into their distribution and impacts began successfully in 2004 with a pioneering study led by marine ecologist Richard Thompson. Describing small plastic particles and separating them from large plastic debris such as trash, bottles, fishing nets (ghost fishing), and bags, the authors refer to them as "microplastics." Recognizing that microplastics are both unique and unparalleled in their impact on the environment, they encouraged scientists to incorporate the fate, pollution and effects of microplastics on different ecosystems, natural cycles and different organisms in their plastic pollution studies. Researchers have written and studied microplastics all over the world, leading to significant advances in terms of the sources, fate and effects of microplastics and related chemicals. Several hundred scientific publications now show that microplastics contaminate the world's oceans, including marine species at all levels of the food chain, from pole to pole and from the surface to sea. Scientists have also focused their study of microplastics in the freshwater ecosystem and terrestrial ecosystem [87, 26, 25, 27, 44, 9].

1.2.1 Microplastics in Seawater

Approximately 8 million metric tons of plastic enter the ocean annually [40, 60], and a conservative estimate indicates that 5.25 trillion plastic pieces weighing about 2,50,000 tonnes are currently circulating in seawater [28]. While some plastics enter the ocean from marine operations, 80% are said to come from land-based sources [45]. Disposable plastic materials enter the marine environment such as trash, industrial waste or landfill, through inland waterways, wastewater outflows and transport by winds or tides [60]. Seawater Microplastics are found as pellets, fragments, or fibers and are composed of various polymers [43], which are thicker than seawater and are expected to sink into the sea including polyamide, polyester, polymerizing vinyl chloride (PVC), and acrylic, among others. Some have lesser density than seawater and are often found floating on the surface, including polyethylene, polypropylene and polystyrene.

1.2.2 Microplastics in Freshwater

Microplastics were first reported in freshwater lakes in 2013 [29]. Since then, microplastics have been reported in freshwater beaches, lakes or rivers in Africa, Asia, Europe, North America and South America. As in the marine environment, microplastics are also common in freshwater systems on a global scale. Although contamination is often greater near densely populated areas, microplastics - often called microfibers - have also been found in remote areas [35], possibly due to atmospheric deposition [26]. Microplastic concentrations in freshwater habitats vary widely, and although these processes are not significantly lower than seawater, the concentrations reported so far appear to be similar to those in marine ecosystems [29]. Microplastic pollution, as seen in marine organisms, has also been reported in freshwater animals, including insects, worms, clams, fish and birds.

2. Microplastics in the food web

Microplastics represent a threat to marine biota because its small size makes them available to organisms throughout the food web [11, 82, 89] as shown in Figure 1. It is taken up by primary consumers (zooplankton) either directly or indirectly with phytoplankton (primary producers). These microplastic particles in this way enter the food chain are transferred through 'Trophic transfer'.

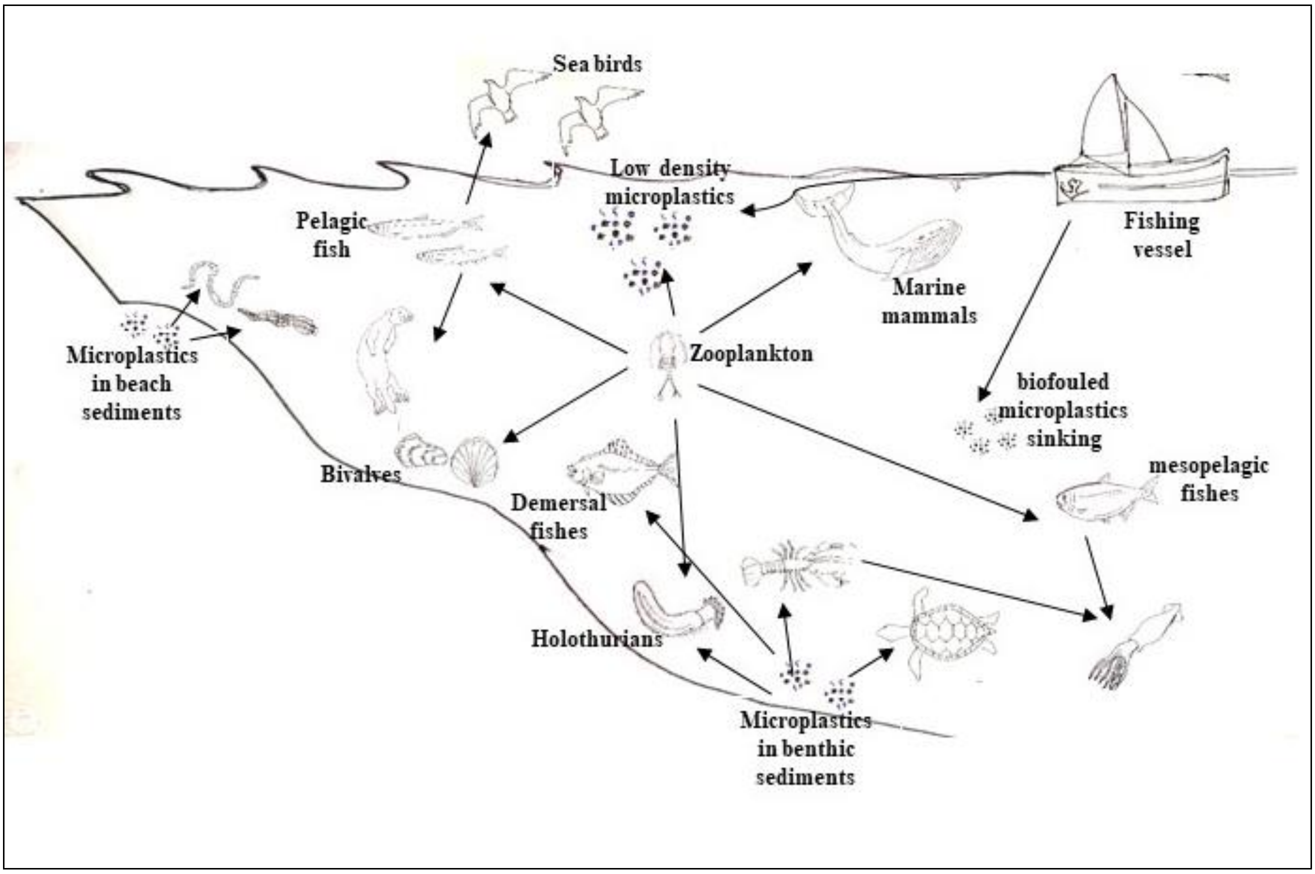

Fig 1: Microplastics in the aquatic food web.

2.1 Microplastic ingestion
Ingestion of microplastics through the mouth into the gastrointestinal tract via eating or drinking either directly or indirectly is a prevalent phenomenon and is aggravated across different trophic levels, habitats and geographic regions. According to a 2016 UN report over 800 species were contaminated with plastic via ingestion or entanglement. This shows a 69% increase in the number of species contaminated with plastics according to a 1977 review, which estimated only 247 species contaminated. 200 of these 800 species contaminated have been found to ingest microplastic debris in nature. Many carcass dissections and laboratory researchers have documented the plastic particles concentrated in the digestive tract of organisms. Several deaths have been reported that are a result of the ingestion of microplastics.

Many researchers have shown the adverse health effects of ingestion of microplastics by fishes [12, 24], invertebrates [62, 21, 39], mammals [31, 33, 34] and seabirds [73, 84]. As a result of physical injury, physiological stress and false satiation [86, 16, 21, 71, 89] caused by microplastic ingestion, organisms show loss of appetite, depletion of energy reserves, and decrease in ecophysiological function. Ingestion of microplastics can also lead to a fatality that has already been documented for many birds, turtles, fishes and marine mammals [50, 76]. In addition to this, microplastics are susceptible to contamination by water-borne organic pollutants and to the leaching of potentially toxic plastic additives known as ‘‘plasticizers’’ [80]. When consumed, microplastics can introduce toxins in the food chain, which can result in its biomagnification to the higher trophic levels [32, 77]

2.2 Microplastic ingestion mechanism
Generally, there are two ways of ingestion of food or any matter
1. Directly (primary ingestion)
2. Indirectly (secondary ingestion)

2.2.1 Primary ingestion
In this mode, the microplastic or other forms of plastic are taken up directly by the organism. Visible scraping or bite marks on the plastic debris collected from the field are a sign of bite by large animals (e.g., sharks, turtles and seabirds), which indicates the active foraging for microplastics [17, 69], or more intricate indications of feeding on microplastics strived by smaller animals.

2.2.2 Secondary ingestion
‘Heteroaggregates’, linked with other organisms like bacteria, fungi, zooplankton and organic or inorganic matter, leads to the misidentification and uptake of microplastic and other plastic debris [74]. Coingestion of microplastics and other associated toxic chemicals through grazing on biofilm by small invertebrates is also a type of secondary ingestion. Studies have already been done on the role of color attractants in feed and are an important factor that mediates the foraging interaction. Organisms are more attracted to the colorful items as kit resembles their prey. Gut content analysis has reported the occurrence of colorful synthetic and semisynthetic items [8]. Studies show active foraging by the organisms due to the prey confusion and chemical signaling facilitated by chemical attractants (algae-derived dimethyl sulfide) linked with the microplastics in seawater. Biofilm assemblage on the microplastics enhances its ingestion by olfactory foragers, which are attracted to the chemical signaling molecules on the biofilm [75].

3. Impacts of Microplastics
Impacts associated with the exposure with microplastics vary from histological to the population level thus affecting the ecosystem (Table 1.). Impacts of microplastics can be physical as well as biological depending on the presence and form. Plastic debris can cause severe physical damages due to entanglement. It can also cause adverse health conditions due to the ingestion of smaller particles (microplastics).

Table 1: Impacts of microplastics at different levels of biological organisation

Level of Biological organisation	Biological Endpoints
Subcellular	Enzyme activity
	Gene expression
	Oxidative damage
Cellular	Apoptosis
	Membrane stability
	Phagocytic response
Organs	Histopathology
	Metabolic demand
	Energy Reserves
Individual	Mortality
	Ingestion rates
	Individual growth
Population	Fecundity
	Offspring viability
	Larval development
Ecosystem	Behaviour
	Ecosystem function
	Community shifts

3.1 Biological fate of ingested microplastics
The biological fate of ingested microplastics is an important factor that determines the level of damage or adverse effects caused by microplastics. This includes: -

1. Retention (accumulation)
2. Translocation (movement)
3. Egestion (elimination)

‘Retention’ can be defined as the prolonged residence time of microplastics in an organism’s body. It is an important factor that determines the biological impacts of microplastics and it depends on many properties of microplastics including its shape and size. Studies show that the smaller sized plastic particles retain for a longer time in the organism’s body [46, 1]. Thus, microplastics can be retained in the organism’s body for a longer period. These smaller particles adhere to the intestinal villi in fishes [7], foot and mantle of mussels [47], which results in the delayed ‘egestion’. Accumulation sometimes may lead to the choking of gastrointestinal tracts which may lead to physical injuries and sometimes death.

Egestion can be defined as the elimination of microplastics from the body through the digestive system. Egestion may occur without causing any damage to the body if the retention time is less. If there is prolonged retention of microplastics it increases the chances of adverse health effects either physical damage or stress to the organism. Retention or accumulation may also lead to the bioaccumulation of toxins that are attached to these microplastic particles and transfer to the higher trophic levels [5].

Translocation is the movement of the microplastics from the target tissue to other tissues. Translocation mainly depends on the size of the microplastics. In the researches on the impact of microplastics on bivalves, it was found that microplastics (10 µm) translocate into the circulatory system of mussels [15], microplastics (<80 µm) ingested by blue mussels through cellular uptake followed by tissue translocation to the digestive gland and gills and accumulated in the lysosomal system [86]. Moreover, translocation of relatively large particles (up to 250 µm) in the gills, ovaries and hepatopancreas have been found in crabs [13]. Microplastic particles (up to 600 µm) are transported to the liver in fishes [6].

3.2 Health effects of ingestion of microplastics in Aquatic organisms

There are direct or indirect negative effects of the intake of microplastics in aquatic organisms. Microplastic uptake into the gills and digestive gland can be analyzed by a new method using polarized light microscopy. Significant histological changes are seen upon uptake and a strong inflammatory response exhibited by the formation of granulocytomas after a few hours and destabilization of the lysosomal membrane, which notably increases with longer exposure to microplastics [86].

Microplastic pollution is a great threat to coral reefs. They survive in a symbiotic relationship with the single-celled algae, present in the tissues of the coral cavity, which is a source of energy through the photosynthesis process. Feeding on plankton provides corals with the important nutrients essential for growth, development and reproduction [78]. Due to the similar size, color and appearance, or sometimes the biofilm developed on the microplastic particles, these are taken up by corals. This microplastic feeding mechanism in corals involves ingestion(intake), retention and digestion of these microplastic particles [57]. Retention of these microplastic particles in the mesenterial tissue of corals results in the reduction of feeding capacity and capability thus lowering the energy reserves [68].

Plankton, which are an important component of the marine ecosystem are also adversely affected by microplastics exposure. Microplastics penetrate along the cell wall of phytoplankton due to their small size and reduce the chlorophyll absorption thus, lowering the photosynthesis [63]. Heterotrophic plankton undergoes phagocytosis and the microplastic particles retain in their tissues [51]. Zooplankton, another essential component of the aquatic ecosystem and basic primary consumers of the aquatic food chain are also adversely affected by microplastics.

Researches showed that zooplankton were found to ingest latex beads when exposed to microplastic [53], also they tend to ingest polystyrene beads (1.7−30.6*µm*). Some of the negative health effects due to ingestion of microplastics are - loss of feeding ability due to ingestion of microplastics by *Centropages typicus* [21], decrease in the growth of *Gammarus fossarum* when exposed to PMMA (polymethyl methacrylate) and PHB (polyhydroxy butyrate) [79], decrease in the growth and reproduction process due to ingestion of PE (Polyethylene) in the benthic organism *Hyalella azteca* [4] and reduction in feeding capability resulting in weight loss in the marine lugworm *Arenicola marina* [10]. The small size, attractive colors and high buoyancy makes these particles easily available for the fishes and confuse the fishes with their prey. Microplastics (< 300µm) have been found in the gut content of planktivorous fish *Acanthochromis polyacanthus* [23]. Studies suggest that the possible effects of the ingestion of microplastics include histopathological modifications in the intestine, leading to detachment of mucosa epithelial lining from *lamino propia* resulting in widening reduction and puffing of villi, increased number of goblet cells and alteration in the structure of serosa [64]. Studies on the effect of different concentration levels of microplastics (polystyrene between 10000 to 80000 particles/m^3) on eggs and larvae of *Perca fluviatilis* showed that higher concentrations of microplastics reduce the hatching rate, larvae exposed to microplastics are smaller and slower in comparison to normal larvae. The responsive ability of larvae to the chemical alarm is reduced which reduces the survival rate of fishes. Microplastics ingestion causes up-regulation of fatty acids and downregulation of amino acids [55]. Also, the ratio of triglycerides and cholesterol in the blood serum level of fish and delivery of cholesterol between muscle and liver is altered [18].

Harmful effects of microplastic ingestion are also studied on sea birds and it was found that negative effects due to the toxic effect of plastic particles could cause altered feeding behavior and reproduction ultimately leading to mortality [88]. Microplastics were found in the seabird species including; *Phalacrocorax bougainvillii*, *Pelecanoides garnotii*, *Pelecanoides urinatrix*, *Pelecanus thagus*, *Spheniscus humboldti* and *Larus dominicanus* with *Larus dominicanus* having the maximum microplastic exposure as it commonly feeds on fishing nets, waste disposal products and plastic container [81]. Studies suggest that size, weight and habitat of these sea birds play an important role in the ingestion of plastic debris for example small size sea birds like *Spheniscus penguins* and *Thalassarche albatross* have smaller ingestion rates whereas in *Fulmarus fulmars*, *Cyclorhynchus auklets*, *Oceanodroma*, *Pachyptila prions* and *Pelagodroma* the ingestion rates were higher due to their larger sizes [88].

Polar bears, sharks, whales, seals and sea turtles are also vulnerable to microplastic ingestion in the oceans throughout the world. Presence of microplastics was detected in the stomach and intestine of the harbor seal, *Phoca vitulina* [67], which are filter feeders and therefore ingests a huge amount of microplastics either directly or indirectly (prey containing microplastics) and presence of microplastics in the stomach of sharks of Sea of Cortez and whales of Mediterranean sea and high concentrations of phthalates in the Baleen whales are a sign of microplastic pollution in the marine ecosystem [34].

4. Microplastics: a threat to human health

Plastic reaches the bodies of its producers, humans, through seafood, to close the full circle. There are different possible pathways of microplastics to the human body. It can easily enter the human body through drinking water, air or food. There is a potential risk to human health due to the microplastic contamination in commercial fish and other invertebrate species which are consumed by human. Some of the reports addressed the presence of microplastics in 25 per cent of fish and aquatic invertebrate species tested on the market [72]. The presence of microplastics has been confirmed in crayfish, fishes, mussels, oysters and seaweed, which are suitable for human consumption. Microplastics have been found in the wild catches as well as aquaculture or mariculture yield [56, 70, 20].

The presence of microplastics in the gastrointestinal duct of fish does to provide evidence of human exposure as normally it is removed during cleaning and is not consumed but the case with the smaller fishes is different as the gastrointestinal duct of the smaller fishes is not easy to clean. Furthermore, in fishes, the microplastic particles may leach and accumulate the associated chemical compounds in edible tissue. There are possibilities of the dietary microplastic exposure in humans if there is the translocation of microplastics across the gastrointestinal tract or gills via paracellular diffusion or transcellular uptake as this may lead to the entry of these particles in the circulatory fluid (blood). Research showed that epidermal cells play a major role in the attachment and entry of the microplastics in aquatic organisms, in research conducted, the uptake of 1µm microplastics from the surrounding water with particles persisting in the surface and subsurface epidermal cells of the skin and in phagocytes underlying the gill surface in rainbow trout was noted [61]. So, the consumption of skin or gill tissue can result in the exposure of microplastics particles to human.

According to the studies, plastic particles can reach our digestive tract and their retention, translocation, and excretion depends on the size of the particles consumed. Based on the size they may be excreted, get trapped in the stomach, attached to the intestinal lining or villi, reach the body fluids such as blood, tissue or various organs of the body. Scientists have reported the presence of microplastics in the human stool and presence of BPA (bis-phenol A), a chemical used in the plastics production was found in the human urine. Microplastics also show a negative effect on the nervous system, hormones, immune system and cancer-inducing property.

Microplastics aggregate in blood, obstructing the blood flow in the body and leaving blood proteins non-functional. Blood proteins (plays an important role in the osmotic pressure, molecular transport, coagulation of blood, immune response, etc) such as albumins, globulins, fibrinogens, are absorbed on the surface of microplastics and form a plastic-protein complex (13-600nm). These plastic-protein complexes are attracted to each other which results in the aggregation of these complexes blocking the blood flow.

5. Microplastics as vectors of contaminants and associated additives

5.1 Plastic monomers and polymers

BPA bis- phenol A which is a plastic additive, is also used as a fundamental component of Polycarbonate plastics. Styrene monomers, dimers and trimers have been detected in the seawater and beach sediments throughout the world which have possibly originated from polystyrene (PS) litter [48, 49], which is a very commonly found contaminant in the aquatic ecosystem.

5.2 Plastic additives

A variable amount of plastic additives is used in the production of plastics. According to some studies plastic additives constitutes about 4 per cent of the total weight of final produced plastics [2, 52], however, some studies suggest that plastic additives may account for up to half of the total produced material [54]. Significant amounts of plastic additives including Polybrominated diphenyl ethers (PBDEs), bisphenol A (BPA), Nonylphenol (NP) and Octylphenol (OP) are found in the microplastics in seawater, sediments in beaches, benthic sediments and coastal regions [66, 80].

5.3 Heavy metals

Several studies have been done on the sorption of heavy metals on the microplastics and their bioaccumulation. Microplastics samples collected in the studies have documented the presence of different heavy metals in significant amount including Copper (Cu), Nickel (Ni), Cadmium (Cd), Chromium (Cr), Aluminium (Al), Lead (Pb), Zinc (Zn), Manganese (Mn), Iron (Fe), etc [58].

5.4 Persistent, bioaccumulative and toxic compounds (PBTs)

Persistent organic pollutants which are hydrophobic, accumulate heavily in the microplastics floating in the aquatic environment. Studies show variable amounts of Polychlorinated biphenyls (PCBs), Polycyclic aromatic hydrocarbons (PAHs), Dichlorodiphenyltrichloroethane (DDT) and analogs dichlorodiphenyldichloroethane (DDD) and dichlorodiphenyldichloroethylene (DDE) [80, 65, 3, 38] present in water bodies.

5.5 Pathogen

Plastic debris acts as a substrate for several microbial communities [41, 42, 90, 59]. This includes plastics decomposing organisms, planktonic communities, and pathogens. These are exposed to different aquatic organisms. These microplastic particles along with the pathogen may be transported to different depths in the aquatic ecosystem. These are sometimes ingested by organisms with the widespread, omnipresent microplastics.

6. Conclusion

The problem of plastic pollution in the Aquatic ecosystem is a matter of concern these days due to its negative effects on aquatic biota. Due to the small size of the microplastics bioaccumulation capacity is very high. Ingestion of microplastics by various organisms including fish, sea birds, plankton, coral and marine mammals results in its trophic transfer. Additives, toxic contaminants, heavy metals and pollutants are absorbed by microplastic polymers which makes them a potential vector. Adverse effects of ingestion of microplastics ranges from molecular to ecosystem level. Thus, strict immediate measures must be enforced against the unnecessary use of plastics and its products. New research studies and methodologies are required to annotate the factors responsible for microplastics in aquatic and its biological impact. General public should be made aware of the deleterious effects of plastics to reduce its use. The most important approach to minimise its use and production is collection and recycling of the plastic waste. The best solution to avoid the future threat of microplastics is to stop its production and find alternative of plastic and its products.

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