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Microplastics in Aquatic Environments: The Effects of Polystyrene on Red Tilapia and Potential Remediation Methods

Ghulam Abbas[1], Ayesha Hanif[2], Misbah Younas[3], Shahana Ejaz[4], Erum Bughio[5], Ali Raza[6*], Minahal Fatima[7], Kainaat Azam[8], Nimra Ather[9]

[1]Department of Zoology, Government College University Faisalabad, Punjab Pakistan

[2]Department of Environmental Science, International Islamic University Islamabad

[3]Department Of Zoology, Wildlife and Fisheries, University of Agriculture Faisalabad

[4]Institute of Pure and Applied Biological Science, Department of Zoology, Bahauddin Zakariya University, Multan

[5]Department of Poultry Production, Faculty of Animal Production & Technology Shaheed Benazir Bhutto University of Veterinary and Animal Sciences SAKRAND

[*6]Department Of Zoology, Wildlife and Fisheries, University of Agriculture Faisalabad

[7]Institute of Zoology, University of the Punjab Lahore

[8]Department of Zoology Wildlife and Fisheries , University of Agriculture Faisalabad

[9]Department of Zoology Wildlife and Fisheries , University of Agriculture Faisalabad

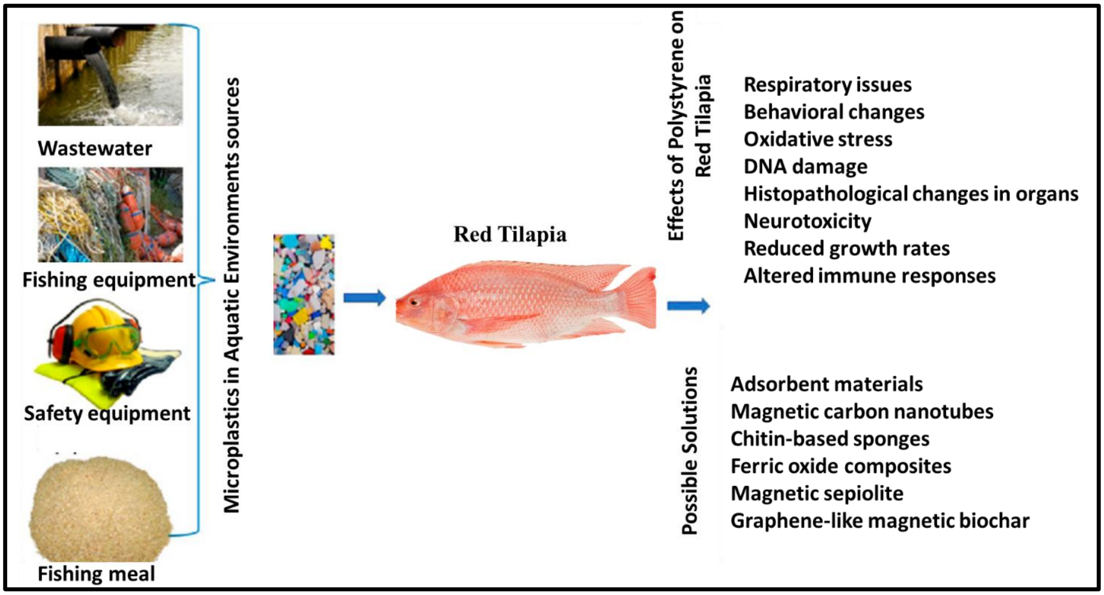
*Corresponding Author: Ali Raza

Abstract

Microplastics have become a major source of pollution across the globe with impacts on marine and freshwater organisms. Among these polymers, polystyrene (PS) is one of the most common polymers that have been found in water bodies because it is commonly used in packaging and other products. The impacts of polystyrene microplastics on Red Tilapia (Oreochromis spp.), a fish that has both economic and environmental value. Due to consumption and bio-uptake of PS

microplastics in Red Tilapia, physical obstruction, compromised feeding rate, compromised nutrient assimilation, and exposure to toxic chemicals that elicit oxidative stress and endocrine dysfunction. These outcomes lead to growth retardation, reduced immune responses, changes in feeding habits, poor evasion of predators, and reproductive dysfunction. Remediation strategies that can be employed to reduce the effects of microplastics; include mechanical removal, filtration, microbial degradation and phytoremediation, nanotechnology, and electrochemical methods. Another significant aspect of the study is the role of policies and awareness in combating plastic pollution. Further studies and advancements are therefore needed to come up with improved solutions that would be friendly to aquatic life and the Red Tilapia as well.

Keywords: Microplastics, Polystyrene, Red Tilapia, Oxidative stress, Remediation strategies, Plastic pollution policies



Graphical abstract

Introduction

Microplastics are small plastic fragments that are below 5 millimeters in size. These microplastics are becoming a focus of attention because their size makes them ubiquitous in water and possibly toxic to organisms and humans (Issac & Kandasubramanian, 2021). Microplastics are found in various sources, both primary and secondary. Micro microplastics are deliberately produced in small sizes, including microbeads used in products like wash and exfoliation products, toothpaste, and cleansers (Elizalde-Velázquez & Gómez-Oliván, 2021).

These microbeads, when washed down the drain, can slip past wastewater treatment processes because of their small size, and end up in natural waters. The other type of microplastics is known as secondary microplastics which are formed from the breakdown of larger plastic products. This breakdown happens by physical, chemical, and biological means (Hale et al., 2020). Mechanical weathering and the impact of waves and sand on the abrasion of plastic debris are examples of physical processes. Chemical processes occur with the breakdown of plastics due to UV radiation where there are photo-oxidative reactions that cause the physical breaking down of the plastic polymers (Fotopoulou & Karapanagioti, 2019). Biological processes include the breaking down of plastics by microorganisms but this is commonly known to take longer as compared to physical and chemical processes (Harne et al., 2022). Another major source of microplastics is synthetic fibers that are found in textiles. Each time polyester, nylon, or acrylic material is washed, microplastics are let loose into the wastewater stream. These microfibers with lengths less than a millimeter cannot be filtered out by water treatment plants effectively and end up in rivers, lakes, and oceans (Bratovcic, 2019; Feldman, 2002).

It is also important to note that microplastics are released into aquatic ecosystems through other activities. Discharge of microplastic particles can also occur through accidental spillage and poor disposal of industrial effluents in the manufacturing of products like plastics .(Habib et al., 2020; Haidri et al., 2023). Even farming also contributes to microplastic pollution; for example, the use of plastic mulch films in agriculture can decompose into microplastics that can be washed into the water bodies by water runoff (Hussain et al., 2024; Fatima et al., 2024). Microplastics that enter aquatic habitats have different fates depending on their characteristics of size, shape, and solubility (Ullah et al., 2024)(Waseem et al., 2023). Microplastics can float with the help of buoyancy on the water surface and can accumulate in large patches such as the Great Pacific Garbage Patch. Spherical microplastics may be denser and sink to the bottom of water bodies where they can become lodged in the bottom sediments and pose a threat to organisms living at the bottom of the water bodies(Haidri, Qasim, et al., 2024). The hydrophobicity of plastics enables them to selectively accumulate toxic substances from the surrounding water – heavy metals, POPs, and PAHs, in particular (Haidri, Fatima, et al., 2024). When ingested by organisms in water bodies, these microplastics can accumulate and biomagnify the pollutants present within them, affecting organisms at higher trophic levels, such as humans (Ummer et al., 2023: Ummer et al., 2024.). The problem of microplastics in water basins is alarming and concerns scientists, legislators, and activists (Dixon et al., 2017). Studies have found that microplastics exist in almost all types of aquatic environments, including surface and deep waters, and even in areas that are considered to be least affected by human interferences such as the Arctic zone. It is now well understood that these substances persist in the environment and are capable of transporting and releasing toxic chemicals, thus emphasizing the need to address this problem (Khan et al., 2022). The issue of microplastics requires a two-pronged approach, which includes better methods of waste disposal, innovation of environmentally friendly products, the enactment of higher standards of plastics' manufacturing and disposal, and the enhancement of public awareness of the problem (Lohmann et al., 2007). It is essential to start with the definition and sources of microplastics to combat the general problem of plastic pollution. Measures that have been taken to lessen the chances of microplastics being washed into water bodies must consider the various pathways through which these particles enter and persist in the ecosystem.

Polystyrene in Aquatic Environments

Polystyrene (PS) is a general-purpose polymer that is commonly used in many applications and is most frequently encountered in marine and freshwater habitats. It has been widely used in products like packing materials, disposable cutleries, food trays, and insulating materials among others (De-la-Torre et al., 2020). The reason for its wide application is the relatively low price of polystyrene (Greven, 2016), its versatility, and useful characteristics such as low density, high strength, and heat resistance. But again, these same properties make it to stay in the environment for long and this causes many ecological issues. Polystyrene microplastics can reach the water bodies through different routes as follows (Alfonso et al., 2021). One of the main pathways is to dispose of it in the wrong manner. The polystyrene products, which are commonly employed as disposable items, are thrown away carelessly and end up littering the environment. These can be done directly over water bodies or in other cases where wind and rain transport these plastics to rivers, lakes, and oceans. Moreover, polystyrene waste can float and is carried by ocean currents to different regions of the country and even the world, thus polluting large territories (Nikiema et al., 2020). Another source of PS microplastics is the breakdown of large plastic products through physical abrasion or chemical breakdown. Polystyrene products erode into smaller pieces over some time through physical, chemical, and biological degradation. Physical processes involve mechanical forces such as the action of waves and rubbing against rocks and sand through which large polystyrene items are broken down into microplastics (Amrutha et al., 2021). Other physical changes include photodegradation whereby UV radiation from the sun breaks the chemical bonds in the polymer chains rendering the plastic fragile to break. The biological degradation while being slower involves the microbial action where microorganisms are capable of metabolizing the polymer and thus taking part in the fragmentation of polystyrene (Courtene-Jones et al., 2021).

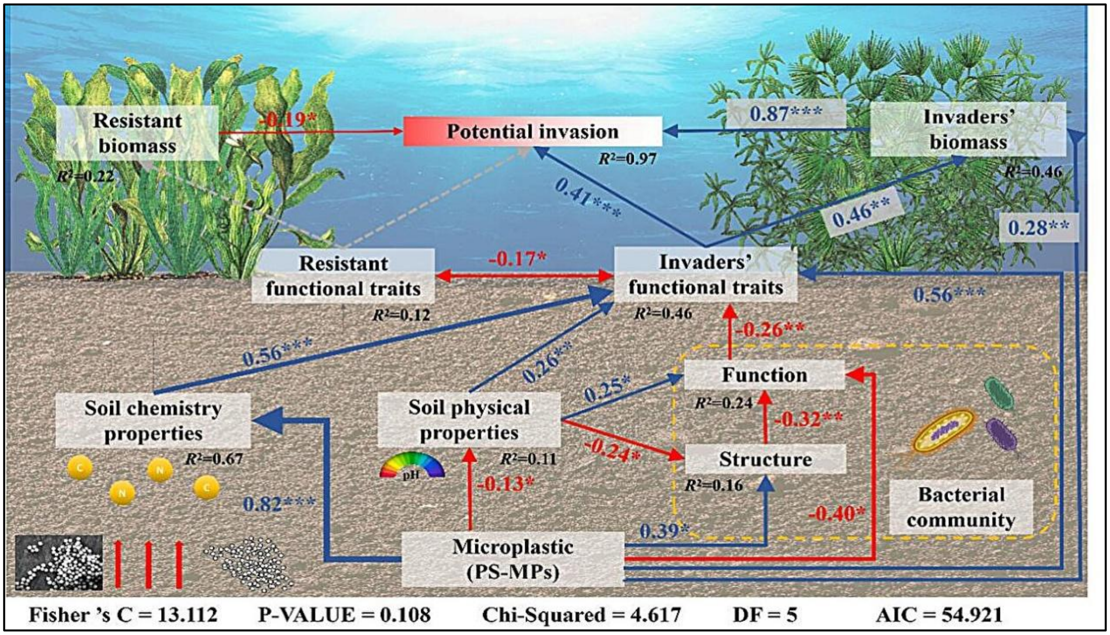


Fig1. Polystyrene microplastics shown to enhance the invasion of exotic submerged macrophytes (phys.org. 2024).

Polystyrene microplastics are found in water bodies and the following are the effects on marine and freshwater organisms (Nugnes et al., 2022). Because of their size, these microplastics are consumed by numerous organisms, including zooplankton, mollusks, fish, and birds. Internalized polystyrene may lead to the obstruction of the alimentary canal or other vital body organs and hence decrease the capacity of organisms to feed and assimilate nutrients (Xiao et al., 2020). Another disadvantage of polystyrene is that it can release toxic substances including styrene monomers as well as other additives that can cause deleterious effects on health such as oxidative stress, liver injury, and endocrine disruption in water organisms (Cao et al., 2022).

Table 1. Spatial Distribution and Characterization of Microplastics in Aquatic Environments

Sampling Site	Source	Concentration of Microplastics (g/L or count)	Sample Characterization Method	Particle Size Range	Types of Plastics	References

Ocean, North Pacific	Surface water	Greater than 1 g	Raman spectroscope	Greater than 500 µm	PP, HDPE, LDPE, PS, PVC, PET, cellulose acetate, nylon	Egger et al. (2020)
Mediterranean Sea	Surface water	Greater than 1 g	Micro-Raman	10 µm to 5.0 mm	PE, PP, PS, PET, PVC, PA	Llorca et al. (2020)
Arabian Sea	Surface water	3252 ± 2766	FTIR	0.5–5.0 mm	PE, PP, PS, PET, PVC, PA	Uddin et al. (2020)
KwaZulu–Natal, South Africa	Surface water	55.4 ± 32.6	Dissecting microscope	1000–5000 µm	Plastic fragments, fibers, films, line, polystyrene, pellets	Naidoo and Glassom (2019)
Hawaii Beach	Surface water	18.1 (±22.9)	FTIR analysis	1–1.9 cm	LDPE, HDPE, PP	Brignac et al. (2019)
South Korean Beach	Surface water	13.2	FTIR	0.5–2.5 cm	Styrofoam, hard plastics	Lee et al. (2017)

Deep-sea Ireland	Subsurface samples	48.1	Raman analysis	Less than 1.25 mm to 10 mm	Cellulosic fibers, synthetic fibers	Kärrman et al. (2016)
Fiji	Sediment	19.8 ± 4.2	ATR-FTIR	300 µm	PE, PP, PET, PS	Ferreira et al., 2020b
Shanghai Megacity	Sediment	7979.5 ± 521.0	Micro-FTIR	80–500 µm	Not available (NA)	Chen et al., 2020b
China Textile City	Industrial wastewater	1600	Micro-FTIR	0.1–1 mm	PP fragments	Deng et al., 2020b
Italy Lake Garda	Sediment	40	Raman Spectroscopy	1 µm to 5 mm	Filaments, pellets, polystyrene	Legambiente (2016)
Tibet River System	Sediment	4–1219	Raman analysis	Less than 0.5 mm to 5.0 mm	PE, PP, PS, PET, PVC	Zhang et al. (2016)

This indicates that polystyrene has a high chance of causing harm to the environment due to its ability to persist for long in the environment and this calls for proper management and control measures to be put in place (Dong et al., 2020). The following measures have been proposed as ways through which polystyrene microplastic pollution of water sources can be addressed: Reducing the manufacture and application of single-use polystyrene items, enhancing waste disposal and management, and supporting the research, production, and use of biodegradable polystyrene products (Lu et al., 2018). Individuals should also be educated on the right methods of disposing of polystyrene products and avoiding littering as a way of minimizing the amounts that go into water bodies. The problem of polystyrene pollution requires a combined effort and multimodal intervention through policy measures, technological advances, and public awareness to foster the preservation of aquatic life and a sustainable environment (Morath, 2022).

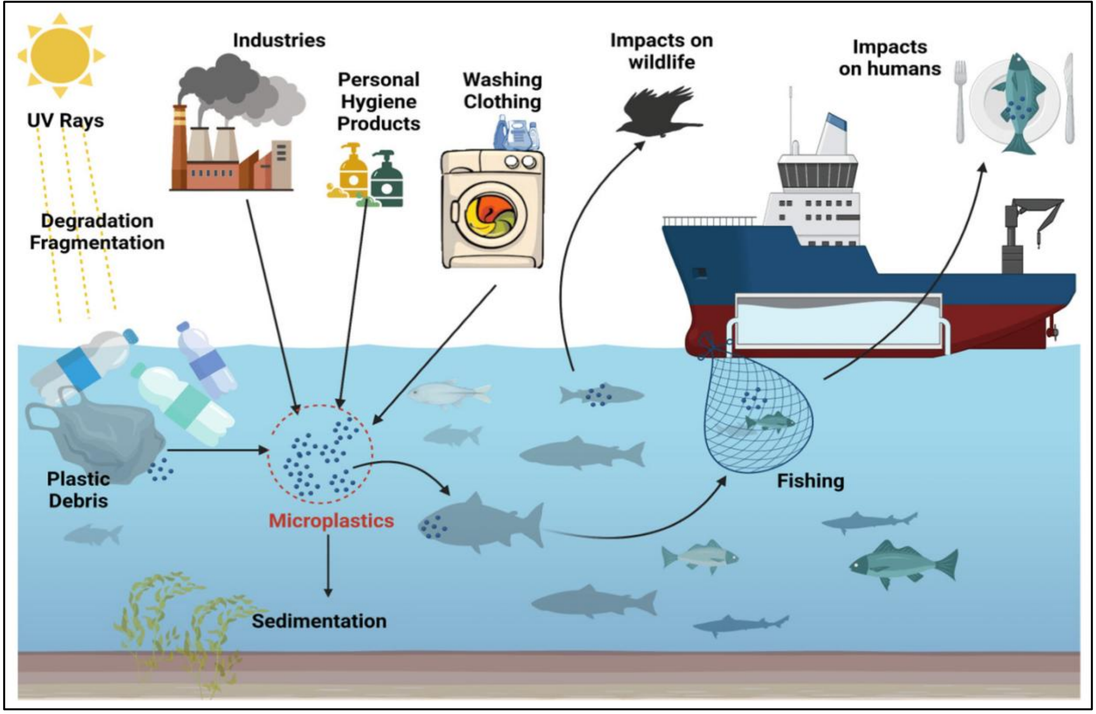


Fig .2 Microplastic in marine environments (Ziani et al.,2023)

Importance of Red Tilapia

Red Tilapia (Oreochromis spp.) is one of the most valued fish species in aquaculture because of its rapid growth rate, tolerance to varying conditions, and high consumer preference (Prabu et al., 2019). This species plays a central role in global aquaculture production, serving as a food source, source of income, and economic buffer for many countries. The fact that Red Tilapia can grow in different water types such as freshwater, brackish water, and even low salinity seawater makes it a valuable fish for farming (Arumugam et al., 2023). It is important for several reasons to understand the effects of microplastics on the growth of Red Tilapia. Eco systemically, Red Tilapia functions as an environmental bioindicator, which shows the state of community waters. The ingestion of microplastic leads to physiological and reproductive disorders that reduce the population size of these fish and the food chain (Kajungiro et al., 2019). Also, because of the high population density in the farms where Red Tilapia are usually bred, they are highly susceptible to the bioaccumulation of pollutants such as microplastics that may be found in densely populated areas (Dee et al., 2021). Economically, the health and productivity of Red Tilapia are sources of income since the profitability of aquaculture businesses depends on the health and productivity of the fish species being cultured. The effects of microplastic pollution include reduced growth, higher mortality, and lower quality fish which will reduce the market supply and price (Wu et al., 2023). In addition, the customers are now more conscious of the harm that they cause to the environment through their diet and the presence of microplastics is likely to lower the market demand for farmed tilapia. Hence, it becomes crucial to tackle the issue of microplastic pollution to maintain the viability of the aquaculture sector, and, in turn, the availability of this valuable source of protein (Lusher et al., 2017).

Effects of Polystyrene Microplastics on Red Tilapia

Physiological Effects

1. Ingestion and Accumulation

Red Tilapia may confuse polystyrene microplastics for food and consequently engulf as well as store them in their stomachs (Ubaldi, 2024). When ingested, these microplastics may lead to physical obstruction, which is a hindrance to the movement of food through the digestive system. This obstruction can greatly limit the feeding of the fish and therefore the intake and digestion of nutrients by their bodies (Mahamud et al., 2022). This in turn leads to stunted growth, and reduced

ability of the immune system and overall well-being, leaving the fish vulnerable to diseases and other factors in the environment (D'Avignon, 2023).

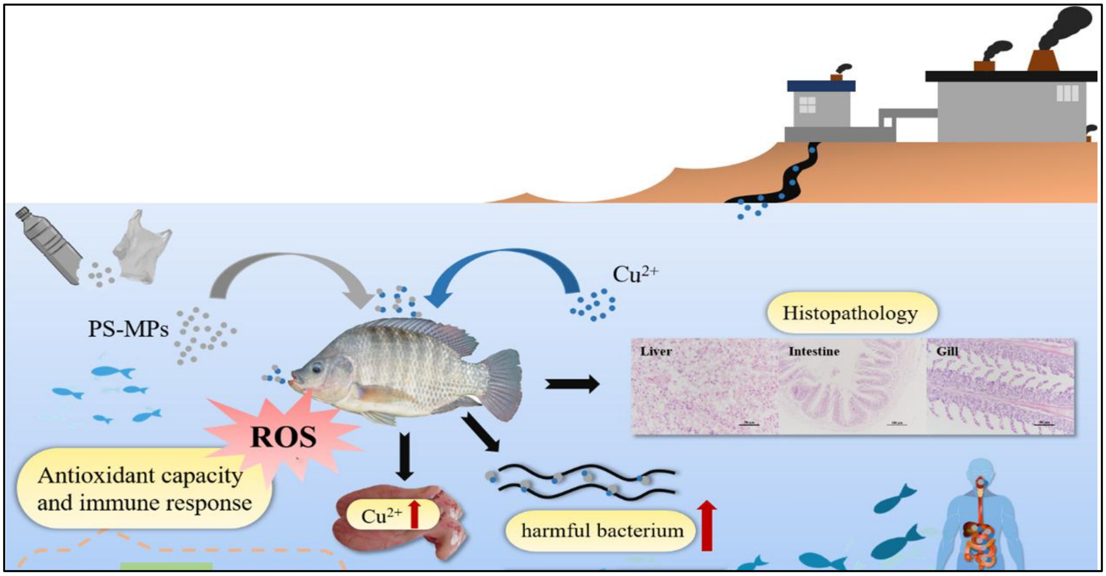


Fig.3 Effects of Polystyrene Microplastics on Red Tilapia

2. Toxicity

Polystyrene microplastics are not biologically passive particles; they release toxic chemicals like styrene monomers and other materials used in their production (Kik et al., 2020). The following chemicals are known to have dangerous effects when administered to Red Tilapia: For instance, styrene monomers can cause oxidative stress and hence cell damage due to an increase in free radicals with little or no antioxidants within the body. This oxidative stress can affect the vital organs, especially the liver, and its function, and this leads to a variety of health complications (Bouwmeester et al., 2015). Also, the endocrine system, which is responsible for the secretion of hormones in the body, is affected by these toxic compounds. Hormonal disruption can impact the growth, metabolism, and reproductive system with consequences such as low fertility and growth abnormalities in offspring. The toxicological impacts of ingestion, bioaccumulation, and bioavailability of polystyrene microplastics further reveal the highly negative effects on the health and survival of Red Tilapia (S. Zhang et al., 2019).

Table. 2 Impact of Different Plastic Types on Various Fish Species and Their Associated Findings in Freshwater Habitats.

Habitat	Plastic Types	Fish Species	Associated Organs	Findings	References
Freshwater	Polyester fibers	Gambusia holbrooki	Head and body	Microplastics (MPs) found in head and body parts	(Su et al., 2019)
Freshwater	Microplastics (MPs)	Oreochromis niloticus	Muscles	Excessive production of reactive oxygen species (ROS) causing oxidative stress and DNA damage	(Hamed et al., 2020)

Freshwater	Polystyrene	Salmo trutta	Muscles	Minor changes observed in resting behavior of fry	(Schmieg et al., 2020)
Freshwater	Polyethylene and polystyrene	Danio rerio	Tissue	Alterations in transcriptional processes, immunity, and behavior	(Limonta et al., 2019)
Freshwater	Microplastics (MPs)	Dorosoma cepedianum and Micropterus salmoides	Gill and gut	Changes observed in feeding and physiological functions	(Hurt et al., 2020)
Marine water	Polystyrene	Girella laevifrons	Intestine	Increased hyperaemia, leukocyte diffusion, and crypt cell loss	(Ahrendt et al., 2020)
Marine water	Cellophane	Thryssa kammalensis, Amblychaeturichthys hexanema	Digestive and non-digestive tissues	Fish with scales show lower intensity of MPs compared to scaleless fish	(Feng et al., 2019)

Marine water	Polyethylene and polyester	Dicentrarchus labrax, Trachurus trachurus, Scomber colias	Gastrointestinal tract and gills	Neurotoxic effects and oxidative damage observed	(Barboza et al., 2020)
Marine water	Polystyrene	Sebastes schlegelii	Tissue Sample	Reduced swimming speed and growth; increased oxygen consumption and ammonia	(Yin et al., 2020)

1 Effects of Polystyrene Microplastics on Red Tilapia

Behavioral Effects

1. Altered Feeding Behavior

The ability of Red Tilapia to feed can be greatly affected if exposed to PS microplastics. These fish may mistake the microplastics for food, leading to a phenomenon (Ding et al., 2018). This occurs when the microplastics occupy the stomach, the fish feel full and they do not need other nutritious food. Therefore, the total feed consumption by Red Tilapia is reduced, thus reducing the amount of necessary nutrients required for their growth and development (Ding et al., 2020). This nutritional deficiency can also affect their growth rate, therefore making them to be dwarfs and less muscular than their normal counterparts (Jahan et al., 2024). Slower growth and development not only affect health but also result in a decline in the productivity of the aquaculture systems hence the loss-making (Koshy, 2021). In addition, when the fish are fed poorly, their immunosuppressive system is affected, thus being prone to diseases and high mortality levels. The impact of changes in feeding time and frequency can eventually affect the reproductive capacity and population sustainability of Red Tilapia because the offspring of undernourished adults can exhibit lower reproductive rates and offspring survival (Cheruiyot & Adhiaya, 2023).

2. Predator Avoidance and Social Interactions

Behavioral alterations caused by microplastics can also affect Red Tilapia in terms of its ability to escape from predators, and to exhibit normal social behaviors (Rios-Fuster et al., 2021). Microplastics interfere with the sense organs and the brain, which results in reduced predator escape reflexes. For instance, fish that are exposed to microplastics will have slowed reactions and less escape instincts when threatened by predators. That increased susceptibility to predation can impact the population in terms of density because higher mortality rates lower population densities (Santos et al., 2021). Moreover, microplastic ingestion can alter social interactions that are very important in maintaining the dominance and unity of a school of fish. Disturbed social relationships may result in heightened levels of aggression or changes in mating strategies, which can impede the reproductive capability and survival of the species (Psarouthakis & Zealand, 2022).

Reproductive Effects

1. Reproductive Health

Studies have shown that exposure to microplastics in water can have detrimental effects on the reproductive capacity of Red Tilapia (Ismail et al., 2021). Accumulated microplastics and the toxic compounds that come with them can cause a decrease in fertility in adult fish. This reduced fertility can be expressed as a decrease in the number of eggs, poor quality of sperm, and low mating capability (Huang et al., 2021). In addition, microplastics can impact the growth of offspring as it causes distortions in the larvae. Such developmental complications may encompass congenital defects, stunted growth, and poor adaptation rates. Heavy mortality rates among the larvae may significantly lower population recruitment, which is a critical issue in the Red Tilapia in both the wild and in aquaculture (Ajiboye & Yakubu, 2010).

2. Hormonal Disruptions

Some of the chemicals that are used in the manufacturing of polystyrene include bisphenol A which is an endocrine-disrupting chemical that has negative effects on the hormonal balance in Red Tilapia (Godswill & Godspel, 2019). Hormones are the chemical messengers of the body that are involved in the control of reproductive processes, growth, and development. Endocrine-disrupting chemicals like BPA can cause changes in hormonal levels that may disrupt the timing and fertility rates of reproductive cycles (Sahardin, 2020). In females, reduced egg production, abnormal spawning, and low egg quality are some of the effects of BPA exposure. In males, it may result in reduced or poor-quality sperm production which decreases their chances of fertilizing eggs. Endocrine disorders also impair general body growth and development, resulting in growth retardation and developmental abnormalities (Maqbool et al., 2016). Altogether, these disruptions collectively contribute to the reduction of reproductive success and fitness of Red Tilapia populations, thus demonstrating the complex nature of polystyrene microplastics on an important aquaculture fish species (Crain et al., 2008).

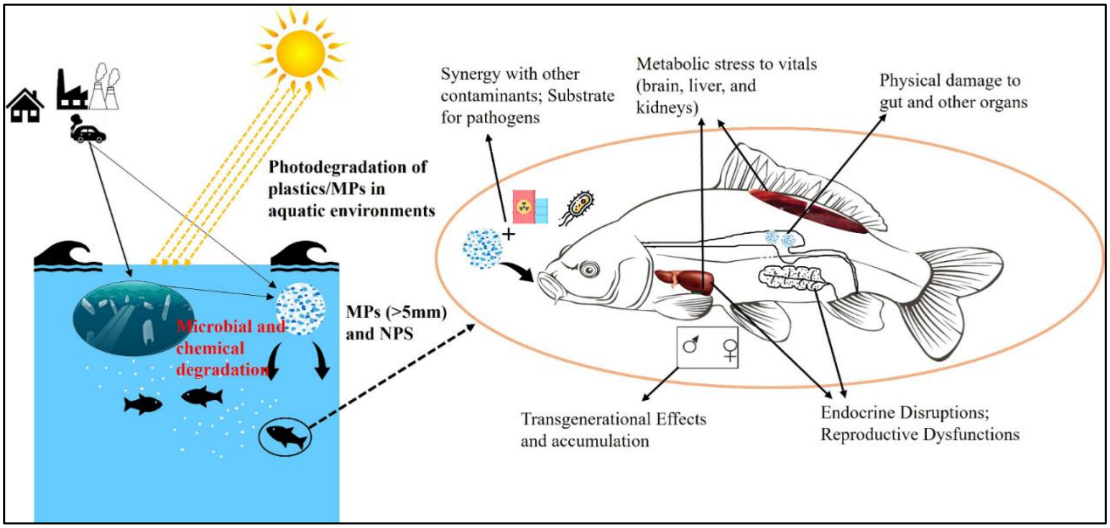


Fig. 4 Effects of Polystyrene Microplastics on Red Tilapia reproduction and hormonal disruption (bhat et al.,2024).

Removal Techniques

Mechanical Removal

1. Mechanical Filtration and Skimming

Physical removal such as mechanical filtration and skimming can be applied to remove the bulk of microplastics in water. These techniques include the use of barriers like sieves, nets, and screens to filter and separate plastics from the water body (Torkashvand & Hasan-Zadeh, 2022). Skimmers are most efficient in scooping water surface plastics that float on the surface of the water. These methods can effectively capture or scoop out larger pieces of plastics and debris but are less capable of capturing or siphoning off small particles, which can easily slip through the filtration systems (Y. Zhang et al., 2021). Moreover, mechanical methods of removal are often associated with frequent maintenance and may be rather time-consuming, thus they are not suitable for mass or continuous use (Cheng et al., 2021). Nevertheless, mechanical removal remains an important starting point in the reduction of the overall burden of plastic pollution in water bodies, particularly those that have high concentrations of plastics (Kwon et al., 2022) Elimination of microplastics at different stages in wastewater treatment plants (Kwon et al., 2022).

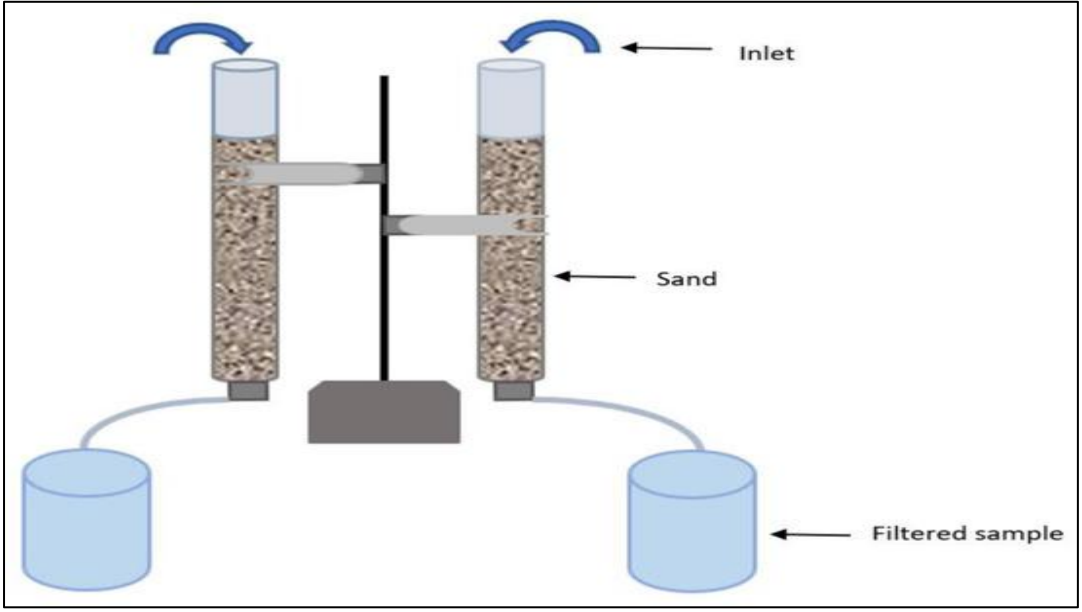


Fig 5. Sand-filter column for removing microplastic from water

Table.3 Different techniques used for the removal of microplastic from the wastewater

Adsorbent Material	Notable Features	References
Cellulose fiber	Achieved over 98% efficiency in removal	Batool and Valiyaveettil (2021)
Eco-friendly and non-toxic		
Magnetic carbon nanotubes	Achieved 100% microplastics removal	Tang et al. (2021)
Reusable		
Chitin-based sponges	Adsorption via hydrogen bonds and electrostatic interactions	Sun et al. (2021)
Biocompatible and biodegradable		
Biochar	Enhanced microplastics removal	Siipola et al. (2020)
Cost-effective process		

Sponge with chitin and graphene oxide	High adsorption capacity and mechanical strength	Sun et al. (2020)
Reusable		
Magnetic biochar	Increased microplastics adsorption efficiency	Wang et al. (2021)
Regenerable by thermal treatment		
Ferric oxide composites	Rapid and effective adsorption process	Elmaci (2020)
Cost-effective		
Magnetic sepiolite	Magnetic carrier for recycling and reuse	Shi et al. (2022b)
90% removal of polyethene plastic		
Graphene-like magnetic biochar	Higher efficiency and reusability	Liu et al. (2020a)
Economically effective		
Graphene oxide	Improved polystyrene adsorption	Yuan et al. (2020)
Follows Langmuir adsorption kinetics		
Magnetic magnesium hydroxide and polyacrylamide	Sweep flocculation and charge neutralization	Zhang et al. (2021c)
92% microplastic removal efficiency		
Cellulose nanofiber aerogel	Modified with quaternary ammonium salts	Zhuang et al. (2022)

2. Advanced Filtration Systems

Membrane bioreactors and nanofiltration are more effective forms of filtration for microplastics and removing them from wastewater before they reach natural water sources (Shen et al., 2023). MBR combines the biological treatment process with membrane filtration and can both remove organic compounds and microplastics (Krishnan et al., 2023). One of the advantages of nanofiltration is that membranes with nanometer-sized pores can filter out even smaller particles of plastics that may not be captured by conventional filters Nanofiltration systems are highly effective in the treatment of wastewater, and can lower the microplastic concentration in the environment (Malankowska et al., 2021). Nonetheless, the high costs and technical difficulty of implementing sophisticated filtration systems can act as constraints for their utilization, especially in the developing world (Ahmed et al., 2024). However, it is equally important to incorporate these technologies into the existing wastewater treatment structures to mitigate the effects of microplastics in the environment (Krishnan et al., 2023).

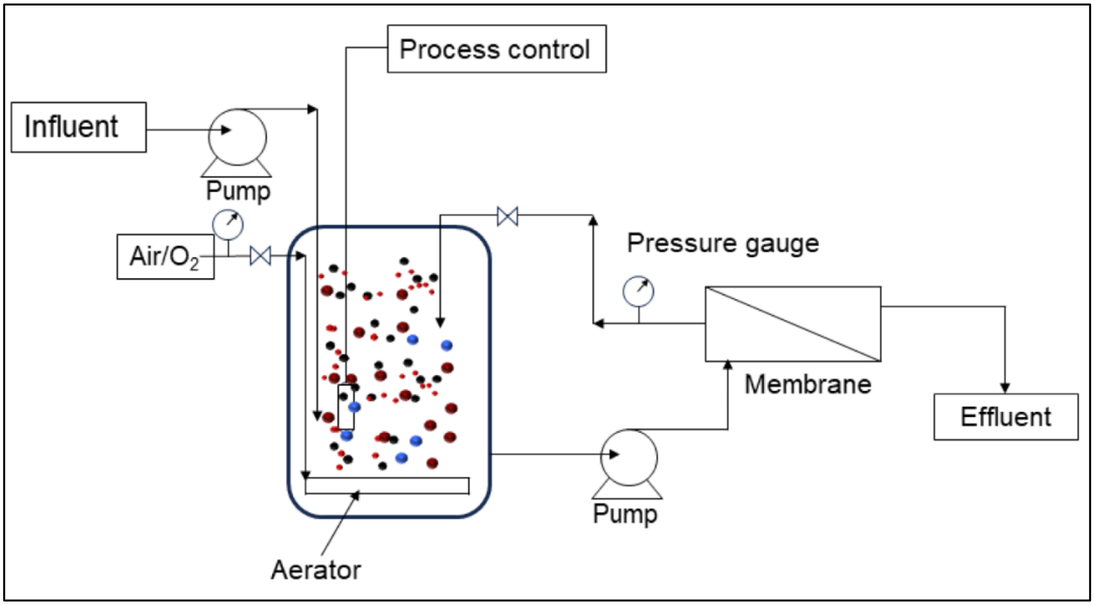


Fig. 6 Membrane bioreactors for the removal of microplastics from wastewater (khan et al., 2024).

Bioremediation

1. Microbial Degradation

Biodegradation of polystyrene and other plastics through microbes involves the use of some bacteria and fungi that can degrade polystyrene (Ho et al., 2018). Such microorganisms secrete enzymes capable of breaking down plastics into smaller and less toxic polymers (Jadaun et al., 2022). There are some bacteria like Pseudomonas and Rhodococcus which are known to degrade polystyrene and some fungi including Aspergillus and Penicillium. The use of microbial degradation in bioremediation processes has proven to be very effective in managing microplastic pollution (Bhardwaj et al., 2013). This approach can be used in places like bioreactors where conditions are optimized to enhance microbial activity. Field applications are difficult because of the fluctuating environmental conditions and the requirements necessary for the viability and functionality of the applied microorganisms (O’Callaghan, 2016). Further studies and innovations are required to improve the effectiveness and practicality of microbial degradation to accommodate it in large-scale environmental remediation.

Table. 4 Efficiency of Various Wastewater Treatment Processes in Microplastic Removal

Treatment Process	**Description**	**Removal Efficiency (%)**	**Reference**
Conventional Activated Sludge (CAS)	A traditional biological wastewater treatment method involving aerobic microorganisms.	96–98	(Lares et al., 2018; Michielssen et al., 2016)
Oxidation Ditch	A type of extended aeration treatment process for wastewater using a ring-shaped channel.	97	Lv et al., 2019
Chlorination Disinfection	A chemical disinfection process using chlorine to kill or inactivate microorganisms in water.	7	Liu et al., 2019
Ozonation	An advanced oxidation process utilizing ozone to break down contaminants in water.	90	Hidayaturrahman and Lee, 2019
Coagulation/Flocculation	A chemical process involving the addition of coagulants to aggregate suspended particles into larger flocs.	47–82	Hidayaturrahman and Lee, 2019

Rapid Sand Filtration (RSF)	A physical filtration process using a bed of sand to remove suspended particles from water.	45–97	Magni et al., 2019; Michielssen et al., 2016; Murphy et al., 2016; Talvitie et al., 2017
Anaerobic, Anoxic, Aerobic (A2O)	A biological treatment process involving sequential anaerobic, anoxic, and aerobic stages for nutrient removal.	72–98	Lee and Kim, 2018; Yang et al., 2019
Sequencing Batch Reactor (SBR)	A fill-and-draw activated sludge system for wastewater treatment operating in batch mode.	98	Lee and Kim, 2018
Discfilter	A mechanical filtration process using a series of rotating discs to filter water.	40–98	Hidayaturrahman and Lee, 2019; Simon et al., 2019; Talvitie et al., 2017
Dissolved Air Flotation (DAF)	A water treatment process that clarifies wastewaters by removing suspended matter such as oil or solids using air bubbles.	95	Talvitie et al., 2017

Reverse Osmosis (RO)	A water purification process using a partially permeable membrane to remove ions, molecules, and larger particles.	90	Ziajahromi et al., 2017
Dynamic Membrane (DM)	A filtration process utilizing a dynamic membrane formed by particles within the liquid being filtered.	99	Li et al., 2018
Membrane Bioreactor (MBR)	A combination of a membrane process like microfiltration or ultrafiltration with a biological wastewater treatment process.	≥ 99	Lares et al., 2018; Michielssen et al., 2016; Talvitie et al., 2017
Ultrafiltration (UF)	A type of membrane filtration where forces like pressure or concentration gradients lead to a separation through a semipermeable membrane.	42	Ziajahromi et al., 2017

2. Phytoremediation

Phytoremediation is the process of using aquatic plants to absorb and retain microplastics and lessen their presence in the water system (Rozman et al., 2023). Some plant species have demonstrated the capability of concentrating microplastics within their tissues. This process not only aids in filtering out microplastics from the water but also captures them in a relatively less fluid form. Further studies are being conducted to determine plant species that can fix nitrogen optimally and the best conditions that can enhance this process. Some of the aquatic plants that are possibilities for phytoremediation research include the duckweed (Lemna minor) and the water hyacinth (Eichhornia crassipes) (Manjate et al., 2020). Phytoremediation provides an environmentally friendly way of addressing the problem of microplastics in water; however, it relies on certain parameters including plant growth rates, water quality, and the types of microplastics. Phytoremediation is one of the most promising approaches to clean up contaminated sites, but it has to be applied following specific guidelines to be effective (Namasivayam & Avinash, 2024).

Policy and Management

1. Legislation and Regulation

Minimizing the use of plastic products, banning specific types of plastics, and increasing recycling measures are necessary to limit the influx of microplastics into water bodies (Prata et al., 2019). Some of the measures that have already been implemented and have been successful in several countries include policies that seek to reduce plastics such as the elimination of microbeads in personal care products (Laskar & Kumar, 2019). Other ways that can help in reducing the issue include promoting the adoption of bio-degradable products as a replacement for normal plastics. Measures such as banning single-use plastics, improving the recycling infrastructure, and implementing EPR can also help in reducing the levels of plastic pollution. Governments therefore have to ensure that such regulations are implemented to the letter and ensure that the appropriate facilities and assistance are put in place to enable compliance (Yusuf et al., 2022). Multilateralism and agreements are important since plastic pollution is an international problem and cooperation is needed to increase the effectiveness of actions taken.

2. Public Awareness and Education

To counter the problem of plastic pollution, it is imperative to increase the public's awareness about the effects of microplastics on water-dwelling organisms and to ensure that people behave as responsible consumers (Smith-Llera, 2018). Public awareness and dissemination programs can help people understand the sources and impacts of microplastics, and therefore, can encourage people to avoid the use of plastics, join recycling initiatives, and support eco-friendly products. Public participation programs including beautification activities like clean-up campaigns or citizen science activities can help develop a culture of stewardship and ownership of the problem to find solutions to the problem of plastic pollution. In particular, schools, non-governmental organizations, and the media act as key informers and influencers (Soltani et al., 2023). Environmental consciousness as a cultural asset can be employed as a tool in public awareness and campaigns that seek to achieve lower levels of plastic pollution and improve the overall ecosystem of water bodies. It is therefore important to understand and mitigate the different effects associated with these microplastics on feeding behavior, reproductive health, and potential impacts on the sustainability of valuable aquaculture resources. An effective mitigation strategy for microplastics requires the use of mechanical extraction, enhanced filtration, and bioremediation, as well as strong policies and management practices (Bhattacharya et al., 2023)vv. By joining forces in science, engineering, policy-making, and education, the occurrence of microplastics in our bodies of water does not have to be a permanent problem to the detriment of both marine and human life.

Innovative Technologies

1. Nanotechnology

In this aspect, nanotechnology seems to hold the key to the removal of microplastics from water bodies. The most impressive example of its application is the creation of nanoscale adsorbents that can selectively and efficiently capture and immobilize microplastics in water (Goh et al., 2022)vv. These adsorbents are developed to have large surfaces and chemical affinities that make them suitable for trapping microplastics (Anik et al., 2021). For example, carbon nanotubes, graphene oxide, and magnetic nanoparticles have been demonstrated to have high adsorption efficiency toward microplastics in lab tests. Magnetic nanoparticles, for instance, are easily separable from water through the application of magnetic fields which makes the removal more efficient. Furthermore, the tagging of these nanomaterials with certain chemical moieties can also improve their ability to trap microplastics (Vidu et al., 2020). Nanotechnology not only enhances the effectiveness of microplastic capture but also allows for the adaptation of the system to existing water treatment technologies, which makes the approach more versatile and effective when it comes to combating plastic pollution (Mehmood et al., 2023).

Table. 5 Efficiency of Various Nanomaterials in Microplastic Removal through Adsorption Processes

Process	Nanomaterials	Microplastics	Microplastic Sample and Concentration	Removal Efficiency	Reference

Adsorption	Graphene Oxide (GO), Graphitic Carbon Nitride (–OC3N4)	Polystyrene (PS)	Synthetic water, 1 ppm, pH: 7	Removal efficiency for Chitin alone: 63.3%, for Chitin with –OC3N4: 90.6%, and for Chitin with GO: 89.6%	Sun et al. (2021)

Adsorption	UiO-66-OH Metal-Organic Framework (MOF)	Polyvinylidene fluoride (PVDF), PS, Polymethyl methacrylate (PMMA)	Synthetic water, 1 ppm	For PVDF: Melamine: 33.0%, Melamine with UiO-66-OH: 90.1%. For PMMA: Melamine: 46.1%, Melamine with UiO-66-OH: 88.2%. For PS: Melamine: 44.7%, Melamine with UiO-66-OH: 85.7%	Chen et al. (2020)
Adsorption	Three-Dimensional Reduced Graphene Oxide (3D rGO)	PS	Synthetic water, 0.25 ppm	The PS removal efficiency is 72.63 %	Yuan et al. (2020)

Magnetism Adsorption	Iron Oxide Nanoparticles (Fe3O4)	Polyethylene (PE), Polyethersulfone (PES)	Real river water, domestic sewage, seawater	Removal efficiency for river water: 81.33 %, for domestic sewage: 82.28 %, and for seawater: 80.56 %	Shi et al. (2022)
Magnetism Adsorption	Fe-Hexadecyltrimethoxysilane (Fe-HDTMS)	PE, PS	Synthetic seawater, microplastic size 10–20 µm	Achieved a removal efficiency of 92%	Grbic et al. (2019)
Magnetism Adsorption	Magnetic Carbon Nanotubes (CNTs)	Polyamide (PA), PE, Polyethylene terephthalate (PET)	Kitchen waste treatment plant, microplastic size 48 µm, concentration 5000 ppm	Achieved 100% removal efficiency for PA, PE, and PET	Tang et al. (2021)

Catalysis	Manganese (Mn) decorated Nitrogen-doped Carbon Nanotubes (N-doped CNT)	Microplastics extracted from cosmetic products	Synthetic water, concentration 5000 ppm	Removal efficiency is 50%	Kang et al. (2019)
Catalysis	Titanium Dioxide (TiO2) nanoparticle film	PS	Microplastic size 5 µm	Achieved a removal efficiency of 99.9%	Nabi et al. (2020)

2. Electrochemical Methods

Electrochemical technologies like electrocoagulation and electrooxidation are considered for the removal of microplastics from water (Liu et al., 2023). Electrocoagulation is a process where an electric current is passed through metal electrodes that are immersed in water and this leads to the dissolution of the electrodes' metal ions (Boinpally et al., 2023). These ions create coagulants capable of uniting microplastics together, creating larger globules that can be separated through sedimentation or filtration. Electrooxidation, on the other hand, generates reactive oxygen species at the anode, which can break down microplastics into smaller and less toxic components. The two mechanisms employ electrical charges and chemical reactions to detach or degrade the microplastics (Malinović et al., 2022). Electrochemical methods are preferable to other treatment methods because they can be accurately regulated, work well across a broad range of water quality, and remove multiple pollutants at the same time. Nonetheless, issues like the amount of energy that these technologies consume, the durability of the electrodes, and the handling of byproducts are critical factors that need to be tackled to fully harness these technologies for larger-scale uses (Chen et al., 2022).

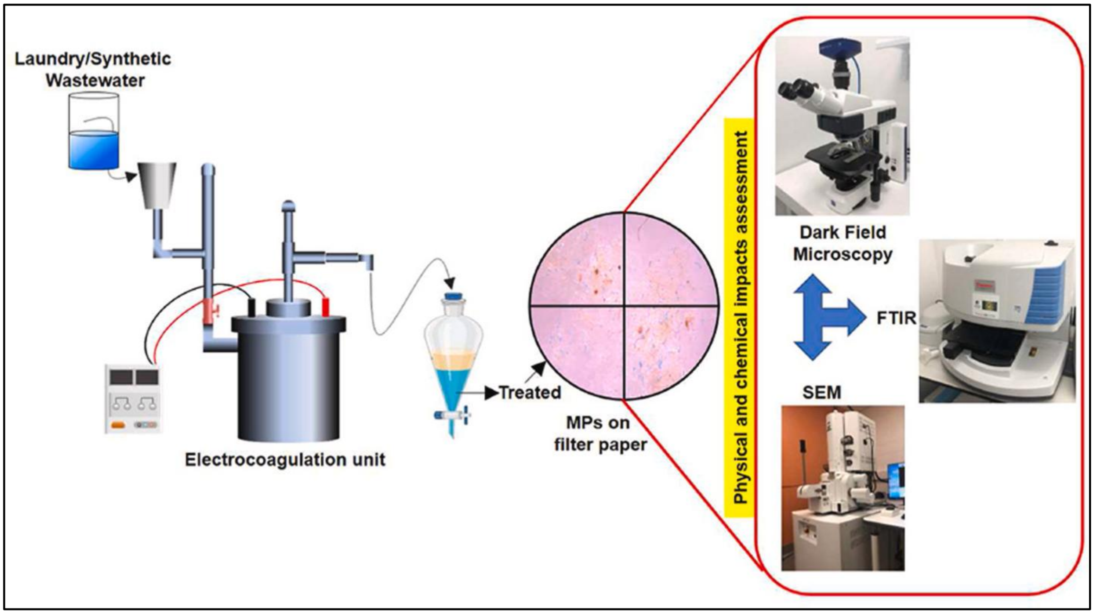


Fig. 7 Electrocoagulation unit for the removal of microplastic from wastewater. (Senathirajah et al.,2024)

Conclusion

The effects of polystyrene microplastics in aquatic ecosystems have potential risks to the Red Tilapia in terms of health and behavioral changes. Accumulation of these microplastics within an organism's body may cause physical obstruction, reduced feeding and nutrient assimilation, stunted growth, and overall poor health. Some of the common harms of polystyrene are oxidative stress, liver damage, endocrine disruption, and other harms that would negatively impact the health of these fish. Further, changes in feeding habits, the inability to avoid predators, and social imbalances resulting from microplastic ingestion can expose organisms to predation and cause shifts in population parameters. The health of the reproductive system in Red Tilapia is also affected, microplastics may lead to low fertility rates, development of offspring abnormality, and low survival rate of larvae. These harms are compounded by disruptions in hormonal balance due to exposure to chemical additives such as bisphenol A (BPA) that interfere with reproductive cycles and development.

To counter the effects of polystyrene microplastics on Red tilapia, several approaches must be employed. Advanced technologies like nanotechnology and electrochemical procedures, and mechanical and advanced filtration like mechanical filtration and filtration systems are critical. Microbial degradation and phytoremediation bioremediation approaches can be deemed environmentally friendly to degrade and immobilize microplastics. Further regulation and enforcement of plastic manufacturing and disposal, raising awareness among the public and educational institutions, are pivotal to curbing the volume of microplastics entering water bodies. Further studies and advancements are therefore needed to come up with long-term measures for addressing the effects of microplastics on water bodies. Through the adoption of scientific research, technology, and policy measures it is believed that the health of species such as Red Tilapia should be safeguarded and the aquatic resources conserved. This global environmental problem requires a collective effort of scientists, policymakers, industries, and the public to reverse the trends and protect the future of our water sources.

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