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# Threats of Microplastic Pollution on Fishes and its Implications on Human Health (Review Article)

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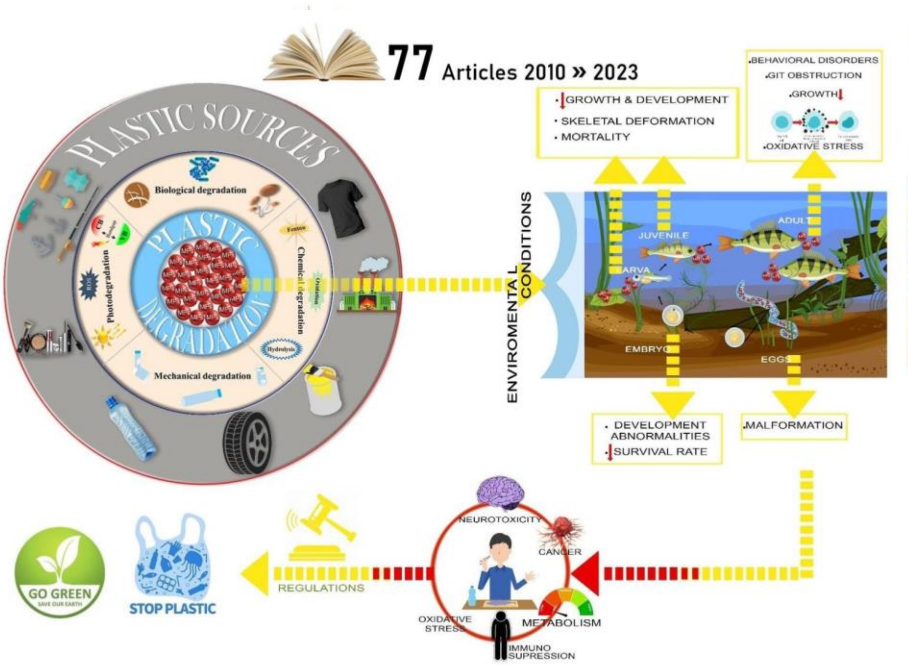
## ABSTRACT

Plastic products are one of the most commonly used materials in almost everything, including water bottles. This is due to its pons being versatile, resistant, and cheap material. Therefore, society depends mainly on this synthetic material. Anthropogenic activities as well as environmental degradation factors including mechanical and biological ones resulted in a globally ubiquitous type of pollution: plastic pollution. In such a type of pollution, plastic polymers break down into smaller particles, classified into five categories: mega-, macro-, meso--, micro, and nanoplastics. The current review summarizes the data obtained from research published in international journals, from the period extending from 2010 to 2023, concerned with microplastics, whose common size is < 5mm. The obtained data involved the characterization of the microplastics in addition to their negative impacts on fish and humans, being the end consumers in the food chain. The negative consequences of microplastic pollution on fishes start from showing abnormal behaviors to complete intestinal obstruction affecting the basic metabolism of fishes. On the other hand, among the major impacts of such polymers on human health are: oxidative stress, immunosuppression, neurotoxicity, and malignant tumors. The aforementioned diseases can eventually lead to either fish mortality, thus affecting the national income or human death. Accordingly, it is recommended to limit the use of plastics globally and shift to green eco-friendly materials. In addition to adopting different scenarios for the reduction of plastic pollution, such as cautious deposition of these solid wastes as well as their reuse and recycling. Hence, paving the way for Egypt to make significant progress toward achieving the sustainable development goals by 2040.

## GRAPHICAL ABSTRACT




## INTRODUCTION

The Plastic age is the best phrase to describe the actual situation which the world faces nowadays **(Cozar *et al.*, 2014)**. Plastics are proven to be one of the most versatile man-made materials **(Vadera & Khan, 2021).** Globally, plastics are widely used in food packaging, building and construction, automobile items, electrical devices, domestic and recreational sports, farming, healthcare, and plastic furnishings. Hence, global plastics' production was close to or even exceeded 360 million tons (Mt) in 2018 **(Plastics Europe, 2019)**, escalating from 1991 to 2021 ten times the production level **(Vadera & Khan, 2021)**. Furthermore, based on the current populations' growth rates, plastics production is expected to double, reaching 634 million tons by 2025 and more than the triple by 2050 to afford public demands, resulting in plentiful plastic debris that spread globally causing the current major problem; the plastic pollution **(WEF, 2022; Haque & Fan, 2023)**.

Plastics are known as ″poorly reversible pollutants‶ such nomenclature was given due to two critical reasons; the first is as a result of the weathering processes, which causes plastics fragmentation into micro- and nanoplastic particles that are invisible to human via the naked eye. It is noted that the aforementioned particles are hardly removed from the environment. On the other hand, the second reason is due to their emissions (greenhouse gases), such as ethylene and methane, with their toxic efficacy on the environment that cannot be curtailed**,** accumulating to levels that exceed the threshold levels **(MacLeod *et al.*, 2021)**. Such transgression will trigger negative impacts that themselves cannot be readily reversed because it will be impossible to rapidly reduce pollution levels below the threshold levels **(Persson *et al*., 2013; Arp *et al.*, 2021)**.

Plastic pollution originates from the weak and/or nihilistic management of plastic wastes and careless anthropogenic activities. Once in the environment, plastic objects degradation processes occur by biotic or abiotic factors, giving rise to smaller fragments with different sizes that can enter the food chain by various methods. For example, fish can find microplastics in their habitats and eat it thinking that these are planktons, and then they find their way through the gastrointestinal tract and accumulate in fish intestine. As humans are the end consumers in the food chain, these microplastics are transmitted to human through human consumption of contaminated food. Additionally, drinking water in reusable plastic bottles may be another route for the transmission of small fragments of plastic particles to humans **(Chen *et al.,* 2020)**.

The presence of small plastic particles in the environment has already been witnessed since the early seventies **(Buchanan, 1971)**. Nevertheless, it attracts an increasing interest from the scientific community nowadays **(Albergini *et al.,* 2022)**. Concerning the dimensions of the fragments themselves and their various shapes, they can vary from several meters to an invisible size to the naked eye, onto which their effects are based **(GESAMP, 2019)**. Interestingly, according to the aforementioned report, the small plastic particle types are classified into five categories depending on the size, namely mega-, macro-, meso-, micro- and nanoplastics, with different six shapes and variant colors, whose formation and differences will be mentioned in detail throughout the manuscript. Meanwhile, their harmful influence differs according to the particle size.

Plastic debris has spread all over the world even on uninhabited islands. Moreover, microplastics (MPs) have been recorded in Egypt. However, the data recorded on the occurrence of MPs in the River Nile particularly were insufficient. The first record was in 2020 **(Khan *et al*., 2020)**. The aforementioned authors noted that MPs can affect everything on Earth from soil and flora (plants), for their significant role in mulching to fauna, involving both aquatic and terrestrial animals as well as their embryos. Unfortunately, as a result of biomagnifications, MPs can penetrate human systems, causing serious and sometimes lethal effects **(Khan *et al*., 2020)**. It is worth mentioning that, the MPs can be transported to the seas through rivers, floods, and winds that pollute the ocean and beaches ecosystems across the branches of the rivers which afford the connection **(Bhuyan, 2022)**.

Among the sources of microplastics are fishing crafts, plastic bags, food containers and plastic drinking bottles (water and cold drinks), which afford many xenobiotic pollutants to the aquatic environment deliberately or accidentally, and hence polluting the environment causing hazard impacts on the aquatic organisms **(Zhou *et al*., 2018; Alimba & Faggio, 2019)**.

Fishes are among the affected aquatic organisms by MPs. MPs' impacts on fishes range from decreasing in predation efficiency (being stressors) to being a vector of serious pathogens infecting human, the end-consumer of fishes, besides the economic problems for fisheries **(de S´a *et al.,* 2015)**.

The human body can accumulate microplastics through the following routes:
(1) fish consumption, as the highest MPs accumulation record was found in fish muscles, the edible part of the fish **(Bhuyan, 2022)**, and (2) inhaling air containing these fine products. Besides, it was detected in (3) the dermal contact **(Albergini *et al*., 2022)**. The previous

authors added that, microplastics cause various consequential health problems to human, such as accumulating in the intestinal tract, which can cause intestinal blockage and invade the membranes with their chemical toxins and pathogens that were adsorbed on their surface before reaching human body, as well as many other major health problems that will be discussed later throughout the manuscript.

As a consequence of the aforementioned critical problem ″microplastic pollution‟ and its detrimental effects on fishes and human, being the end consumer, the current review was delved to summarize the data covering the following points:

1) Plastic pollution (types of plastic degradation product), its formation, classification, and variant spreading methods in the aquatic environment.
2) Identification of MPs and their characterization.
3) MPs' impacts on fishes (embryos, fry, larvae, and adults).
4) Influence of MPs on human health and food security.
5) The latest solutions and proper treatments for such type of pollution.

## MATERIALS AND METHODS FOR DATA COLLECTION AND ANALYSIS

**- Online study sites**

**Data were obtained from articles that scientists and researchers have presented.**

**- Data collection**

The first phase involved the identification of related studies. In order to conduct a systematic literature search, the following specifications were made for database; the vast majority of the papers and review articles used in the current review were published in the international journals during the period extending from 2010 to 2023. A total of 77 articles were investigated.

**- Searching database**

• Scopus, Google scholar, PubMed, Sci-hub and Multidisciplinary Digital Publishing Institute (MDPI) websites were explored.

**- Keywords utilized for the current investigation:**

" Plastic pollution"; " Plastics"; " The link between plastic pollution and climate change"; " Plastic emissions"; " Plastics types"; "Microplastics" "Identification of microplastics"; "Characterization of microplastics"; "Microplastics effects on water pollution"; “Microplastics impacts on fish"; "Effects of microplastics on fish embryos”; "Microplastics influence on organs and tissues of fish"; "Histopathological effects of microplastics on fish"; "Microplastics efficacy on human"; "Microplastics as vectors of pathogens", and "Amelioration and treatment of microplastic pollution in water".

## 1. Plastics and their fate in the environment

Plastics' use has expanded 25-fold during the last 40 years due to their minimal cost, durability, low weight, and elasticity **(Sutherland *et al.*, 2016)**. The issue of plastic pollution has become a more serious and widespread worldwide catastrophe. Plastics have an adverse effect on several environmental domains including animals and may extend to human health, as well as global health and social ramifications, starting with the extraction of raw materials for production, and ending with the final disposal of huge garbage **(Rhodes, 2018)**. As pollution rates rise, these consequences of plastics are expected to rise as well. By 2040, mishandled end-of-life plastic waste will be entering land and aquatic environments at rates of annually 11 million and 18 million tons, respectively, which are more than twice higher than those recorded in 2016 **(Lau *et al*., 2020)**. Plastic wastes "missing plastic" can be sideswiped into smaller particles via the following five processes, namely mechanical, thermal, chemical, photo and biodegradation processes, as summarized in Table (1).

### *1.1 Mechanical degradation*

It occurs due to wind and ocean current as well as thawing of snow. The external force from the surroundings leads to the mechanical breakdown of plastics, the wind as well as ocean movement, causing friction of plastics on the coastal shores with rocks and sand. Additionally, in colder areas, freezing and thawing of ice degrade the accumulated plastics **(Cooper & Corcoran, 2010; Zhang *et al*., 2021)**.

### *1.2 Thermal degradation*

It happens as a result of temperature's elevation. When plastics absorb heat, their polymeric chains breakdown, releasing sequential forms of radicals, ending with alkoxy radicals. Such radicals contribute to the formation of aldehydes, ketones, esters, or alcohols, leading to plastics degradation **(Kamweru *et al.*, 2011)**. The aforementioned authors added that, the plastic debris on the coastal shores undergoes thermo-oxidative degradation due to the increasing temperatures. Due to prolonged exposure to sunlight, it undergoes gradual thermal degradation, along with an enhanced photo degradation.

### *1.3 Chemical degradation*

Chemical degradation takes place as a result of anthropogenic activities, mainly industrial activities, where vapors radiating from factories mix with the atmosphere and precipitate in the form of acid rain. Acid rain contains pollutants, such as sulfur dioxide, nitrogen dioxide, ozone, and other volatile organic compounds. The previously pollutants can, either degrade plastics directly or facilitate radical formation through photochemical reactions. The aforementioned mechanisms can be well described in the following examples: (1) Sulfur dioxide and nitrogen dioxide, through ultraviolet (UV) excitation and reaction with oxygen, can promote ozone formation, which can break the carbon double bonds in plastic polymers through a chain scission mechanism. (2) Acid rain can result in enhanced degradation of the plastic debris present on the terrestrial soils or alter the pH of the water environment resulting in plastics degradation **(Hocker *et al*., 2014; Lee & Li, 2021)**.

### *1.4 Photo degradation*

It occurs as a result of exposure to both high-energy UVB (290–315 nm) and medium energy UVA (315–400 nm) sunlight. This process involves the formation of free radicals and oxidation of plastic polymers, leading to the creation of peroxides that break down into alkoxy and hydroxyl radicals; e.g. prolonged exposure of plastic litter on terrestrial soil or coastal shorelines to increased UV radiation enhancing plastic degradation **(Zhang *et al.*, 2021)**.

### *1.5 Biodegradation (microbial degradation)*

This process takes place via microbes, such as wax worms or any other decomposers in general. The enzymes secreted by these microbes can cause plastics degradation **(Haque & Fan, 2023)**.

**Table 1**. Summary of plastic degradation processes from articles published from the period 2010 till 2023

| Plastic degradation | | |
|---|---|---|
| **Process** | **Mechanism** | **References** |
| **Mechanical degradation** | It occurs due to wind and ocean current as well as the thawing of snow. | **(Cooper & Corcoran, 2010; Zhang *et al.*, 2021)** |
| **Thermal degradation** | When plastics absorb heat, their polymeric chains breakdown, | **(Kamweru *et al.*, 2011)** |
| | releasing sequential forms of radicals, ending with alkoxy radicals. Such radicals contribute to the formation of aldehydes, ketones, esters, or alcohols, leading to plastics degradation. | |
| **Chemical degradation** | It takes place as a result of anthropogenic activities, mainly industrial activities, where vapors radiating from factories mix with the atmosphere and precipitate in the form of acid rain. Acid rain contains pollutants, such as sulfur dioxide, nitrogen dioxide, ozone, and other volatile organic compounds. | **(Hocker *et al.*, 2014; Lee & Li, 2021)** |
| **Photo degradation** | It occurs as a result of exposure to both high-energy UVB (290– 315 nm) and medium energy UVA (315–400 nm) sunlight. This process involves the formation of free radicals and oxidation of plastic polymers. | **(Zhang *et al.*, 2021)** |
| **Biodegradation (microbial degradation)** | This process takes place via microbes, such as wax worms or any other decomposers, in general. The enzymes secreted by these microbes can cause plastics degradation. | **(Haque & Fan, 2023)** |

## 2. Classification of plastic degradation products

According to the guidelines for the Monitoring and Assessment of Plastic Litter and Microplastics **(GESAMP, 2019)**, plastic degradation products are classified into five major types, according to the paticles' size, in descending order, namely: mega, macro, meso, micro and nanoplastics, as shown in Table (2).

## 3. Microplastics

Microplastic particles in the marine environment exhibit significant heterogeneity differing in size, color, shape, density and chemical composition. They can originate from one of two sources, either primary or secondary **(Duis & Coors, 2016; Hermabessiere *et al*., 2017)**.

It is noteworthy to mention that, microplastic particles can be divided into two sub-classes, viz. primary and secondary microplastics. The primary sources include MPs that are directly produced and released to the environment in a micro-size range, originating from items such as personal care products (PCPs), e.g. cosmetic products, medical products, industrial applications (e.g. drilling fluids and abrasives), plastic pellets which are used as feedstock for the production of larger items, and clothing fibers **(Thompson, 2015; Duis & Coors, 2016; Hermabessiere *et al*., 2017)**. Furthermore, a crucial and often underestimated primary microplastic source is originated from the discharge of microplastic fibers by washing machines **(Browne *et al*., 2011; Napper & Thompson, 2016)**.

**Table 2.** Classification of plastics according to the size of the resultant particles following degradation **(GESAMP, 2019)**.

| Plastics types | Common size | Measurement units |
|---|---|---|
| Mega-plastics | >1 m | Meters |
| Macro-plastics | 25–1000 mm | Meters, Centimeters, Millimeters |
| Meso-plastics | 5–25 mm | Centimeters , Millimeters |
| Microplastics | <5 mm | Millimeters, Microns |
| Nanoplastics | <1 µm | Nanometers |

On the contrary, the secondary MPs result from the fragmentation of larger pieces due to ultraviolet light (UV), mechanical, photochemical oxidation, microbial degradation and physical action by wind and waves **(Reisser *et al*., 2014; Duis & Coors, 2016; Hermabessiere *et al*., 2017)**.

Most common sources of MPs include synthetic textiles, car tires, city dust, roads marking or colors used in paintings, fishing equipments and plastic pellets, as shown in Fig. (1) **(Sharifinia *et al*., 2020)**.

Global investments in the field of research on MPs have increased significantly in the past 10 years owing to the increased awareness of the issue of microplastics as a new pollutant **(Frias & Nash, 2019)**. Interestingly, these plastic fragments may cause many concerns since they are small enough to be ingested by living organisms, and therefore reach humans through the consumption of contaminated food **(CONTAM, 2016; Mercogliano *et al*., 2020)**. The first record of food contamination with MPs was only reported at the beginning of 2010 **(Boerger *et al*., 2010)**.

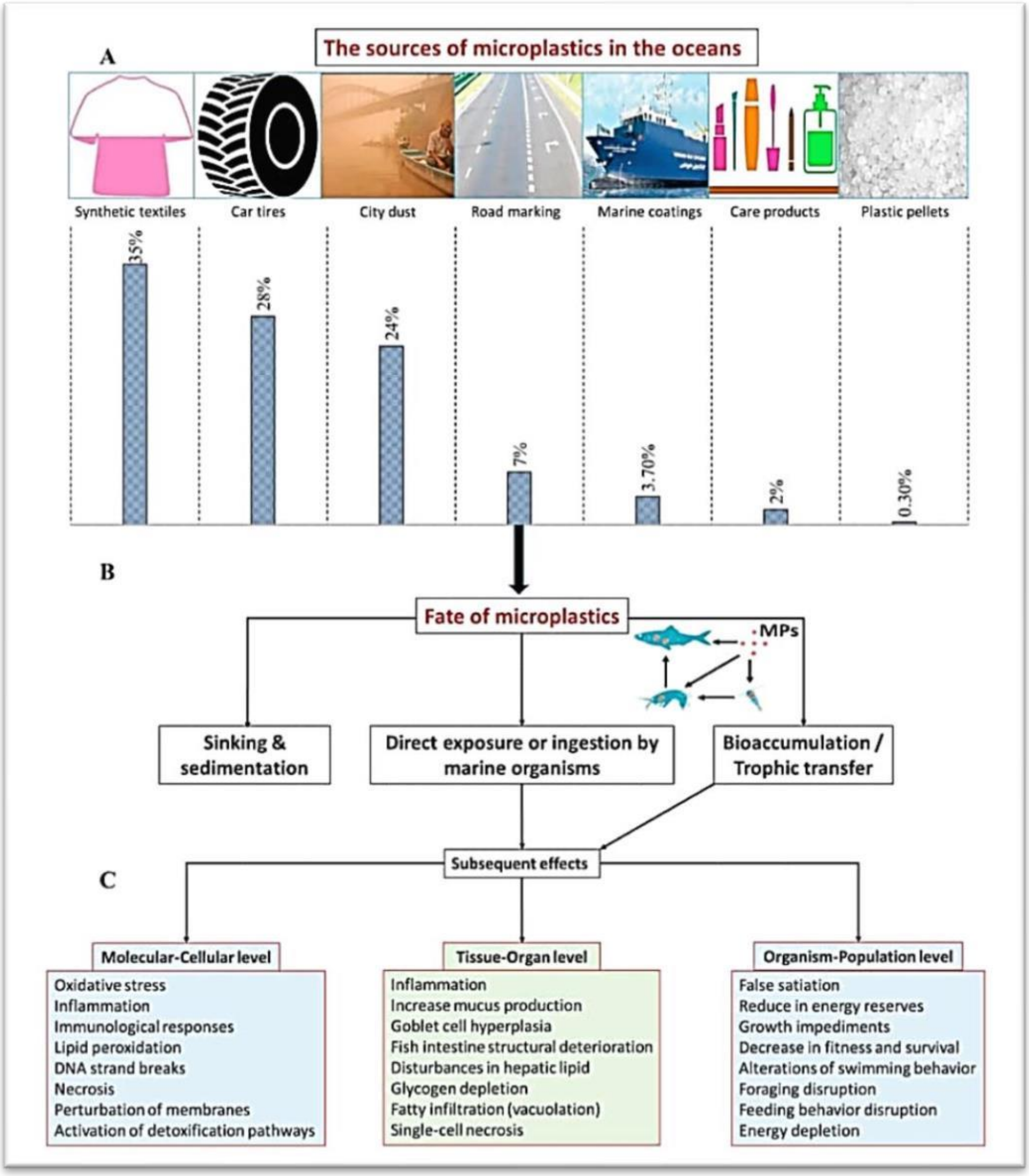



**Fig. 1.** A schematic representation of: (A) Sources, (B) Fate and (C) An overview of some of the subsequent effects of MPs that have been documented from the molecular to population levels **(Sharifinia *et al*., 2020)**

### *3.1 Identification of MPs*

To date, there is still no clear definition that is broad enough to encompass all the criteria needed to describe microplastics **(Frias & Nash, 2019)**. So far, the most widely used definition is that microplastics are particles smaller than 5mm in their longest dimension. This definition has been adopted in practical terms as it considers the size, below which ingestion by many species of marine biota occurs **(GESAMP, 2015)**. Such a definition was approved by the National Oceanographic and Atmospheric Administration of the USA **(NOAA)** and the Marine Strategy Framework Directive of the EU **(MSFD) (Lusher, 2017)**.

Depending on their types, shapes, size, and composition, microplastics impose different toxic levels on the environment and ecology. Toxicity is an inverse proportion with a microplastic size **(MacLeod *et al.*, 2021)**.

In order to identify the exact type of MPs, the following processes must be adopted in any environmental matrix, namely sampling, extraction, identification and quantification, as displayed in Fig. (2).

### 3.1.1 Separation and purification

#### 3.1.1.1 Sampling

Identification starts with taking samples from the field, including water (examination by smear on slide under light microscope) or biota, mostly fishes (histological examination may be under light or electron microscope) **(Mai *et al*., 2018)**.

Sometimes, scientists make porous media samples from the superficial layer of coastal or lakeshore beaches or from the seafloor or lake bottom due to the simplicity of such a method **(Ng & Obbard 2006)**.

#### 3.1.1.2 Flotation

Briefly, the sample matrix is mixed with a flotation solution, typically by shaking to homogenize the slurry. This slurry is then allowed to sit for several hours so that denser materials (e.g., sand) are settled. Supernatant factions are normally collected for further analysis. To improve extraction efficiency, the solution above the sediment or the overall solution is subsequently separated by filtration **(Zobkov & Esiukova 2017)**.

Density separation is widely used to isolate low-density particles from higher- density sand, mud, sediment, and other sample matrices. For example**,** polypropylene (PP) and polyethylene (PE) have lower densities than sea water (~ 1.10 g $cm^{-3}$). High-density plastics (e.g., polyvinyl chloride (PVC)) have densities up to 1.40 g $cm^{-3}$ or greater, depending on additives and attached biofilms **(Mai *et al*., 2018)**.

That's why for high densities, various solutions have been employed to isolate MPs from these matrices. The most popular, used solution is the saturated NaCl, which is cheap and nonhazardous and has a density of approximately 1.20g $cm^{-3}$ to drawback MPs with a higher density (e.g., PVC) though not all being completely extracted **(Fries *et al*., 2013)**.

**Nuelle *et al*. (2014)** developed a two-step method, using the air-induced overflow with NaCl solution for pre-extraction and NaI solution (1.80g $cm^{-3}$) for further flotation with recovery rates ranging from 67% (expended polystyrene, EPS) to 99% (PE) for different plastic classifications.

Interestingly, the best to extract almost all MPs and widely used flotation solution is $ZnCl_2$ (relatively toxic) 1.50– 1.70g $cm^{-3}$ **(Liebezeit & Dubaish, 2012)**. In some cases, oil can also be used. Nowadays, technical instruments with 98 and 100% respectively recovery percentage use an elutriation column and a Munich Plastic Sediment Separator **(Claessens *et al*., 2013)**.

Generally, the previous method may contain other plastic contaminants out of the specimen measured from tools, thence, sieving and filtration were suggested by **Masura *et al*. (2015)**. These are stainless steel sieves or glass fiber filters; instead of plastic tools, they are used to minimize procedural contamination, and rinsing is always required after each sieving or filtration.

#### 3.1.1.3 Extraction and purification

Purification is the key to an accurate identification of MPs. Although the effects of solutions used on MPs characteristics have been demonstrated, potential influences on organic chemicals affiliated to MPs remain unknown. Therefore, future efforts should be directed toward the effects of pretreatment on environmental MPs **(Mai *et al*., 2018)**.

In order to allow clear identification of the type of plastics, organic matter attached to the surface of MPs in the environmental samples should be removed. **Nuelle *et al*. (2014)** demonstrated that, 35% $H_2O_2$ is better recommended than other solutions, such as 30% $H_2O_2$, 20% HCl, and 20–50% NaOH in dissolving organic matter although it could cause color fading on MPs. To dissolve biogenic matter from the environmental MPs, enzymatic digestion can be used **(Cole *et al*., 2014)**. For biota samples, 10% KOH solution was applied to isolate MPs from the contents of digestive tracts **(Zhang *et al*., 2017)**.

Moreover, **Roch and Brinker (2017)** developed a novel procedure combining NaOH and $HNO_3$ to yield an accelerating digestion process and recovery rates higher than 95%, with few changes in the characteristics of MPs isolated.

### 3.1.2 Identification

#### 3.1.2.1 Visual sorting

After separation and purification, target MPs need to be sorted and counted from the remaining matrix. Large ones can be sorted directly and easily. While, smaller- sized ones need further observation under a dissection microscope, typically a stereomicroscope, after the samples are dried under cover in an oven, generally at 60 °C, all visually **(de Carvalho & Baptista Neto, 2016)**.

#### 3.1.2.2 Pyrolysis-Gas Chromatography-Mass Spectometry (Py-GC/MS) and Thermal Desorption- Gas Chromatography-Mass Spectometry (TDSGC/MS)

Pyr-GC/MS allows only one particle at a time to go through the pyrolysis tube, which is both time consuming and limited by the aperture size of the tube (< 1 mm). On the other hand, the TDS-GC/MS method has been used in the analysis of MPs composition in the environmental samples compared with Pyr-GC/MS; TDS-GC/MS can process larger sample mass and measure more complex matrices **(Dümichen *et al*., 2015)**.

As a consequence, the best advantage of the latter technique is its ability to analyze both the polymer type and organic additives of MPs simultaneously. Upon being extracted from environmental matrices, plastic particles are thermally deconstructed before determining the polymer composition of each particle with GC/MS **(Fries *et al*., 2013)**.

**Fischer and ScholzBöttcher (2017**) employed characteristic fragment ions from each type of plastic as markers to identify and quantify trace amounts of MPs in the environmental samples with Pyr-GC/MS; however, this approach could yield only the mass of each type of MPs.

### 3.1.2.3 Fourier Transform Infrared Spectroscopy (FT-IR spectroscopy)

FT-IR and its optimized technologies, such as micro FT-IR, attenuated total reflectance (ATR) FT-IR, and focal plane array detector-based micro FT-IR imaging are likewise used in MPs identification **(Cheung *et al*. 2016)**.

**Harrison *et al*. (2012)** postulated that, both micro FT-IR and ATR FT- IR give satisfactory performance in identifying polyethylene MPs. However, ATR FT-IR was better in obtaining spectra of MPs with irregular shapes than micro FT-IR; nevertheless, it was solely suitable for analyzing particles larger than 500µm **(Löder & Gerdts, 2015)**.

**Löder and Gerdts (2015)** suggested that a resolution of 8 $cm^{-1}$ was optimal for micro FT-IR to produce high-quality data and save the measurement time. Additionally, FT-IR usage at a resolution of 8$cm^{-1}$ was examined by **Song *et al*. (2015)** and proved its success in MPs identification and counting directly on filter paper after drying at 60°C.

### 3.1.2.4 Raman spectroscopy

This is another promising analytical technique frequently used for MPs detection **(Zhang *et al*., 2016)**. It is mostly used for examining small particles up to 1µm. Moreover, Raman spectroscopy proved better responses to non-polar plastic functional groups than other analytical methods after rigorous strong sample purification **(Lenz *et al*., 2015)**.

### 3.1.3 Quantification

Quantitative data are needed to illustrate the abundance of MPs in the environmental matrices and can be manually done with the assistance of microscope or weighted with a scale with concentration units of "items/particles per $m^2$ " and "items/particles per $m^3$" which are used to characterize MPs in the surface water sampled by trawling, while MPs concentrations in the water column or bulk surface water are usually quantified as "items/particles per $m^3$ "**(Mai *et al*., 2018)**.

## *3.2 Microplastics types*

Microplastics are heterogeneous in composition which are manufactured with different polymers, namely polyethylene, polystyrene, polyvinylchloride and polyurethane, with varied densities. They either float in neutrally buoyant state or sink to the river/ocean floor with biofilm on its surface, moreover they often incorporate additives, such as fillers, plasticizers, colorants and stabilizers **(Cole *et al*., 2011)**.

In Bahr Shebeen Canal, the Nile Delta in Egypt, the most common polymer types for *O. niloticus* and *C. gariepinus*, as estimated by **Khallaf *et al*. (2023)**, were polyamide 6, alkyd resin, poly propylene, polyethylene terephthalate, rayon and polyethylene.

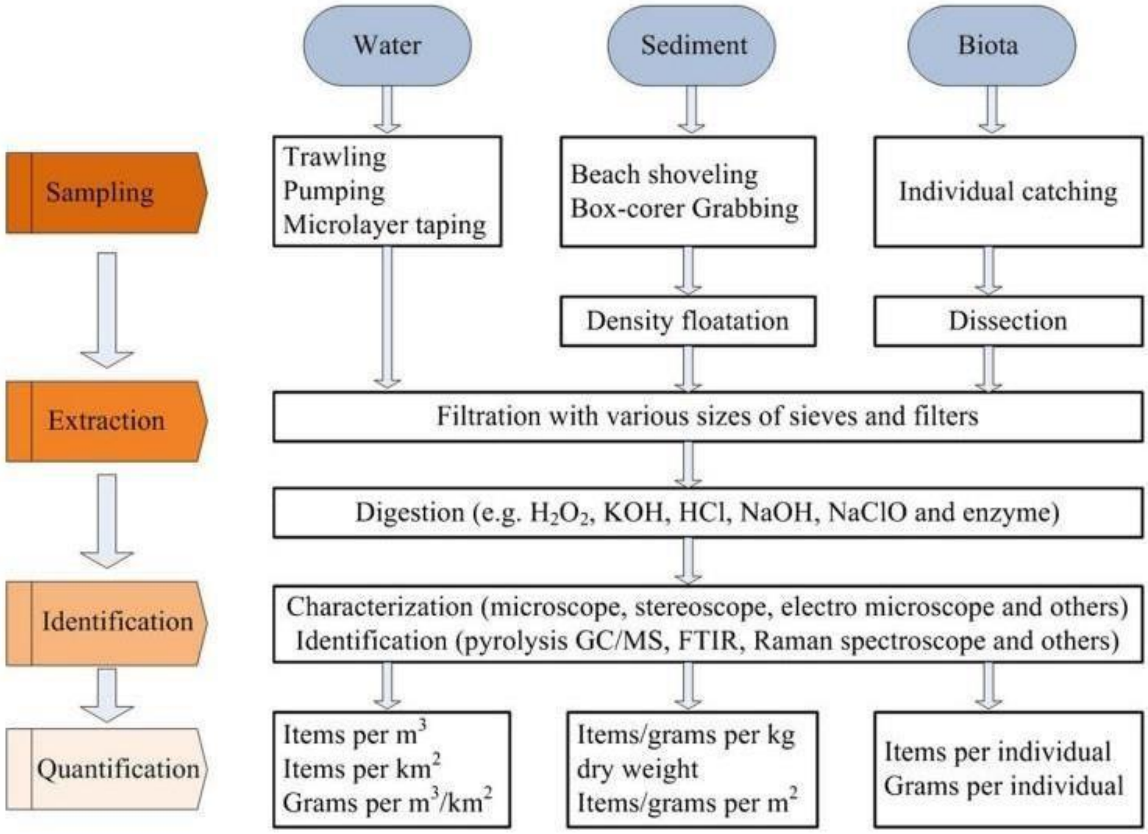



**Fig. 2.** A flow chart of the analytical processes for analyzing MPs in various environmental matrices **(Mai *et al*., 2018)**

### *3.3 Shapes of microplastics*

As previously mentioned in the fate of plastics in the environment, plastic litter can be broken up into microplastics via photodegradation, mechanical impact, ambient weathering, or microbial degradation **(Haque & Fan, 2023)**, with variable shapes, such as fragments, fibers, films, foam, and beads, as exhibited in Figs. (3, 4 & 5). Notably, fibers are the most common and abundant shape of microplastics, followed by the thicker, longer or more elongated particles and the random or irregular shaped particles **(Wu *et al*., 2018; D'Hont *et al*., 2021)**.

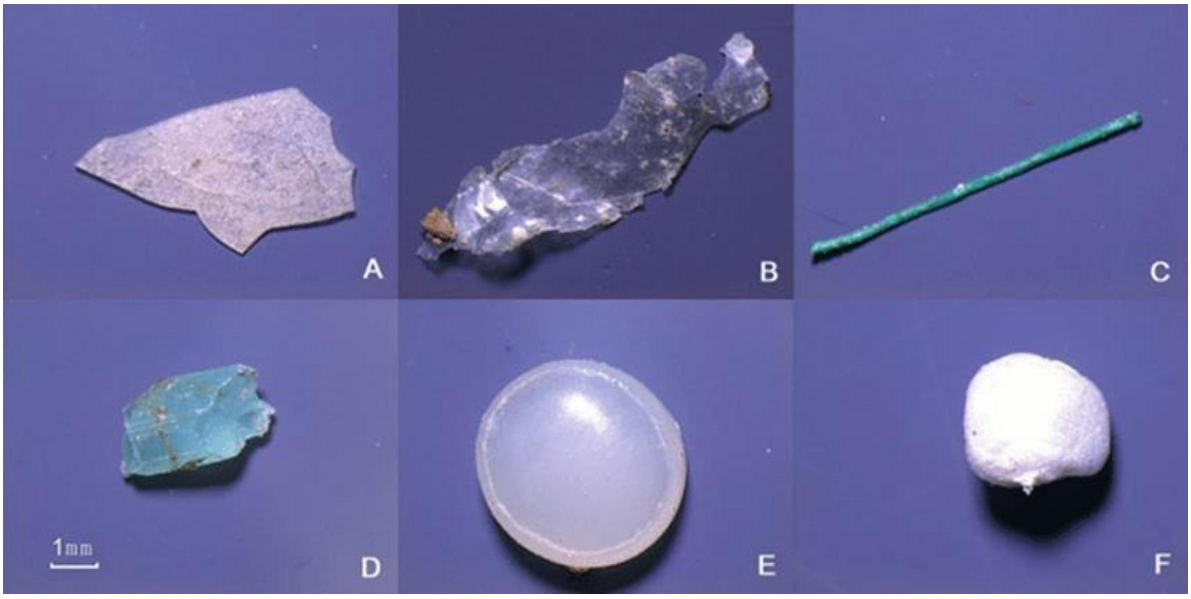



**Fig. 3.** Shapes of typical microplastics collected from inland waters (Qinghai Lake and Three Gorges Reservoir) in China (A: Sheet; B: Film; C: line/fiber; D: Fragment; E: Pellet/Granule and F: Foam) **(Wu *et al.*, 2018)**

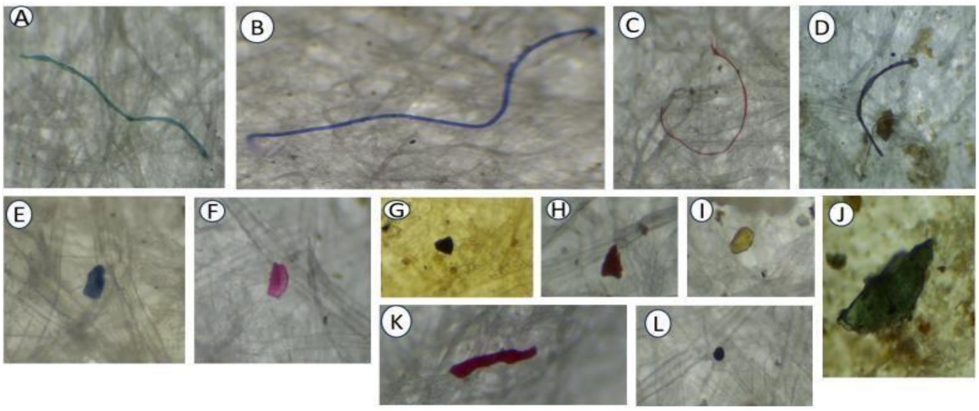



**Fig. 4.** Photomicrographs showing various shapes and colors of MPs present in the stomach and muscles of *O. niloticus* and *C. gariepinus* (Images A, B, C and D correspond to fibers; E, F, G, H and I to fragment; J and K to film and L to pellet) **(Khallaf *et al*., 2023)**

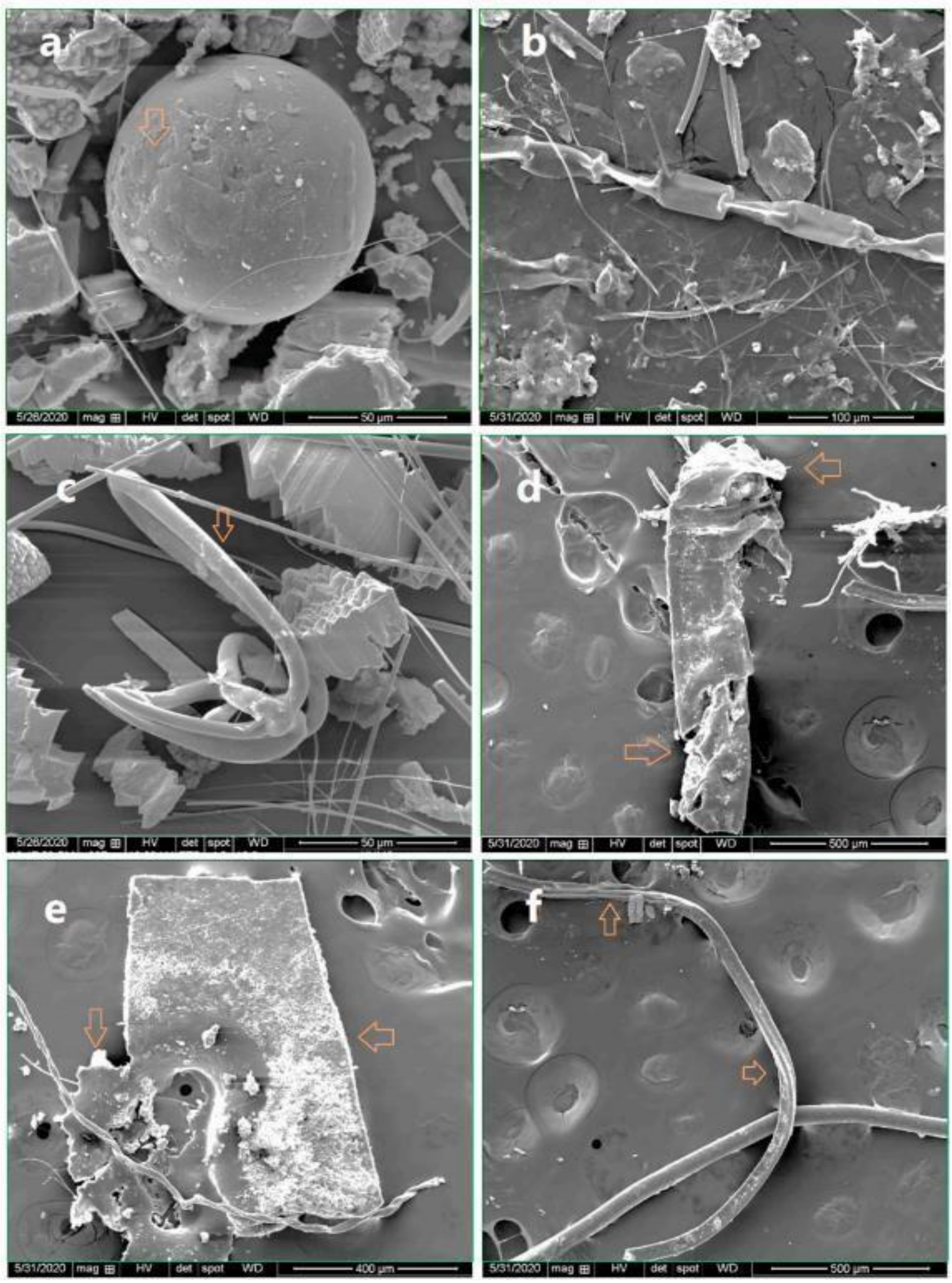



**Fig. 5.** Scanning electron-micrographs of MPS isolated from the stomachs of some riverine fishes. (a) Microbeads, (b,c & f) Fibers, (d) Irregular fragments and (e) Film **(Heshmati *et al*., 2021)**

### *3.4 Microplastic colors*

Microplastics can possess variant colors, viz. white, transparent, yellow fibers, green angular, blue, red and green regular or irregular particles, as illustrated in Fig. (6). Such colors may be acquired from the interaction in the environment or from the stabilizers and additives added during plastic production. The most abundant microplastic colors are white or transparent, followed by red and black, whereas the green color was the least abundant color

**(D’Hont *et al*., 2021)**.

Besides, the color of MPs is useful to identify potential sources of plastics and potential contamination **(Zhang *et al*., 2020)**. The MPs extracted from dewatered sewage sludge could be distinguished by their colors: blue, yellow, black, red/orange and white. The percentages of the abundance of MPs in color were as follows: white (58.18%), yellow (21.82%), black (10.00%), red/orange (9.09%) and blue (0.91%) in order. The light MPs (yellow and white) occupying for a higher proportion could be caused by weathered and faded function of light and hydraulic effect **(Galafassi *et al*., 2019)**. On the other hand, the consumption of black plastics for agriculture was responsible for a relatively higher proportion of MPs featured with such a color (**Li *et al***., **2018)**.

## 4. Sources and percentage of microplastics in the environment

Anthropogenic activities are the first line of all types of environmental pollution on the Earth, moreover they are the fundamental sources where plastic debris makes its way to the aquatic environment **(Goswami *et al*., 2020; James *et al*., 2020; Alfaro-Núñez *et al*., 2021)**. For example, packaging, which depends mostly on plastics, is often disposed of carelessly in the environment after use instead of using a special plastic bin purposed for recycling, then the prevalent waste materials are brought to the seas through the rivers, floods, winds, ocean, and beaches ecosystems. Additionally, the discarded fishing crafts pollute the water ecosystem **(Zhou *et al*., 2018)**. On the other hand, the extreme weather events, such as storms, hurricanes, and floods can transport and disperse plastic debris across larger areas, thereby increasing their distribution in the environment **(Cooper & Corcoran, 2010)**.

The first report of MPs in the aquatic environment dates back to the early 1970’s **(Jambeck *et al*., 2015)**. MPs were found all over the world’s water environment even the uninhabited islands, such as the Black Sea and Caspian Sea basins **(Haque & Fan, 2023)**. Moreover, microplastics were observed in the Egyptian River Nile, where they were recorded in the two most purchased types from local sellers in Cairo; *Oreochromis niloticus* and *Clarias garipienus*, which after examination showed that 75.9% of the Nile tilapia and 78.6% for the catfish of the examined samples possess clogged digestive tracts with MPs (65% fibers, 26.5% films, while the rest were fragments) **(Khan *et al*., 2020)**.

It was noticed that the global release of MPs into the ocean is about 1.5 million tons per year. The vast majority of MPs originate from land-based sources, while only approximately 4% is generated from ocean-based activities. Synthetic textiles (35%), erosion of tires while driving (28%), city dust (24%) are reported to be the most principal routes of MPs release into the marine environment. On the other hand, marine coatings (3.7%), personal care products (2%), and plastic pellets (0.3%) seldom account for 6% of the MPs released into the oceans. Road runoff (tires, road markings, and pellets represent 66%), wastewater treatment systems (25%), and wind transfer (7%) are assumed to be the main pathways of MPs to the oceans. Considering the input of MPs in the marine environments, it is crucial to know the fate and subsequent effects of these particles on the marine animals **(Boucher & Friot, 2017)**.

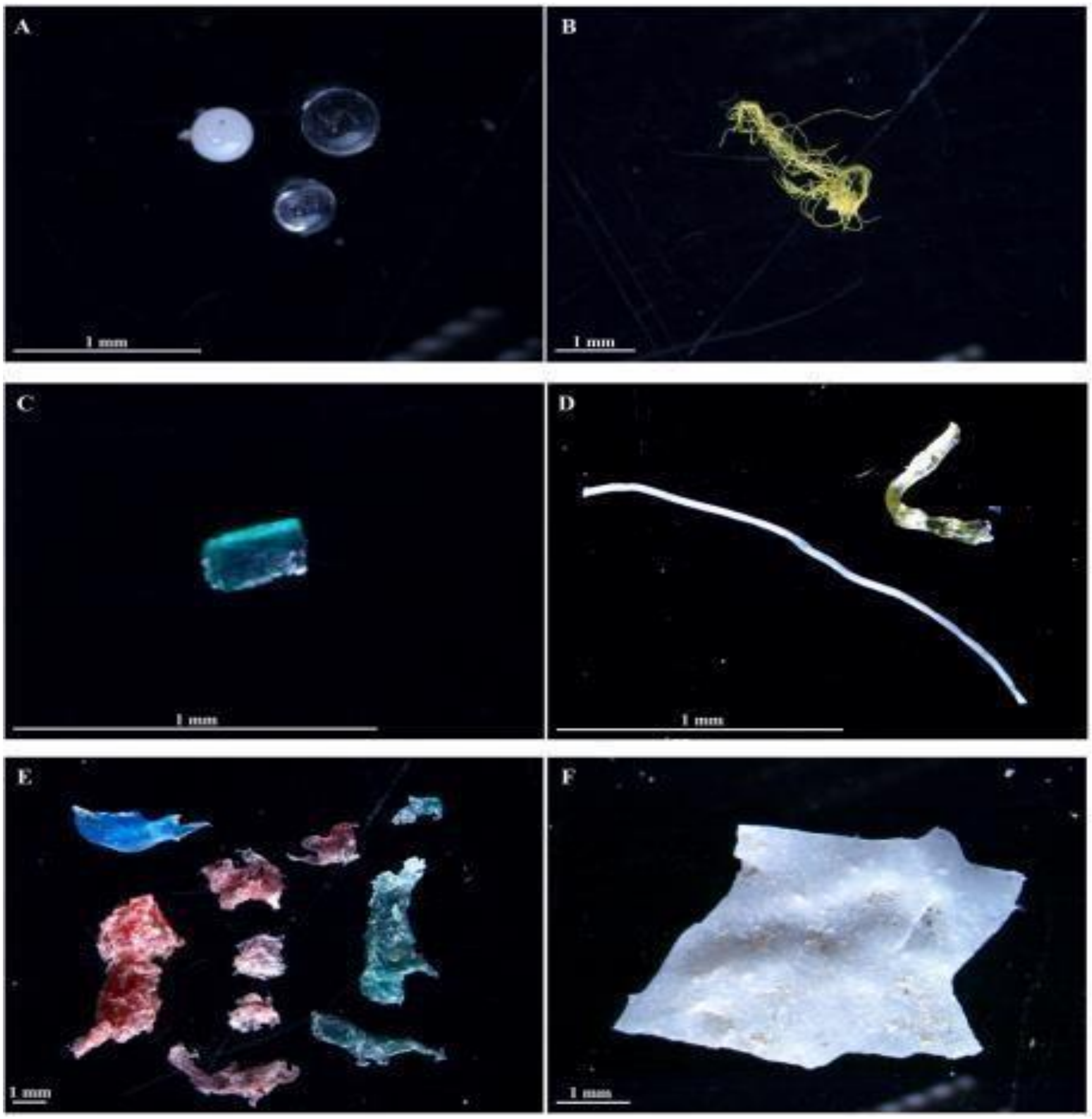



**Fig. 6**. Different colors and shapes of microplastics: A) White and transparent spheres, B) Yellow fibers, C) Green angular fragment, D) White and yellow elongated fragments, E) Blue, red and green irregular particles, F) White films. Types (A, C–F) are considered to be fragments, while (B) are considered to be fibers **(Wu *et al.*, 2018)**

## 5. How plastics debris reach the aquatic environment

### *5.1 Climate change - Plastics pollution cycle*

Plastics are the most common type of anthropogenic waste representing 95% of the litter accumulated on the shorelines, water and the seabed **(Galgani *et al.*, 2019)**.

It is worth mentioning that, there is an interaction between the climate change and plastic pollution that creates an unhealthy cycle in each of them intensifying the effect of each other and hence the impact on the ecosystems and environmental health that affects the pedosphere, hydrosphere, and atmosphere of the environment. Additionally, today's global warming and the extreme rise in the temperature cause plastic thermal degradation, meanwhile increasing small plastic particles' (microplastics) quantities, especially the fragment shape causing an extra elevation in the global warming by affecting the carbon cycle and carbon dioxide absorption in the oceans; when fragments increase in the oceans, both $CO_2$ in atmosphere and global worming increase, as illustrated in Fig. (7) **(Haque & Fan, 2023)**.

The previously mentioned authors added that, the elevated temperature leads to extreme weather events, such as glacier thawing, which can increase the distribution and accumulation in various environmental compartments of their particles, especially the small plastic particles stored in the ice after melting in any ocean around it or farther to reach the aquatic environment.

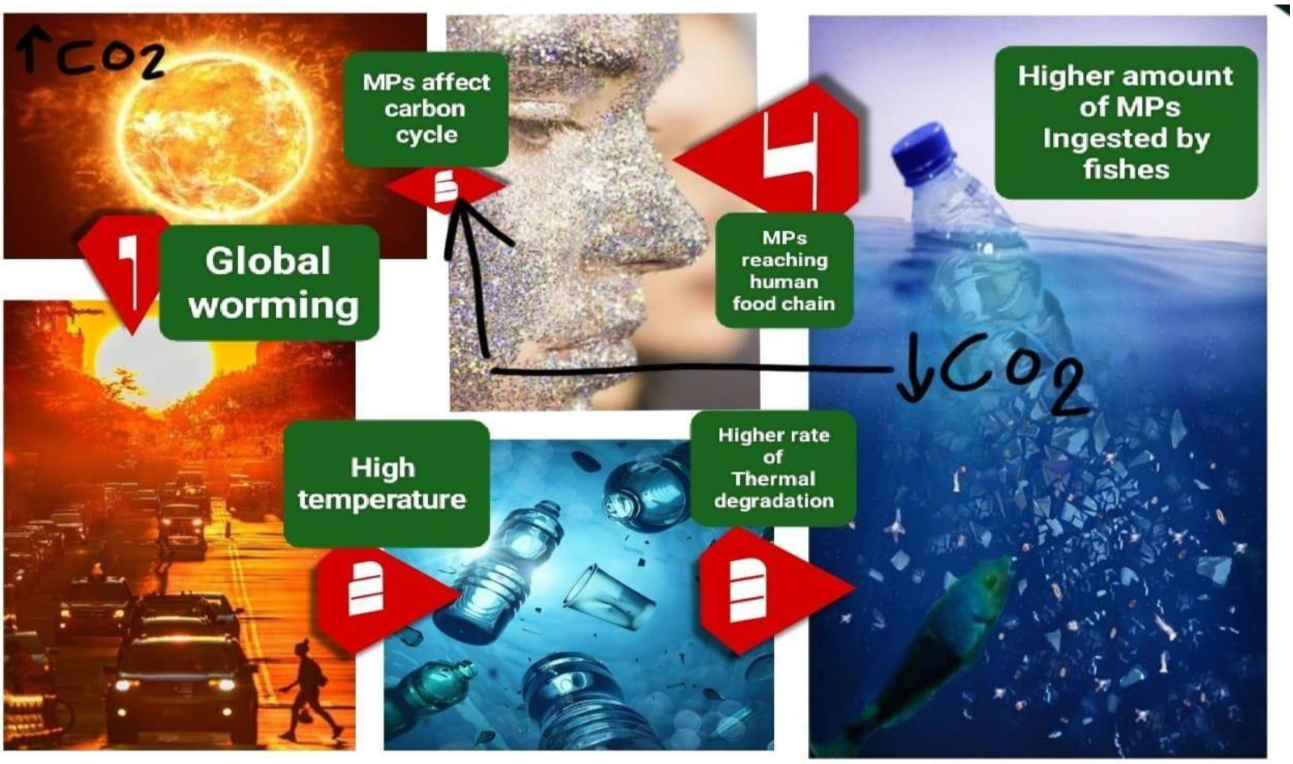



**Fig. 7.** A diagram illustrating the relationship between climate change and plastic pollution

### *5.2 Microplastics and mulching*

MPs can be used in agricultural soils through plastic mulching with polyethylene films or “biodegradable” plastic films, compost, and sludge-derived biosolids with plastic residues **(Bläsing & Amelung, 2018)**, and polymeric stabilizers against soil erosion, as shown in Fig. (8) **(Arp *et al*., 2020)**. Current plastic fractions in the soils reach up to 0.1% of the soil organic carbon **(Bläsing & Amelung, 2018)**.

The percentage of plastics in the agricultural soil is larger than that on the ocean’s surface. Mismanaged mulches lead to surrounding or wrapping of the soil particles with plastics that can escape to lakes or rivers reaching and affecting the aquatic animals then humans as end-consumers. The body ingest or inhale particles that can be accsumulated in the body cavities, releasing fragments and chemicals that potentially penetrate the epithelial layers and tissues **(MacLeod *et al*., 2021)**. Accordingly, plastic pollution of soils is poorly reversible **(Chamas *et al*., 2020)**.

It was found that about half of the annual global litter production, which reached 370 million tons in 2019, accounts for non-biodegradable materials, whereas about 80% of the marine wastes has a terrestrial origin **(Jambeck *et al.*, 2015)**. Consequently, the anthropogenic wastes are present in all compartments of the water bodies, ranging from the shorelines to the remote deep-sea, owing to their high mobility in the marine environment, where they are transported by currents and winds **(Van Cauwenberghe *et al.*, 2013; Ryan, 2015)**.

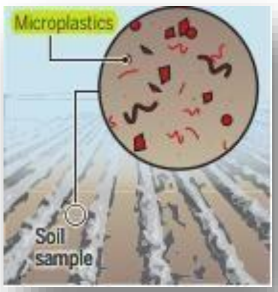



**Fig. 8.** A diagram illustrating the presence of microplastics in the soil samples **(MacLeod *et al.*, 2021)**

### *5.3 Microplastics vertically positioning in the oceans' layers*

Upon reaching the water column or seafloor, the small particles of plastics floating on the ocean surface that is sometimes called "missing plastic," can turn into a film or foam or any small plastic particle by the weathering processes. It may stay in the water column or accumulate in the seafloor according to the biofilm (heteroaggregates of plastic particles with natural organic matter) formed on the surface of fragments (Fig. 9) **(Koelmans *et al.*, 2017; Coyle *et al.*, 2020)**.

Accordingly, plastics in the global oceans can reach several thousand meters of depth in many areas, and as **Koelmans *et al*. (2017)** mentioned that the water column is a huge potential reservoir for neutrally buoyant plastic pollution that could have very poor reversibility. The previously mentioned authors added that the mass balance modeling estimated that 99.8% of the plastics that entered the ocean since1950 is located below the surface so can affect fishes and subsequently humans.

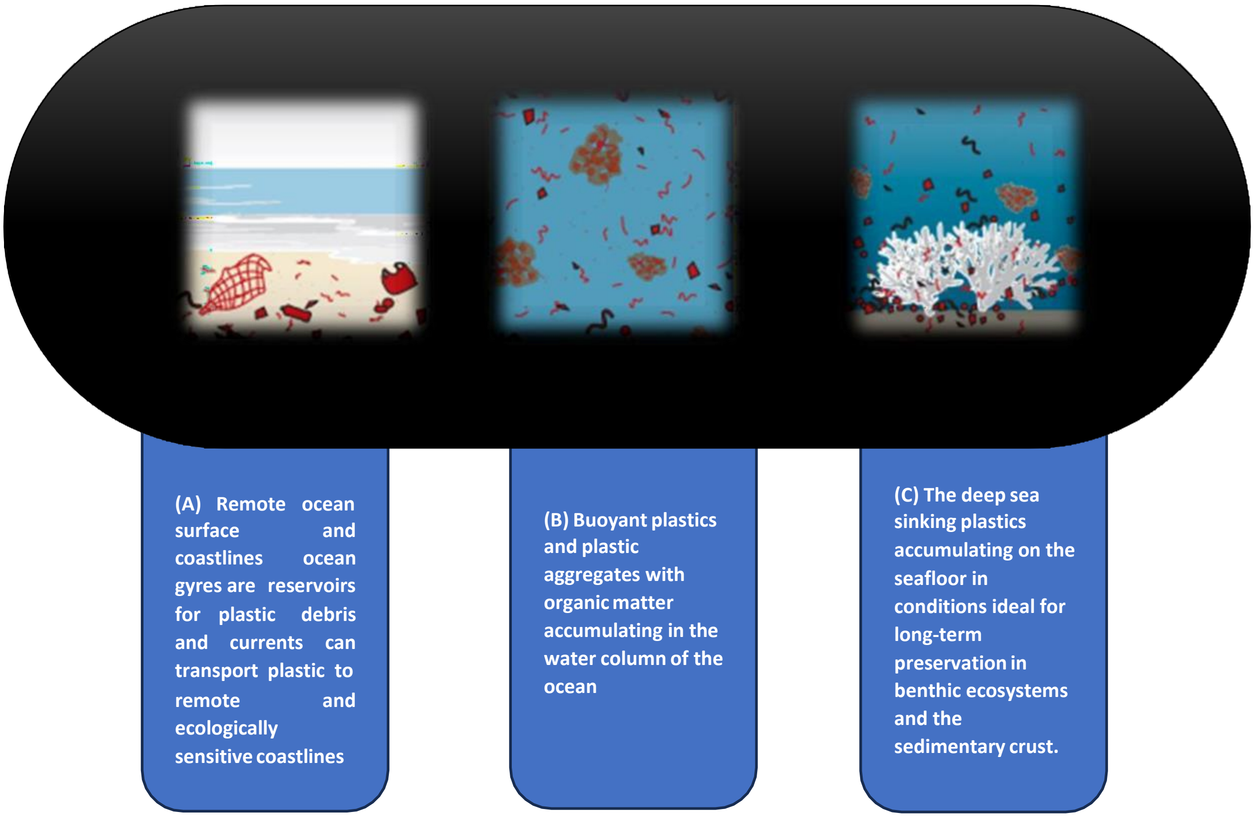



**Fig. 9.** (A), (B) and (C) showing the stages of plastic debris degradation products in the ocean's layers **(MacLeod *et al.*, 2021)**

## 6. Microplastics influence on aquatic organisms and human

The floating and incessant properties of MPs enable them to be widely dispersed in the aquatic environment as a marine contaminant via the ocean currents **(Lusher, 2015)**. MPs can be introduced to all phases of the marine food chain **(Setälä *et al.*, 2018)**. Therefore, aquatic organisms can swallow MPs with their food by default because of the size similarity. Notably, the consumed MPs differ according to the organisms and location, moreover they can vary even in the same region **(Desforges *et al.*, 2015; Walkinshaw *et al.*, 2020)**.

Recently, MP ingestion has been documented in marine species from the smallest planktonic animals to the top predators, including microzooplankton, fish, and sea turtles **(Raju *et al.*, 2019)**. Nevertheless, lower trophic levels organisms, such as zooplankton, invertebrates, and echinoderms appear to be more vulnerable to their harmful impacts **(do Sul & Costa, 2014)**.

It is worth mentioning that, there are three deleterious consequences that would happen upon organisms' exposure to MPs, including physiological disorders as well as toxic & noxious effects **(Davidson & Dudas, 2016)**. The physiological disorders may be attributed to the ingestion process of MPs **(Pedersen *et al.*, 2020)**. The more MPs intake, the more likely risks encountered on the consumed species, such as reduced development and variance in feed habits **(Horton *et al.*, 2018)**.

On the other hand, the toxic reactions occur due to the discharge of hazardous substances additives, such as plasticizer, antioxidants, flame retardant and pigments that are added during the manufacture of plastics. The previously mentioned substances may be leached into the tissues of the body, resulting in induced changes or bioaccumulation. The toxicity can differ according to the ratio of additives needed for each plastic **(Botterell *et al*., 2019)**.

Nevertheless, noxious reactions may take place as a result of pollutants and biofilm on the MPs surface area. They result from two factors, namely weathering and hydrophobic nature. The latter promotes the adsorption of pollutants to the MPs' surface at a higher concentration, thus making MPs act as carrier for contaminants to enter the aquatic species (**Issac & Kandasubramanian, 2021)**. Polycyclic aromatic hydrocarbons, organohalogenated pesticides, hexachlorocyclohexanes, and chlorinated benzenes are some of the most common contaminants present on the surface of MPs **(O'Donovan *et al*., 2018)**. On the other hand, biofilm may be bacteria or viruses **(MacLeod *et al*., 2021)**.

The dynamics of the absorption of organic pollutants into plastic material depend on the properties of both the particular polymer and the specific contaminant **(da Costa *et al.*, 2017)**.

Since humans are the end-consumers of the aquatic organisms, detrimental impacts are expected upon exposure to MPs. As previously mentioned in the manuscript, the routes of administration of MPs to humans could occur via different routes: their infiltration and direct release into the drinking-water resources, cosmetics, eating habits, dust particles, and recurrent use of plastic containers **(Issac & Kandasubramanian, 2021)**.

### *6.1 MPs effects on fishes*

There are two types of microplastics affecting fishes. First is the pure or pristine MPs with no additives from production or environment. While, the second is mixed MPs which may contain stabilizers or Bisphenol A (BPA), phthalates, as well as brominated flame retardants **(Campanale *et al.*, 2020)**. **Bhuyan (2022)** mentioned that immature fishes are more susceptible to mortality by MPs than adult fishes. Consequently, we will demonstrate the detrimental influence of MPs different developmental stages of fish.

#### 6.1.1 Impact of MPs on adult fishes

As shown in Fig. (10) and Table (4), the cumulative effects of MPs on fishes, including intestinal damage, oxidative stress, inflammation, behavioral change, reproductive organs malformations, neurotoxicity and severe case mortality of the fishes is the final destination. We will illustrate some of the most prominent impacts.

##### 6.1.1.1 The impact of MPs on the digestive system

The gastrointestinal tract (GIT) is one of the main routes for MPs exposure, they are usually found in the stomach, intestine (Fig. 11) and metabolic system tissues and cause unfavorable cellular alterations in fishes. MPs can also concentrate in the gills and epidermis, but the effect is not explored that much like the digestive tract **(Karbalaei *et al.*, 2018)**. It is noteworthy mentioning that, the cellular uptake of MPs to the GIT lumen occurs, either via endocytosis or paracellular persorption process, as shown in Fig. (12) **(Bhuyan, 2022)**.

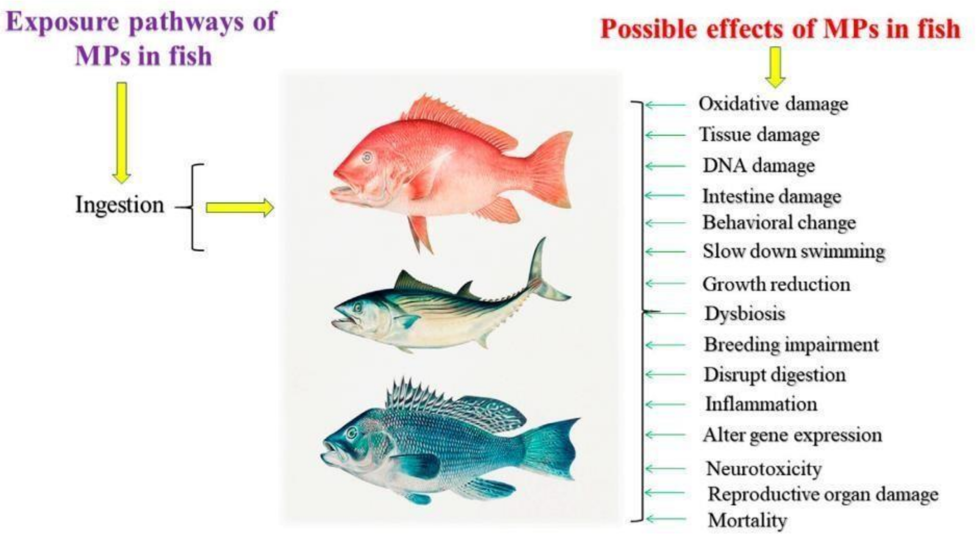



**Fig. 10.** The possible effects of MPs in fish body after ingestion
**(Bhuyan, 2022)**

Interestingly, MPs mostly build up in the GIT of fishes following their consumption, producing obstructions across the digestive tract and decreasing the feeding efficiency owing to the loss of appetite **(Lusher *et al*., 2013; Wright *et al*., 2013a)**.

At the tissue level, MP exposure impacts include GIT damage **(Wright *et al*., 2013b)**, disturbances in hepatic lipid and energy **(Lu *et al*., 2016)**, goblet cell hyperplasia **(Asmonaiteˇ, *et al*., 2018),** and inflammation **(Qiao *et al*., 2019)**.

Structural deterioration of the fish's intestine was reported by **Ped` a *et al*. (2016)**, along with cellular and metabolic alterations, including the distribution of cholesterol between muscle and liver, single cell necrosis, glycogen depletion and fatty vacuolation **(Rochman *et al*., 2014)**.

Additionally, the exposure to both pristine and contaminated MPs decreases the number of the intestinal goblet cells in the European seabass **(Espinosa *et al*., 2019)** and the 90-days post fertilization zebrafish, as shown in Fig. (13) **(Limonta *et al*., 2019)**. Additionally, **Tarasco *et al*. (2022)** suggested that contaminated MPs may alter the intestinal homeostasis and trigger inflammation.

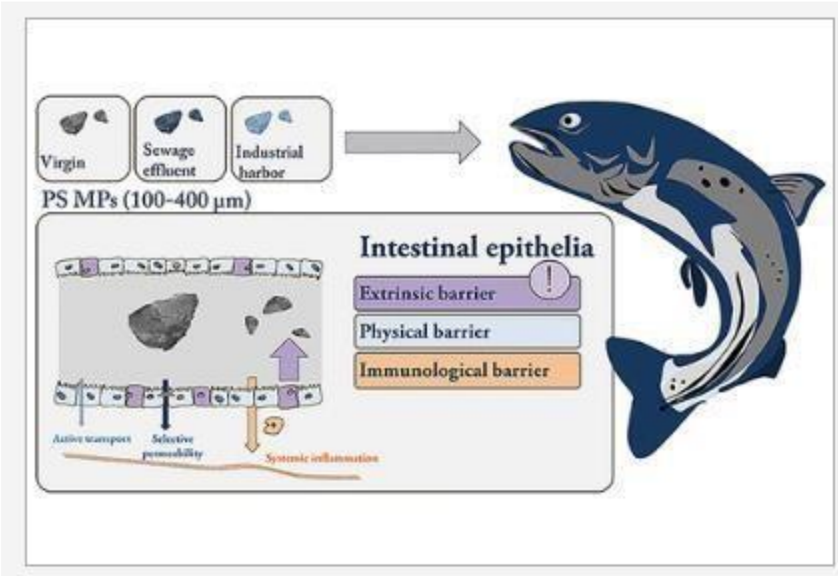



**Fig. 11.** A diagram showing MPs inside the intestinal epithelia of the rainbow trout (**Asmonaite *et al.*, 2018)**

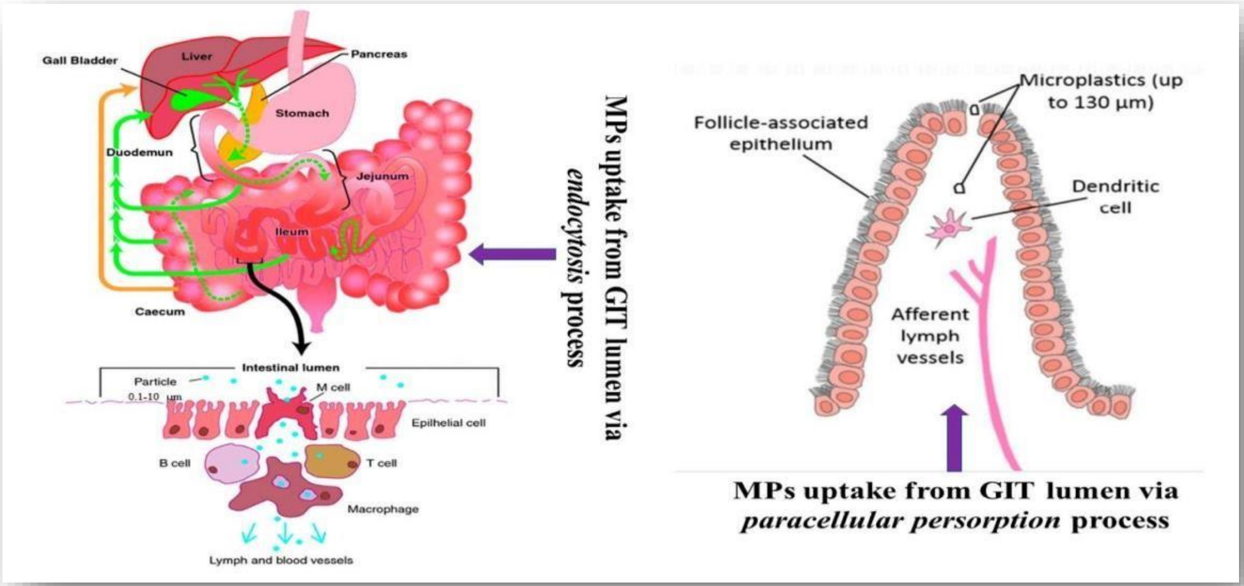



**Fig.12.** A diagram revealing different ways of MPs uptake from gastrointestinal tract (GIT) lumen after exposure **(Bhuyan, 2022)**

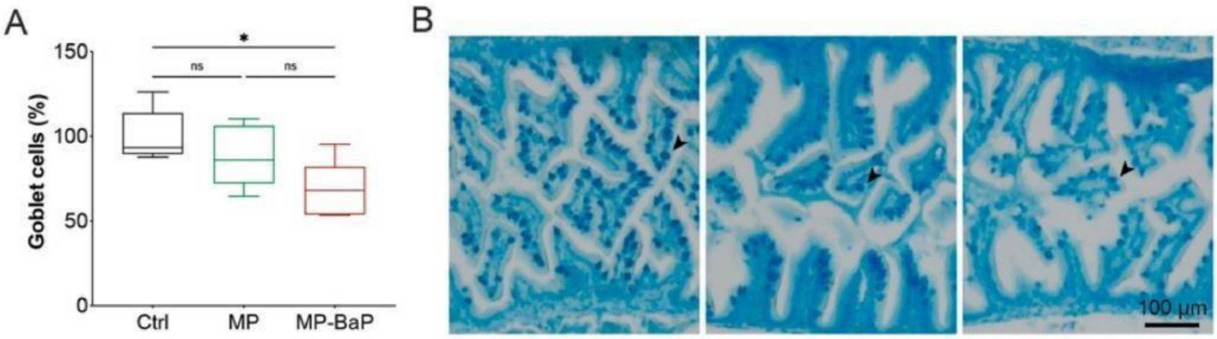



**Fig. 13.** (A) A schematic diagram showing the percentage of reduction of the number of goblet cells in the intestines of 90-days post fertilization zebrafish upon supplementation with pristine MPS and MPs spiked with benzo[α]pyrene, respectively, compared to the control. (B) Photomicrographs of T.S. of the intestines of 90-days post fertilization zebrafish showing the reduction in the number of the goblet cells (arrow head) along with MPs supplementation (**Tarasco *et al*., 2022)**.

*Oryzias melastigma* was the second most studied fish subjected to physical impairment due to MPs ingestion **(Xia *et al*., 2022)**. Growth inhibition, dysbiosis of fish gut, reduction of weight, disturbances of the liver, and growth retardation are visible effects in this fish **(Wang *et al*., 2022)**.

Last but not least, the intake of MPs could induce anatomical and functional changes in the digestive tracts, causing dietary and developmental issues in fish, even though fishes can reject MPs in pseudo feces, but this process consumes a lot of energy, and thus weakens the fish **(Huang *et al*., 2022)**.

#### 6.1.1.2 The MPs significance on the fish's immune system

MPs can induce an immune response in fish species via the regulation of neutrophils and granulocytes cells or cytokine production causing disruption in the endocrine system **(Espinosa *et al*., 2018)**. Fig. (14) demonstrates the most probable effects of MPs on the immune system of fishes.

Moreover, inflammation is usually a protective reaction in the tissues in response to harmful stimuli, such as damage, infection, or chemical stimulants. Mostly, this process helps the immune system and its ability to clear the stimulus **(Jeong *et al*., 2017)**.

Moreover, inflammation due to MPs exposure can cause interference in the immune system components leading to response in the neutrophil trap release, lysosomal membrane destabilization, and granuloma formation, eventually, MPs can hinder or prevent cell fixing mechanisms **(Greven *et al*., 2016)**. They added that, polycarbonate and polystyrene particles act as stressors to the innate immunity of *Pimephales promelas*, where they significantly increase degranulation of primary granules, neutrophil extracellular trap release and weakly increase oxidative burst activity.

The aforementioned authors postulated that the activation of neutrophils is crucial for any animal's defense, and their function is a valuable tool for assessing the health status of individuals and animal populations. If the normal functioning of neutrophils is interrupted, and their ability to phagocytose and kill microorganisms is disrupted, the normal growth and survival of an individual animal are at risk **(Maddison *et al*., 2023)**. The worst-case scenario is the MPs ability to transport microorganisms and pollutants, and they work as a non-living vector for chemical and biological contamination **(Wang *et al.*, 2016)**.

Among the immunological responses of *Girella laevifrons* upon exposure to a high MPs concentration are: severe effect on leucocytic infiltration and hyperemia compared to goblet and cryptic cell loss and villi cell loss (**Ahrendt *et al.*, 2020)**. This case can further be linked to microbiota dysbiosis in intestines, as described in zebrafish **(Qiao *et al.*, 2019)**. The damage of the gut reduced the abundance of actinobacteria and increased the abundance of pathogenic bacteria **(Ouyang *et al.*, 2021)**, which weakened the function of the intestinal barrier and increased the sensitivity to the immune response, triggering leucocytic infiltration and accounted largely for the overall high small-intestine histomorphological lesion indices. Furthermore, a delay in the full recovery of villi and epithelial lesions, as indicated by their indices, might contribute to the situation.

Cells have mechanisms for handling and detoxifying these substances as previously mentioned. However, many biological processes produce reactive oxygen species (ROS) in sufficient concentrations causing cell damage and, as a result, tissue is damaged or experiences over inflammation **(Jeong *et al.*, 2017)**. The latter authors and **Espinosa *et al*. (2018)** added that, among the most prominent effects of MPs at the molecular-cellular level, in fishes, is the induction of oxidative stress causing impairment in fish immune parameters, as that found in the studies of **Solomando *et al*. (2021)** and **Zhang *et al.* (2022)** on *Sparus aurata* and *Danio rerio*, respectively.


**Fig. 14.** Potential impacts of MPs particles on fish immune system. lysozyme (LZM); acid phosphatase (AcP); alkaline phosphatase (ALP); haemocyanin (Hc); alkaline phosphatase (AKP); phenoloxidase **(**PhO) **(Sharifinia *et al.*, 2020)**.

### 6.1.1.3 Effects of MPs on fish behavior

Behavior represents the unique interface between the internal and external forces that determine an organism's fit and survival **(MacPhail *et al*., 2009)**. Behavior anomalies can happen without any obvious morphological deformations or subsequent decrease in survival rates. Behavior changes have proven to be more sensitive and act as the important endpoints for toxicological study **(Little & Finger, 1990)**. It was noted that, MPs induce some changes in the behavioral patterns of fish, such as foraging and feeding behavior, alteration of swimming behavioral activities and mating behavior in addition to speed **(Qiang & Cheng, 2019)**.

### 6.1.1.4 MPs influence on fish reproduction

Reproduction is an energetically intensive process; thus, nutritional intake can have adverse effects on an organisms' fecundity. Reproductive toxicity refers to detrimental impacts on any stage of the animals' reproductive cycle, such as gametogenesis, gamete and oocyte quality, fecundity, egg production, and sperm swimming speed **(Sussarellu *et al*., 2016)**.

It was noted that, dietary supplementation of polyethylene MPs contaminated with benzo[α]pyrene (Bap) in the diets of *Danio rerio* at a level of 1%, impaired the relative fecundity and the success of breeding events, as shown in Fig. (15A, B) **(Tarasco *et al*., 2022)**. The previous authors suggested that Bap plays a crucial role in disrupting the female reproductive performance. Moreover, a delayed maturation of the gonads and decreased fecundity were reported in a 3- monthold marine medaka exposed to 10μm polystyrene particles for 60 days, while hatching rate and offspring body length were also affected **(Wang *et al*., 2019)**. Similarly, waterborne exposure to BaP decreased the number of spawned eggs; the fertilization rate and the hatching success in both zebrafish and medaka **(Gao *et al*., 2018; Sun *et al*., 2012)**. Furthermore, **Yan *et al*. (2020)** discovered an emerging paradigm that MPs diminish reproductive output of *Oryzias melastigma* by changing organism food consumption and energy allocation, and the major impacts on the reproductive performance is summarized in Table (3).

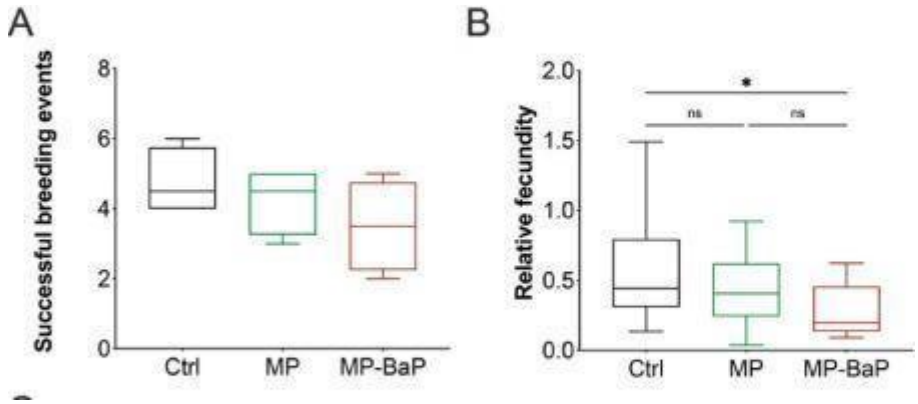



**Fig. 15.** Histograms showing the reproductive performance of sexually mature 3-4 months zebrafish fed normal diet, diet supplemented with polyethylene MPs and/or contaminated with MPs contaminated with benzo[α]pyrene (A) Average number of successful breeding events. A value of 0 or 1 was given to breeding events for which couples did not lay eggs (or eggs aborted) or for which couples successfully laid eggs, respectively (n = 4). (B) Relative fecundity

**Table 3.** The impact of polysteryne MPs on the reproductive performance of *Oryzias melastigma*

| MPs type | MPs size | Organism | Exposure time | Main findings |
| --- | --- | --- | --- | --- |
| Polysteryne | 2.5 µm | *Oryzias melastigma* | 30 days | -Decrease in the number of days that the fish held live/viable eggs.<br>-Developmental stages of oocytes and spermatocytes were affected. -Empty follicle, follicular atresia and follicular lining loose were observed.<br>- The relative ratio of primary oocytes (PO) showed a reducing trend.<br>-Relative ratio of mature spermatocytes (spermatids and mature sperm) did not significantly change. |

**Table 4.** The cumulative effects of MPs on adult fishes

| Affected Systems | **Effect** | **References** |
|---|---|---|
| Digestive system | The gastrointestinal tract is one of the main routes for microplastics exposure, found in stomachs and metabolic systems tissues and causes unfavorable cellular alterations in fish, producing obstructions across the digestive tract and limiting feeding owing to appetite. | **(Lusher *et al.*, 2013; Wright *et al.*, 2013; Karbalaei *et al.*, 2018)**. |
| | At the tissue level, MP exposure impacts include gastrointestinal tract damage, inflammation, disturbances in hepatic lipid and energy, goblet cell hyperplasia | **(Wright *et al.*, 2013b; Lu *et al.*, 2016; Asmonaiteˇ ˙ *et al.*, 2018; Qiao *et al.*, 2019),** |
| | Structural deterioration of fish intestine has also been reported along with cellular and metabolic alterations, including the distribution of cholesterol between muscle and liver, single cell necrosis, glycogen depletion and fatty vacuolation. | **(Rochman *et al.*, 2014; Ped` a *et al.*, 2016).** |
| | Contaminants induce direct mechanical and toxicological effects, or further accumulate through the food chain. | **(Wang *et al.*, 2018)**. |
| | The small intestine histomorphological lesion indices. | **(Mbugani *et al.*, 2022)** |
| Immune system | Altering organismal defense mechanisms and neutrophil function, which indicates innate immunosupression. | **Greven *et al.*, (2016)** |
| | - MPs (internalized into cells) can induce the oxidative stress, which could cause impairment in the fish immune parameters. | **(Jeong *et al.*, 2017; Espinosa *et al.*, 2018; Zhang *et al.*, 2022)** |

| | | |
|---|---|---|
| | - MPs can induce an immune response in fish species via the regulation of neutrophils and granulocytes cells or cytokine production and cause disruption in the endocrine system. | |
| | The worse is the MPs ability to transport microorganisms and pollutants working as a non-living vector for chemical and biological contamination. | **(Wang *et al.*, 2016)** |
| | The inflammation due to MPs exposure can cause interference in immune system components, leading to a response in the neutrophil trap release, lysosomal membrane destabilization, and granuloma formation, eventually, MPs can hinder or prevent cell fixing mechanisms. | **(Greven *et al.*, 2016)** |
| | Elevating losing energy, including disruption of endocrine system and so foraging and feeding behavior, alteration of swimming behavior activities, such as mating, feeding and swimming false satiation**,** reduction in fecundity, reproductive success and offspring viability and a decrease in energy reserves. | **(Wright *et al.*, 2013a, b; Sussarellu *et al.*, 2016; Yin *et al.*, 2018; Choi *et al.*, 2018; Qiang & Cheng, 2019)** |
| Reproductive system | Their reproductive performances i.e., breeding success, relative fecundity and embryo hatching rate in females, and sperm viability and motility parameters in males decrease. | **(Tarasco *et al.*, 2022)** |
| | Decrease in the number of days that the fish held live/viable eggs.<br>-Developmental stages of oocytes and spermatocytes were affected. - Empty follicle, follicular atresia and follicular lining loose were observed. - The relative ratio of primary oocytes (PO) showed a reducing trend.<br><br>-Relative ratio of mature spermatocytes (spermatids and mature sperm) did not significantly change. | **(Yan *et al.*, 2020)** |

### 6.1.2 Effect of MPs on fish developmental stages

The significance of MPs on the developmental stages of fishes is summarized in Table (5).

#### 6.1.2.1 Impact of MPs on fish larvae

Microplastic particles were detected in the gut of zebrafish. As a result, inability to absorb nutrients, weakness in fish, mortality, decrease in weight and total length were determined in zebrafish after exposure to MPs. Moreover, microplastic exposure leads to osteotoxicity as it affects the development of zebrafish axial skeleton **(Tarasco *et al.,* 2022)**. Zebrafish larvae were raised in ZEB316 stand-alone housing systems and chronically exposed throughout their development to polyethylene particles of 20- 27μm, pristine (MP) or spiked with benzo[α]pyrene (MP-BaP), supplemented at 1% w/w in the fish diet. The results showed that chronic exposure to pristine microplastic affects zebrafish skeletal development, and incidence of skeletal deformities increases when microplastics are contaminated with BaP **(Tarasco *et al*., 2022)**.

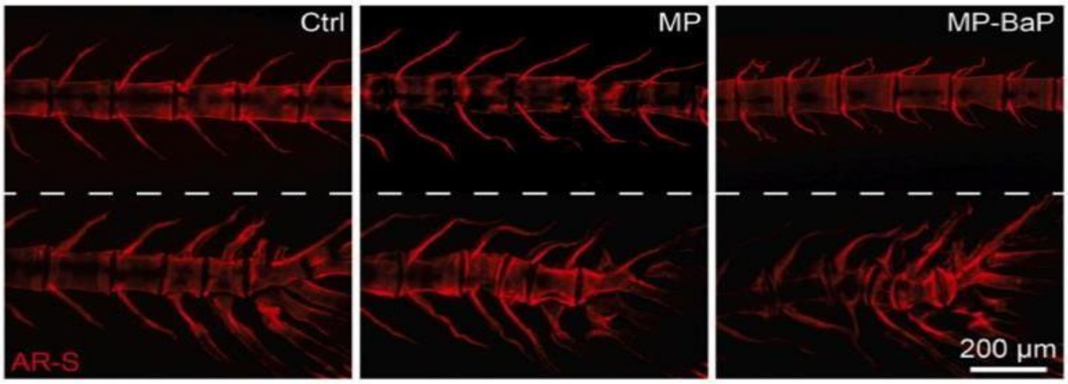



**Fig. 16.** Representative fluorescence images of AR-S-stained skeletal structures in fish fed experimental diets, fed MPs and MP-BaP **(Tarasco *et al*., 2022)**

Parental exposure to microplastics also affects the offspring bone growth. It was assessed the intergenerational effect of microplastics exposure, on fish development and bone growth, operculum area, head area and body standard length and depth were determined through morphometric analysis of 6 days post- fertilization (dpf) offspring larvae born from parents fed the experimental diets **(Tarasco *et al.,* 2022)**.

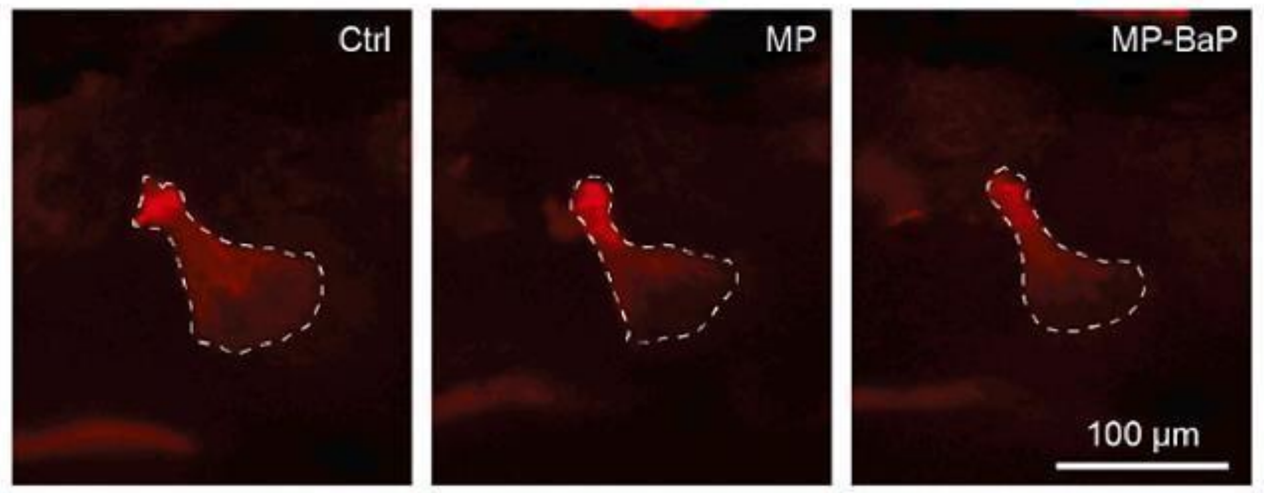



**Fig. 17.** Representative images of operculum of 6dpf offspring larvae **(Tarasco *et al.*, 2022)**

#### 6.1.2.2 Impact of MPs on fish egg

The presence of microfiber and polyethylene terephthalate MPs in the eggs suggests the transmission of MPs through the feeding of the mother fish to the yolk sac **(Fyhn, 1989)**. Although microplastics were found in small amounts, it is reassured that, the microplastic fibers had not yet affected the normal development of the embryo in the early stages of fish eggs **(Bunge *et al*., 2021)**.

Since the mother fish may need food to feed the embryo in the egg, microplastics may have the potential to increase in the eggs as they develop **(Rønnestad, *et al*., 1999)**.

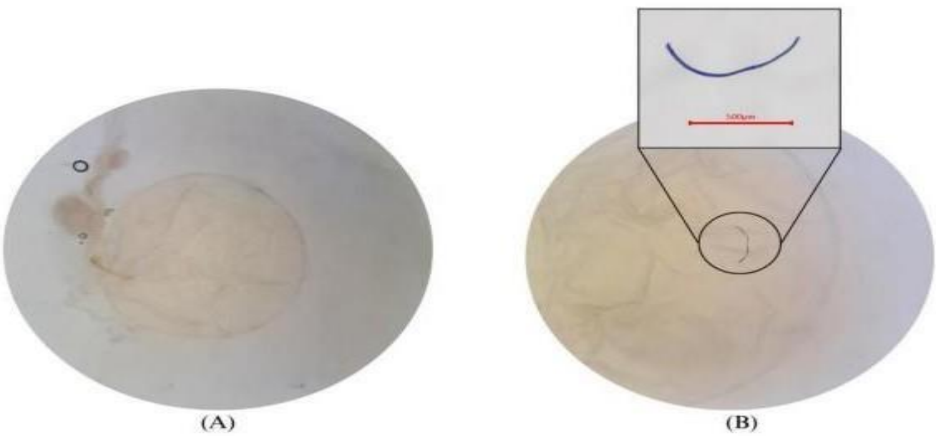



**Fig. 18.** The presence of microfiber contamination in fish eggs: (A) microfiber-free pierced eggs, and (B) Microfiber-contaminated fish eggs **(Pradit *et al.*, 2023)**

#### 6.1.2.3 MPs influence on fish embryos

Research studies have provided evidence of the detrimental effects of MPs on fish embryos. One study conducted by **Lu *et al.* (2016)** investigated the impact of MPs on zebrafish embryos. The researchers exposed the embryos to environmentally relevant concentrations of MPs and observed significant developmental abnormalities, including delayed hatching, reduced growth, and malformations in the skeletal structure.

Another study by **Sussarellu *et al*. (2016)** focused on the effects of MPs on the European sea bass embryos. The researchers exposed the embryos to MPs and found that they were accumulated in the digestive system, causing inflammation and impairing the normal functioning of the gut. This disruption in the gut function can lead to nutrient absorption issues and hinder the overall development of the embryos.

Furthermore, in his study, **Browne *et al*. (2008)** investigated the impact of MPs on the reproductive success of Japanese medaka fish. The researchers exposed the fish to MPs and observed a decrease in hatching success and an increase in abnormalities in the offspring. These findings suggest that microplastic exposure can have long-term effects on the reproductive capabilities of fish, as previously mentioned in the manuscript.

These studies, along with numerous others, highlight the negative consequences of microplastic exposure on fish embryos. The specific effects may vary depending on factors such as the type, size, and concentration of MPs, as well as the species of fish being studied. Nonetheless, the collective body of research provides substantial evidence that microplastics pose a significant threat to the development and survival of fish embryos.

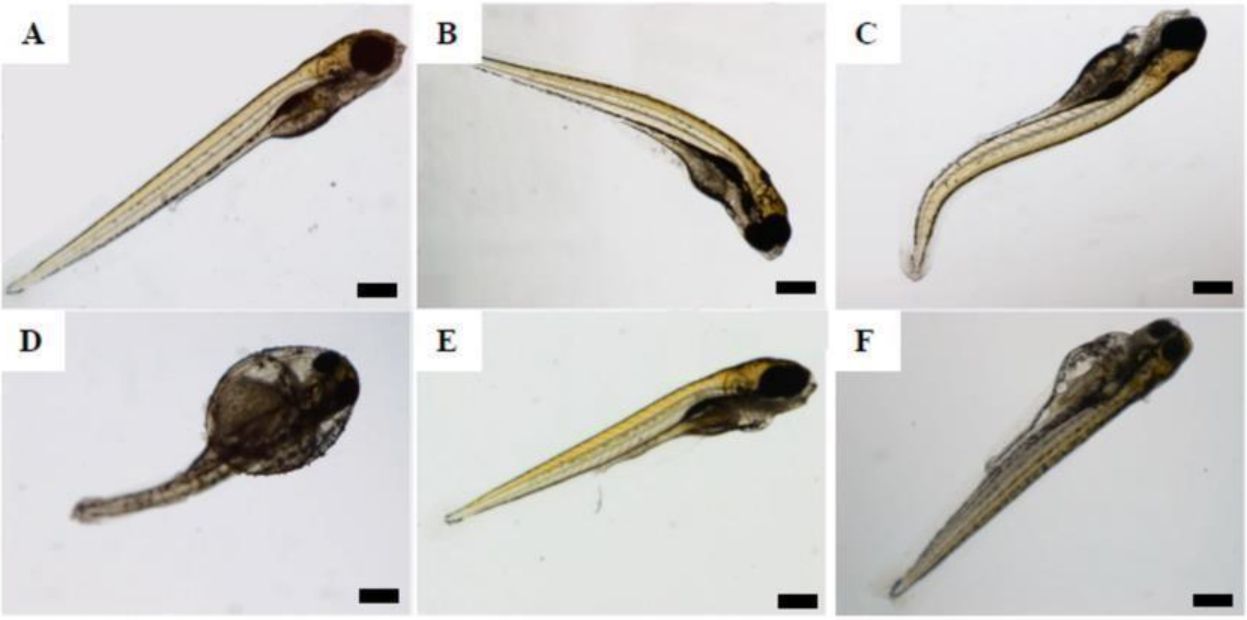



**Fig. 19**. Malformations found in exposed zebrafish embryos at 120hpf. (A) Unexposed control embryo showing normal morphology; (B) Embryo exposed to 0.687mg/ L of 500nm nanoplastics (NPs) showing spinal cord flexure; (C) Embryo exposed to 0.069mg/ L of 500nm NPs-B(a)P showing pericardial edema and spinal cord flexure; (D) Embryo exposed to 50.1mg/ L of 4.5µm MPs-B(a)P showing multiple malformations, such as pericardial edema, yolk sac edema, and spinal cord flexure; (E) Embryo exposed to 10mg/ L of B(a)P showing pericardial edema; (F) Embryo exposed to 1mg/ L of B(a)P showing yolk sac edema. Scale bars: 100µm **(Martínez-Álvarez *et al*., 2022)**

Table 5. Effects of MPs on fish developmental stages

| Stages | Effects | References |
|---|---|---|
| Egg | Microfibers may enter fish eggs, causing malformations and affecting the fertilization process. | **(Bunge, *et al*., 2021)** |
| Embryo | Developmental abnormalities and lowering the survival rate. | **(Lu *et al*. 2016; Sussarellu *et al*., 2016)** |
| Larva | Negative consequences on the growth rate and development.<br>Skeletal deformations.<br>Mortality. | **(Tarasco *et al*., 2022)** |

***6.2 Detrimental effects of MPs on human***

As previously mentioned in the manuscript, the toxicological impacts of MPs on fishes reduce the fish performance and may eventually lead to their mortalities. Moreover, since fishes are major sources of cheap animal protein, economic-wise humans will be affected by the aforementioned consequences **(Naji *et al*., 2017; Kor *et al*., 2020; Kor & Mehdinia, 2020)**. Additionally, given that humans are the end-consumers of fishes, MPs will accumulate in their organs and tissues causing detrimental health problems (Fig. 20) **(Bhuyan, 2022)**.

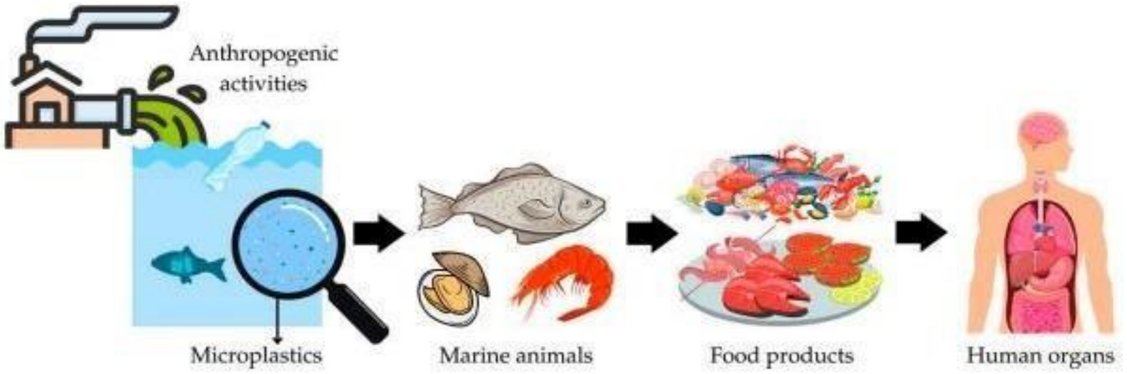



**Fig. 20.** A model showing the pathway of MPs till reaching humans **(Bhuyan, 2022)**

**6.2.1 Toxicological influence of MPs on human health**

There are three main routes of administration of MPs to humans: inhalation, ingestion and dermal contact **(Bhuyan, 2022)**. Among the major impacts of MPs on humans are, oxidative stress **(Galloway, 2015)**, immunosuppression **(Prata, 2018)**, neurotoxicity, GIT disorders **(Yan *et al*., 2021)** in addition to carcinogenicity and metabolic disorders **(Bhuyan, 2022)**, as shown in Fig. (21).

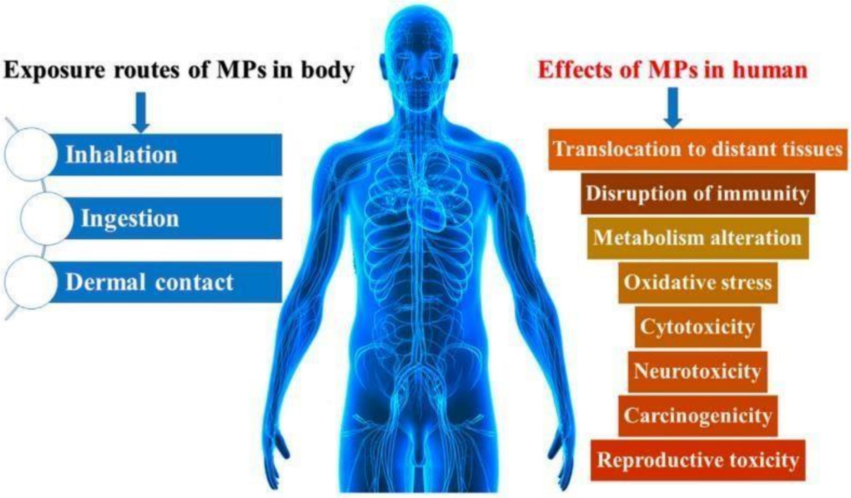



**Fig. 21.** Possible effects of MPs in human body following exposure **(Bhuyan, 2022)**

### 6.2.2 Oxidative stress and cytotoxicity

Oxidative stress, inflammatory, and cytotoxic effects are the major impacts of MPs entering the body via inhalation **(Valavanidis *et al.,* 2013)**. Upon MPs entrance to the human body, an inflammatory response is initiated by cytokines inducing acute toxins and free radicals released and incorporate with the MPs, increasing the oxidative stress causing hydrolysis, which lead to polymer degradation, breaking, and leaking **(Sternschuss *et al.,* 2012)**. It was noted that, polystyrene MPs at concentrations of 0.05–10 mg/L produce reactive oxygen species at high levels contributing to cytotoxicity in the human brain and epithelial cells in addition to the cytotoxicity of the adenomatous cells of the small intestine **(Wu *et al.,* 2018)**.

### 6.2.3 Metabolic disorders and changes in the energy flow

Humans have high energy requirements for all the systems to function actively, thence high metabolic demands **(Bhuyan, 2022)**. The previous authors added that MPs influence the body metabolism via two mechanisms, either directly by boosting or lowering the energy consumption, decreasing nutritional intake and altering metabolic enzymes, or indirectly through upsetting the energy equilibrium **(Bhuyan, 2022)**.

### 6.2.4 Immune system dysfunction

MPs were reported to cause systemic or local immune responses after exposure, based on their dispersion and human reaction. Nevertheless, environmental exposure to MPs, on the other hand, was enough to impair immune systems in biologically vulnerable individuals, resulting in autoimmune disorders or immunosuppression **(Prata, 2018)**.

**Farhat *et al*. (2011)** illustrated that chronic damage in cells, the production of immune modulators, and the misleading stimulation of immune cells may all contribute to MPs-induced autoimmune disorders. Moreover, antibodies against self-antigens would be produced as an outcome of this chain of events. In addition, exposure to MPs has been linked to autoimmune rheumatic illness and systemic lupus erythematosus **(Bernatsky *et al.,* 2016)**.

#### 6.2.5 Neurotoxicity

**MohanKumar *et al.* (2008)** reported that neurotoxicity could be the result of direct interaction with teleported particles or the effects of circulating pro- inflammatory cytokines that results in long-term neuronal injury (immune cell activation and oxidative stress in the brain). Moreover, it was noticed that the exposure of human to MPs elevated acetylcholine-E (AChE) activity in the brain and altered serum neurotransmitters **(Deng *et al.*, 2017)**.

#### 6.2.6 Effect of MPs on the gut

According to the study of **West-Eberhard (2019)**, human ingestion to a large number of MPs can affect the gut variety and activity microbiota, resulting in a rapid growth in opportunistic species, an upsurge in pro-inflammatory responses, and endotoxemia.

#### 6.2.7 Carcinogenicity

Chronic exposure to MPs can cause malignancies, additionally prolonged inflammation and irritation caused by MPs consumption may induce cancer by causing DNA damage **(Bhuyan, 2022)**.

#### 6.2.8 MPs with other pollutants

##### 6.2.8.1 MPs injecting chemicals in the human body

Upon the manufacture of MPs variety of exogenous chemical substances are applied as additives to plastics, such as pigments and persistent organic pollutants (POPs) and phthalates, bisphenol A (BPA), triclosan, organotin, and brominated flame retardants and heavy metals **(Galloway, 2015)**.

Persistent organic pollutants and some other chemicals have been found to imitate natural hormones, causing disorder in reproduction **(Issac & Kandasubramanian, 2021)**. Moreover, BPA is a component monomer in polycarbonate that is used in catering packaging **(Cole *et al.*, 2011)**. BPA is utilized as an antioxidant and a stabilizer that has the potential to damage the endocrine system **(Halden, 2010)**. It can move out of polycarbonates and adhere to consumable food, allowing it to be consumed by humans **(Calafat *et al*., 2008)**. In addition, BPA levels in the urine of 167 men were shown to be negatively proportionate to serum levels of inhibin B and the estradiol- testosterone ratio, indicating a detrimental effect on hormone levels **(Meeker *et al.*, 2010)**. Furthermore, BPA may potentially have a role in the development of overweight by disrupting alpha and beta receptors in fat tissues, changing fat tissue hormone levels, interacting with the action of lipoprotein lipase, aromatase, and lipogenesis regulators. Additionally, it has the potential to cause breast and prostate cancer in mammalian species, as well as cancer in humans **(Michalowicz, 2014)**.

Many chemicals found in plastics or firmly attached to MPs, such as pharmaceutical drugs, which include their metabolites, are toxic to humans causing genotoxicity and hormonal disruptors after being ingested **(Bhuyan, 2022)**.

### 6.2.8.2 MPs as vector (Biofilm formation)

Surfaces of buoyant Mps provide habitats for rafting organisms. For example, pelagic insects (*Halobates micans* and *H. sericeus*) utilize microplastic pellets for oviposition, increasing the opportunity to bacteria and other parasites colonization on it **(Goldstein *et al.*, 2012)**. Moreover, MPs can deliver germs to target tissues, causing pro-inflammatory replies, and potentially facilitating infections **(Kirstein *et al.*, 2016)**. Besides, when MPs are into touch with bacteria and chemicals, their large surface area made them vulnerable to becoming vectors when pathogens use it as a substrate to encyst or populate on **(Prata *et al.*, 2020)**. The *Vibrio* sp. are among the most aggressive bacteria that could populate the surface of MPs, according to **Kirstein *et al.* (2016)**.

The harmful effects of chemicals or microbes adsorbed onto MPs, on the other hand, are greatly reliant on the types and concentrations of swallowed particle, vector particle transportation, release profile, and pollutant lethality in human body cells **(Campanale *et al.*, 2020; Prata *et al.*, 2020)**.

**The aforementioned detrimental effects of MPs on human are summarized in Table (6).**

**Table 6.** Effects of MPs on human

| Effect | Mechanism | References |
|---|---|---|
| **Oxidative stress and cytotoxicity** | -It causes inflammation because it is a foreign body then cytokines form in inflammation process induce.<br><br>MPs induce oxidative stress causing hydrolysis, which led to polymer degradation, breaking, and leaking.<br>Inflammation and oxidative stress lead to cytotoxicity but MPs interacted easily with intracellular organelles since they were not membrane-bound, posing a risk of damage. | **(Sternschuss *et al.*, 2012; Bhuyan, 2022)** |
| **Metabolic disorder** | Directly by altering metabolic enzymes or circuitously by upsetting the energy equilibrium. Indirectly, by boosting or lowering energy consumption, decreasing nutritional intake, and regulating metabolic enzymes, MPs exhibit metabolic impacts. Humans on the other hand, have higher energy requirements and are more sophisticated.<br>Therefore, it increases the effect danger. | **(Bhuyan, 2022)** |
| **Immune system dysfunction** | Linked to autoimmune rheumatic illness and systemic lupus erythematosus. | **(Bernatsky *et al.*, 2016)** |

| | | |
|---|---|---|
| | Chronic damage in cells, the production of immune modulators, and the misleading stimulation of immune cells may all contribute to MP-induced autoimmune disorders. | **Farhat *et al*., (2011)** |
| | Impair immune systems in biologically vulnerable individuals, resulting in autoimmune disorders or immunosuppression. | **(Prata, 2018)** |
| **Neurotoxicity** | Exposing MPs elevated acetylcholine-E (AChE) activity in the brain and altered serum neurotransmitters. | **(Deng *et al*., 2017)** |
| **Carcinogenicity** | For generations continuously exposed to MPs, humans are in danger of malignancies. prolonged inflammation and irritation caused by MPs consumption may induce cancer by causing DNA damage. | **(Bhuyan, 2022)** |
| **Impact on gut** | Once humans are exposed to a large number of MPs, they can affect the gut variety and activity microbiota, resulting in the rapid growth of opportunistic species, an upsurge in pro-inflammatory responses, and endotoxemia. | **(West-Eberhard, 2019)** |
| **MPs as vector (chemical or biological)** | Infection with different microorganisms and toxicity with chemicals. | **(Issac & Kandasubraman ian, 2021)** |

## 7. Potential solutions for microplastic pollution

Getting rid of all microplastics in global oceans looks too difficult to be accomplished and requires lots of expensive strategies. Hence, the sole way to reach this stage is people's contribution **(Calero *et al*., 2021)**.

Obviously, the first step to solve any type of pollution is the raising people's awareness and setting firm regulations for the continuous use of the resources **(Rhodes, 2018)**. As a progression step, the European Union has established bans or levies on selected plastic products, with a particular focus on banning microbeads in cosmetic products and single-use carrier bags **(Dauvergne, 2018)**. The scientific community and non-governmental organizations are also working to identify solutions **(Cordier, 2019)**.

Avoiding the generation of microplastics and wastes management are alternative methods for such a type of pollution, based on a variety of strategies to reduce, reuse, recycle and recover plastics. Moreover, the best way to reduce the amount of plastic wastes, along with reducing the production of plastic materials using alternative green materials, such as glass, cardboard or other recycled or biodegradable products, as well as reusing discarded plastics by creating other safe products, as demonstrated in Fig. (22) **(Solis & Silveira, 2020)**.

Concerning strategies, cost-effective solutions to manage plastic wastes vary considerably across geographies and social settings. Accordingly, a variety of solutions to the plastic pollution problem have been proposed at local, national, and regional levels **(Abbott & Sumaila, 2019)**. Some of these suggestions focus on the post-consumption management, requiring considerable growth in investment and the capacity of waste management solution **(Lau *et al*., 2020)**. The previous authors suggested the prioritization of reducing plastics through their replacement with alternative products, reuse, and the development of new delivery models.

Furthermore, the aforementioned authors designed an effective global strategy that requires the understanding of the mitigation potential of plastics. Additionally, they illustrated the magnitude of global effort needed to significantly reduce plastic pollution through adopting the following three strategies: reduce, substitute and change strategies.

**Reduce** strategy means using plastics in some products, while excluding them in others, in turn other materials will **substitute** the excluded plastics. These two strategies will occur gradually till complete substitution is achieved, leading to the **change** strategy **(Lau *et al*., 2020)**.

The substitution strategy was recently applied in Egypt in COP 27, where the Egyptian water company has launched the first eco-friendly plant-based bottles “good water box” to get rid of plastic bottles, which are made from recyclable materials, involving only plants and bio-based sugarcane for the bottle body and even the packaging box is made up from wood fibers from sustainably managed forests **(Climate conference, 2022)**.

### 7.1 Models for amelioration of plastic wastes

Considering that plastic usage plus mismanagement of the resulted debris gives rise to the current massive pollution. Thus, **Lau *et al*. (2020)** adopted two strategies by which plastic wastes could be mitigated, namely Plastics-to-Ocean ($P_2O$) and Plastic-to-Fuel ($P_2F$) models.

Interestingly, the $P_2O$ model is a data-driven coupled ordinary differential equation (ODE) model that calculates the flow of plastics through representative systems. Properly, this model is used to characterize the key stocks and flows for land-based sources of plastic pollution across the entire value chain for municipal solid waste (MSW) macroplastics and the four sources of primary microplastics (those entering the environment as microplastics). In addition, it provides estimates of plastic wastes input into the environment. Costs are then calculated as a function of modeled plastic flows, and changes in the costs due to the production scale and technological advancement are computed for through learning curves and returns to scale.

The projected growth in demand for plastic is then calculated, using country- level population size, microplastic-generating product use and loss rates, per capita waste generation and waste management processes, e.g. collection costs, collection and processing rates, and recycling recovery value, and rates of primary microplastic generation that vary according to the geography and plastic type. Afterward, sensitivity analyses were conducted to quantify the influence of the individual model inputs and key drivers of plastic pollution.

On the other hand, the $P_2F$ model is defined as the chemical processes by which the non-recyclable waste products from plastic debris degradation (e.g. greenhouse gases and dioxin) can be transformed to fuel, useful chemical substance or even electricity**.**

It is noteworthy mentioning that the aforementioned models, strategies and global waste management operations were planned to be performed starting from 2016 to completely eliminate plastic pollution by the year 2040, as shown in Fig. (23).

However, if there were neglections and delays for the commencement till 2025, these calculations will be impractical, as well as pollution & costs **(Lau *et al*., 2020)**.

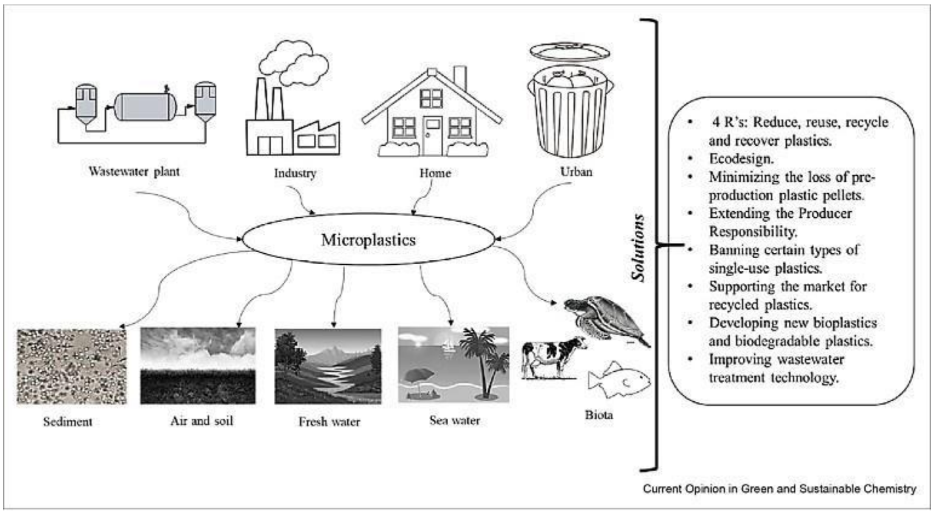



**Fig. 22.** Microplastics pollution from various environments and some suggested solutions to reduce this problem **(Calero *et al*., 2021)**

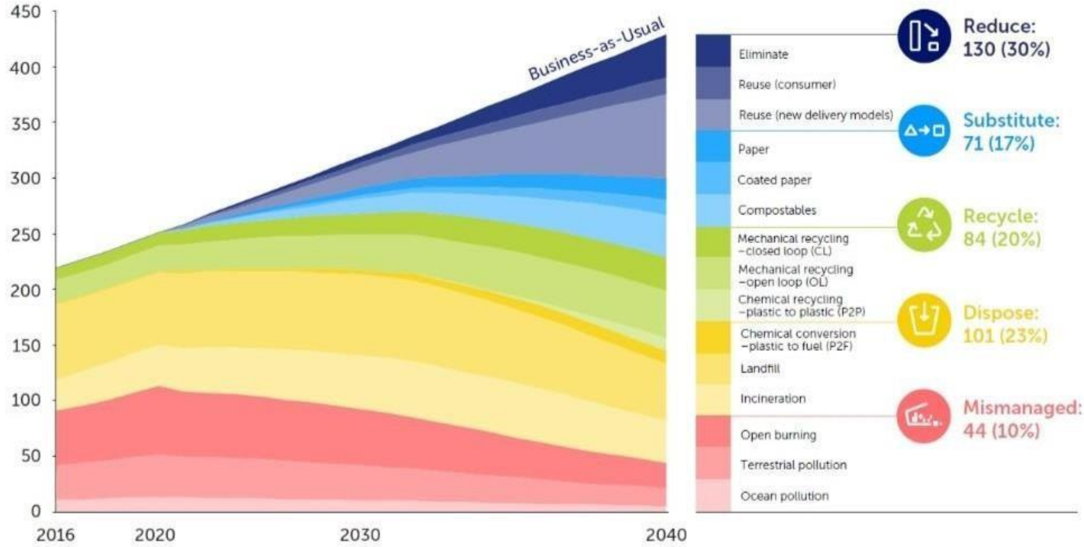



**Fig. 23.** The predicted fate for all MSW plastic from the period 2016- 2040 under the system change scenario (SCS) **(Lau *et al*., 2020)**

## CONCLUSION AND RECOMMENDATIONS

Plastic pollution, especially microplastics, resulting from plastic debris after its different degradation processes, including mechanical, thermal, chemical, photo- or biodegradation, is a serious type of neglected contamination causes, which few people are aware of their hazard effect. They can reach water surfaces around the uninhabited islands by many means such as the air, which is filled with these degradation products from city dust, road marking, synthesized texture, cosmetic products, etc. The microplastic pollution has a negative influence on both fish and humans, starting from showing abnormal behaviors to complete intestinal obstruction in fish at different stages of the life cycle (eggs, embryos, and larvae) and negative consequences on their reproduction, thus affecting their basic metabolism. On the other hand, humans can be exposed to serious threats through this type of pollution via inhalation, ingestion or dermal contact, causing several diseases, such as oxidative stress, immunosuppression, neurotoxicity and malignant tumors. The aforementioned diseases can eventually lead to either fish mortality, thus affecting the national income, or human death. Accordingly, it is recommended to limit the use of plastics globally, and shifting to green ecofriendly materials. In addition to adopting different scenarios for the reduction of plastic pollution, such as cautious deposition of these solid wastes, as well as their reuse and recycle. Hence, paving the way for Egypt to make significant progress toward achieving the sustainable development goals by 2040.

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