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Review
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REVIEW

Microplastics – Ecosystem pollutants

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Abstract: The presence of microplastics in different ecosystems has been intensively studied since the beginning of the 21st century. They have since been found in all components of the environment as well as in a number of organisms. Microplastics (MPs) is a term for particles whose size is 1 μm–5 mm that are formed during the breakdown of larger plastic products or are produced in microsizes for various industrial and cosmetic products. The distribution of these particles is due to their rapid transportation over large distances which is facilitated mainly by their small size and low density. There are still no uniform methods and standardised procedures for sampling and analysis. Therefore, the facts about the occurrence, distribution and threats to ecosystems and human health from MPs are not yet fully understood. This literature review is a broad presentation of the state of knowledge on the distribution of MPs in the atmosphere, water, soil and organisms. In addition, this document describes the most widely used methods for separation, identification and characterisation of MPs.

Keywords: microplastics; environmental protection; toxicological effects; health impacts.

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1. INTRODUCTION

Polymeric materials pose a serious threat to the environment and human health when they enter ecosystems. Once inside, they slowly degrade to microplastics, pollute soil, water, air and cause biodiversity loss. In 2021, more than 390 million tons of plastic were produced worldwide. "Plastics – The Facts" announced in 2022 that 90 % of plastic produced were polypropylene (PP), high- and low-density polyethylene (HDPE and LDPE), polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET) and polystyrene (PS), which are the most commonly used materials in packaging, construction, automotive, electronic and agricultural use.[1–3]

Factors such as hydrolysis, ultraviolet light irradiation, wave and wind effects, oxidative decomposition, biodegradation and biological uptake gradually break down plastic waste into smaller particles. Physical, chemical and biological processes reduce the size and change their shape, color, concentration depending on the exposure time, which plays a crucial role in assessing their impact on the environment.[3–7]

The size of plastics is the most commonly used criterion for determining their class and ecological importance. Depending on their size, plastics can be classified as nano-, micro- or macroplastics. The size of plastics affects the way they interact with biota and the environment. Some plastic particles can pass through the digestive tract of living organisms without harming them, while others (1–4 μm PE, 1–10 μm PS) can penetrate into cells and cause various cytotoxic effects.[8] According to their size, plastic particles are divided into mega (>1 m), macro (25 mm–1 m), meso (5–25 mm), micro (1 μm–5 mm) and nano (<1 μm), Fig. 1.[9]

Microplastic (MP) are observed in most living environment and their concentrations are expected to increase in the coming decades, given the ongoing and in places increased production of synthetic polymer products.[1] Authors review the status of the occurrence and transfer of MP in and between three of the Earth's subsystems – atmosphere, lithosphere and hydrosphere. Microplastics are observed in all possible environments from air, sediments, soils, freshwater, seawater and organisms, including humans. Their occurrence and distribution are influenced by their characteristics and interaction with the environment, particle mobility and transport processes.[10] In the lithosphere, significant amounts of MP (PP, PE, PS, PET, PES) accumulate (25 particles/L in landfill sludge)[11].

The atmosphere plays an important role in the transfer of MP, with higher concentrations (175–300 particles/m^3) occurring in the more densely populated areas. In the hydrosphere, freshwater ecosystems alternate transfer of MP (rivers) and deposition (lakes), with flow velocity identified as a key factor determining the movement and fate of MP. Conversely, marine ecosystems act as a major sink for MP pollution (*e.g.*, MP comprise 94 %, approximately 1.7 trillion pieces, of plastic pieces in the Great Pacific Garbage Patch), driven by direct deposition or by transport *via* the atmosphere or fresh water conveyance systems (*e.g.*, streams, rivers or ice sheets). Once ingested by organisms, and confirmed trophic transfers and bioaccumulation, plastic particles can accumulate in or affect fauna, flora, microbes and humans (Fig. 2).[11]

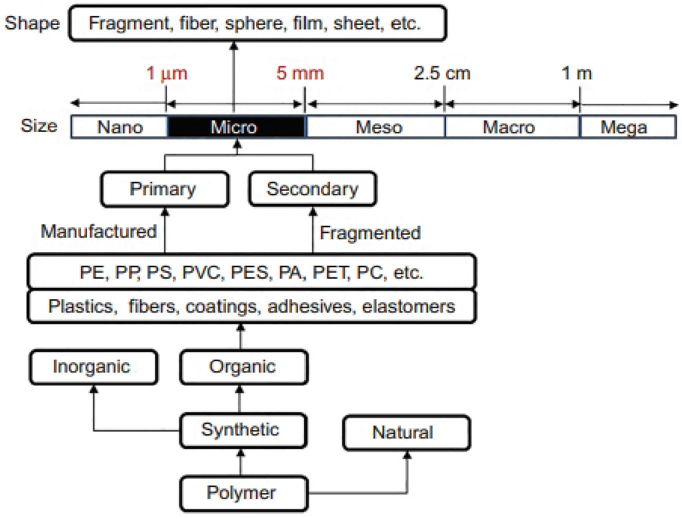

Fig. 1. Size and types of microplastics.[9]

High degradation resistance, lack of proper recycling and inadequate management lead to release and/or disposal of plastics into the environment and their significant accumulation as a heterogeneous group of particles in ecosystems (Fig. 1), where natural degradation plastic waste can persist for decades (Fig. 3).[12]

2. IN THE AIR

Air is the medium in which suspended atmospheric microplastics (SAMPs) are spread, which are small particles of plastic materials up to 5 mm in size. These particles can have different origins, shapes, colors and chemical compositions, depending on their source and the physical and chemical processes they are subjected to in the atmosphere. SAMPs can be carried over long distances by wind, dispersed by turbulence or deposited on the surface by precipitation, sedimentation or retrieval. The speed and direction of the transfer depend on many factors, such as the size, shape, density and electric charge of the MPs, as well as on the characteristics of the atmosphere, such as temperature, humidity, pressure, *etc.*[13]

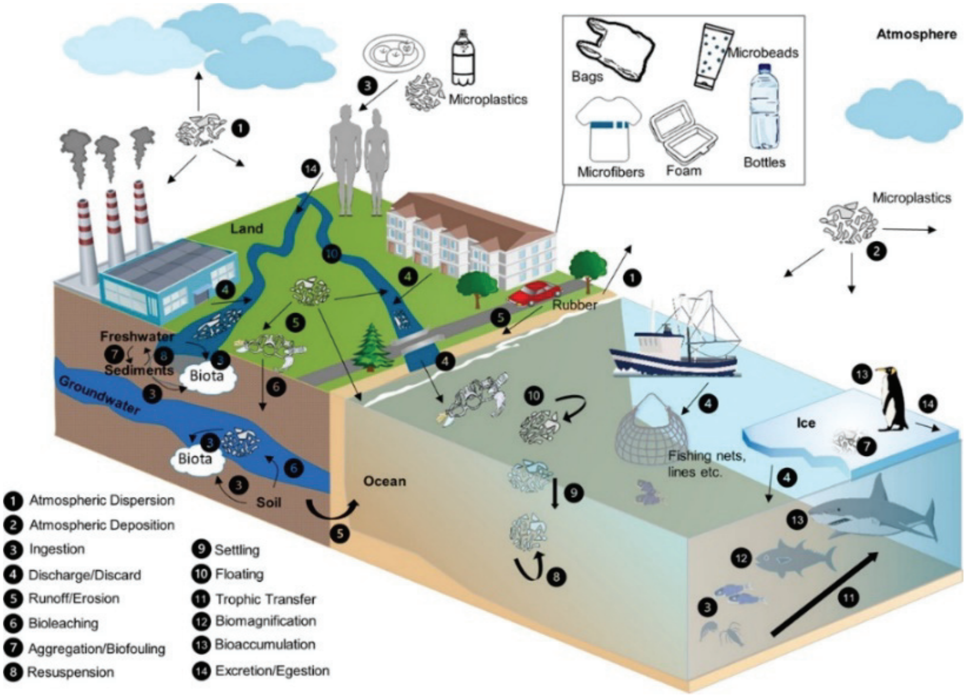

Fig. 2. Emergence and transport of microplastics.

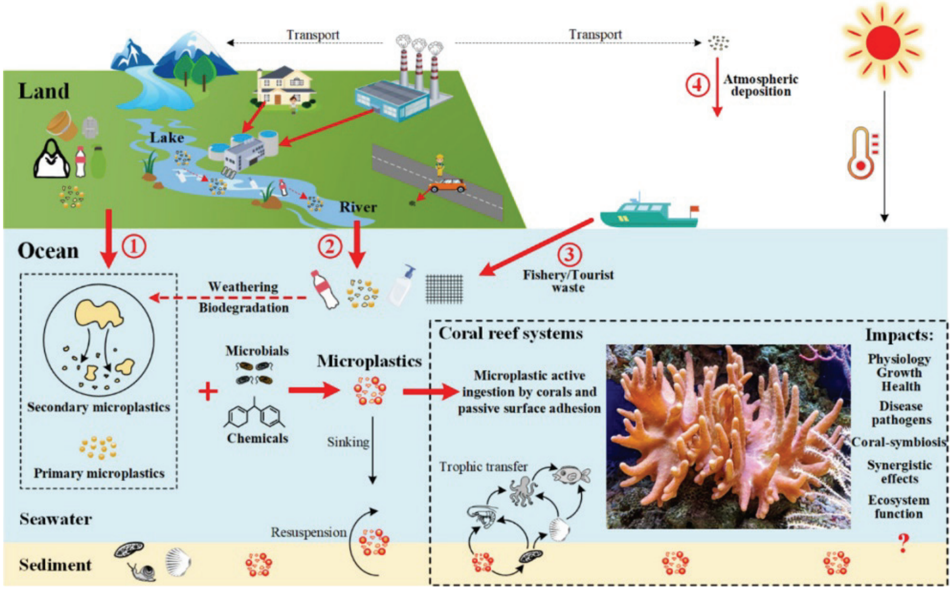

Fig. 3. Propagation of plastics.

SAMPs can be emitted from the atmosphere in various ways: by rain, snow or other types of precipitation, by sedimentation on surfaces such as soil, plants or buildings or by extraction from other agents namely gravity, magnetic field or chemical reactions. This process is called deposition and is important for the distribution of MPs in the environment.[14]

Some studies have shown that the atmosphere is a significant source of MPs for other environments, such as oceans, seas, rivers, lakes or soil. For example, in large cities such as Paris, Dongguan or London, high concentrations of microplastics in atmospheric deposition have been measured.[15–17] These deposits can be influenced by urban rivers, which serve as secondary sources of MPs for the atmosphere.[16]

Also, it is shown that SAMPs can be transported from the oceans to the continents by aerosolization (by waves and bubble bursting) at the sea surface.[13] The transport and deposition patterns of SAMPs play an important role in determining the sources and potential effects of these particles in different environments.[18]

SAMPs transport and deposition models are key to understanding pathways and the fate of plastic pollutants in the environment. These models can provide information on the sources, distribution and accumulation of MPs in different ecosystems, as well as on interactions between the marine and terrestrial environments.[19,20] With the help of models, we can assess the risk of plastic pollution for human health and biodiversity.[13,21,22]

For the modelling of SAMPs transport and deposition, different approaches are used, such as Lagrangian atmospheric models, Eiler atmospheric models and global climate models (FLEXPART, HYSPLIT and LAGRANTO).[13,23,24] Lagrangian atmospheric models trace the trajectories of individual particles in the atmosphere and can determine potential regions of origin and acceptance of SAMPs. These models can also give detailed information about the characteristics of the SAMPs, such as height, speed, distance and residence time in the atmosphere.[13,25]

Factors that affect the transport and deposition of SAMPs include the size, shape, density and morphology of the particles.

According to Dris *et al*. the small particles, have a greater tendency to linger in the atmosphere and have the prospect of being transported to distant regions.[14] The shape and density determine the transfer rate and the ability to mix with other atmospheric particles.[19] The morphology can also determine the zone of influence for MPs deposition after they are carried away from the point sources. As an example, one can mention the morphology of the microfilm as thin and flat particles, with a wide surface area, facilitating their transfer compared to fragments of comparable sizes.[13]

It is noted that additional factors such as site topography, climate and meteorological conditions (*e.g.*, precipitation) also have a perceptible influence on the transport, dissipation and deposition of air MPs.[13] Wind, snowfall, temperature, precipitation and atmospheric pressure in the lower atmosphere have been proven to determine the deposition concentration profile of the MPs. Given the temperature, the vertical gradient supports the upward movement of MP, although they may be retained in the lower atmospheric layers, especially when there is temperature inversion, and subsequently cause episodic pollution.

There is a relationship between wind speed, turbulence, wind direction (vertical or horizontal), increase in dispersion and the amount of MPs in atmospheric precipitation. Research has found that small plastic materials can be carried to greater heights than the wind and subsequently subjected to dry or wet deposition.[26]

The transfer of microplastics from the atmosphere to different environments is a serious environmental problem that requires deeper investigation. According to scientific sources, MPs were found inland, in marine and remote areas, polar regions and glaciers.[27–30] This means that MPs can get into the water resources, soil and food chain. One of the main factors for the spread of MPs is atmospheric deposition, which depends on the concentration of particulate matter in the air. In urban areas where dust pollution is higher, street dust can accumulate in street dust and be washed away by rain or snow, therefore street dust is a potentially important source of microplastic pollution in the urban environment.[31]

Analysing the characteristics of atmospheric deposition in the urban area, the contribution of atmospheric deposition to microplastic pollution in urban waters was determined.[32] The MPs deposition flux showed moderate to strong correlation with particulate matter (PM) concentrations in the atmosphere, especially $PM_{2.5}$ concentration (R^2 0.76–0.93), suggesting that $PM_{2.5}$ concentration could serve as an indicator to estimate the deposition flux of microplastics**.**

Because of their size, MPs can accumulate in dust and soil, and can eventually be carried into the food chain and hence to humans.[33,34] In addition, they can be easily suspended in the atmosphere and retained due to their low density and, through external factors, can reach the respiratory tract of living organisms.[35]

3. IN THE WATER

In the aquatic environment, microplastics are subject to various factors that affect their behaviour and fate. One of these factors is the degradation of larger plastic waste under the action of chemical, physical and biological processes. These processes lead to the formation of a heterogeneous group of particles that have different characteristics such as size, density, shape, chemical composition, colour and origin. The shape of MPs determines their origin and source. The density of microplastics determines their distribution in different layers of water. The chemical composition of MPs determines their stability and reactivity. These particles can be classified according to their residence time in the aquatic environment and their potential impact environment and human health.

MPs can be transported over long distances by atmospheric movement and wind directions, meteorological factors including wave currents, cyclones, tides, river hydrodynamics, water runoff and wastewater treatment plants. They can reach various aquatic ecosystems, such as rivers, estuaries, lakes, seas and oceans.[36] Some of the main routes for penetration of MPs into the aquatic environment are direct discharge, wastewater from treatment plants and surface runoff. According to recent studies, urban drainage systems can be an essential source of microplastics to aquatic ecosystems.[37–39]

The presence and distribution of MPs in the marine environment depend on many factors, such as the salinity of seawater, polymer density, particle size and shape. Studies have shown that the marine environment that is closer to urban areas has higher levels of MPs and aquatic animals from these areas show a high accumulation of microplastics in their tissues. This can lead to disruption of their food chain, physiology and behaviour.[40] Size and shape are important physical properties for characterizing the source and origin (primary or secondary) as well as their potential to produce physical and/or physiological effects on biota. For example, the dominance of fibres found in samples collected in the Black Sea is associated with wastewater, runoff, ports, vessels and fishing activities.[41]

Although marine plastic litter is recognized as a global problem, there is insufficient data on the extent of pollution in the Black Sea.

The brief overview of scientific studies that look at the pollution of the Black Sea with marine plastic pollutants shows that the problem is serious and further studies are needed to clarify their extent and distribution.

A study conducted in 2020 found large amounts of floating marine litter (60.3–93.8 pieces/km^2 bottles, packaging, fragments and bags) and MPs with concentrations (1.14×10^4–1.91×10^5 pieces/km^2, 0.33–490.52 g/km^2). However, MPs concentrations along the Southwest coast of the Black Sea are on average lower than those in other parts of the Black Sea, the Baltic Sea and the Mediterranean Sea.[42]

Another study conducted during the period from 2009 to 2020 focused on the presence of MPs in seawater on the southeastern coast of the Black Sea. The study shows that MPs sizes range from 118 to 4998 μm and that the most common plastics are polyethylene (44.9 %) and polyethylene terephthalate (25.3 %). No significant spatio-temporal changes in the presence of MPs in seawater are noticeable (Fig. 4).[43]

The comprehensive assessment of waste pollution along the Bulgarian Black Sea coast presents data collected during the period from 2016 to 2019 on the basis of studies conducted on 10 beaches and around the channel between the sea and Varna Lake during the summer and autumn seasons.[44] The summarized data show that over 150,000 elements have been registered, removed and classified into 8 main groups of material types on an aggregated basis. The largest amount of pollutants, approximately 80,000 pieces were reported in 2017, followed by 50,000 units in 2019 and 40,000 in 2018. The majority of pollutants are in the category "artificial polymeric materials", and their percentage varies slightly within the period from 2017 to 2018, decreasing to 60 % in 2018. The average annual density of pollutants within the entire coastline of the country ranges from 0.6 pieces/m^2 in 2017 to 0.2 pieces/m^2 in 2019 (Figs. 5 and 6). These data provide useful information on the pollution of the Black Sea coastal region of Bulgaria and can be used to formulate strategies to reduce pollution in the future.[44]

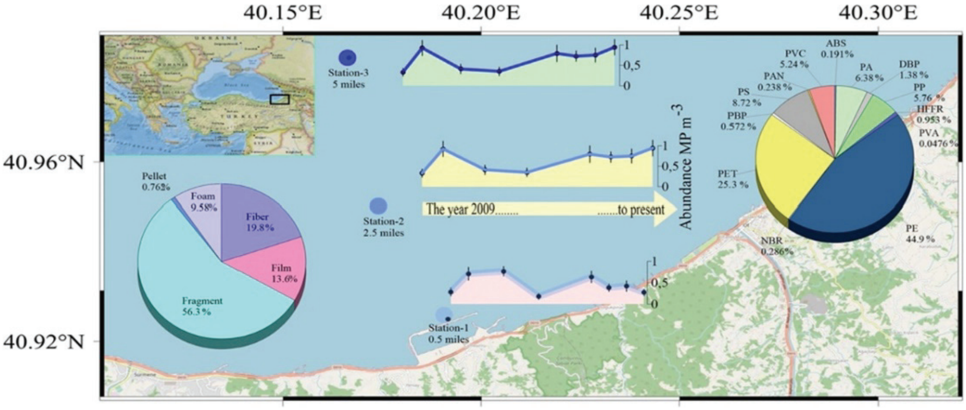

Fig. 4. Presence of microplastics in the Southeast coast of the Black Sea.

Fig. 5. Map with the surveyed beaches along the Bulgarian Black Sea coast.

One of the beaches is classified as "very dirty" due to intense pollution from land-based sources, such as coastal tourism, recreational fishing, people, *etc*. Scientists have analysed the most common plastic items on the beach and found that those associated with smoking are the most. Among them are cigarette butts and filters, as well as cups, caps and bottles. Over the past two years, there has been a decline in the amount of plastic on the beach, but action still needs to be taken to reduce pollution and raise public awareness of the harm of plastic in the marine environment.[44–46]

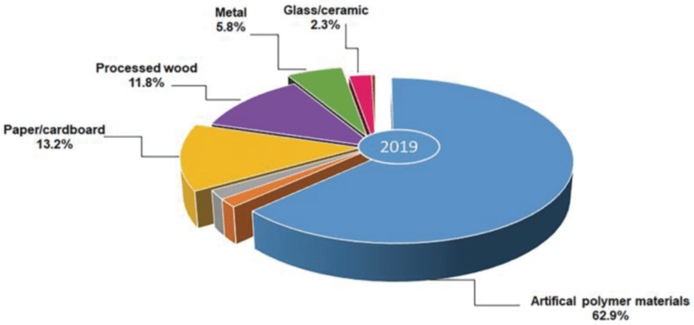

Fig. 6. Total litter items per category type in percentage, 2019.

In the scientific article from 2022, Terzi *et al*. have studied the distribution and properties of microplastics in the aquatic environment along the southern Black Sea coast in Turkey. They have found that 70 % of the MPs are very small (below 2.5 mm) and have a fibre or fragment shape. The average concentration of MPs in the sediment samples was 64.06±8.95 particles/kg and in the seawater samples it was 18.68±3.01 particles/m^3. Analysis of the chemical composition of MPs has shown that styrene acrylonitrile copolymer (40.53 %), polyethylene terephthalate (38.75 %) and polyethylene (6.91 %), and in sea water – polyethylene terephthalate (57.26 %), polyethylene (13.52 %) and polypropylene (11.24 %). The authors found no correlation between the amount of MPs in sediments and in seawater, as well as between the demographic characteristics of adjacent settlements and pollution by MPs.[47]

Scientists are investigating how microplastics are distributed in the sediments of the Black and Caspian Seas and what factors affect their distribution. They used a combination of methods to extract MPs from sediment samples, including density separation, elutriation and hydrophobic adhesion. They analyze the concentration and morphology of MPs depending on the distance to rivers, coasts, cities, sediment grain size and water depth. The results show that the average concentration of MPs in the sediments of the Black Sea is 2 times higher than that in the Caspian Sea. Furthermore, the concentration of MP fragments decreases as depth increases, which may be due to the movement of MPs in the aquatic environment. At the same time, the fiber concentration of microplastics does not depend on depth, which can be related to the ability of the fibers to persist in the sediment (Fig. 7). Furthermore, the study shows that the concentration of microplastics in sediments is interrelated with distance to rivers, coasts and cities. This may be related to the increase in water pollution near settlements and industrial areas. Finally, the size of sediment grains may have an influence on the concentration of microplastics in sediments.[48]

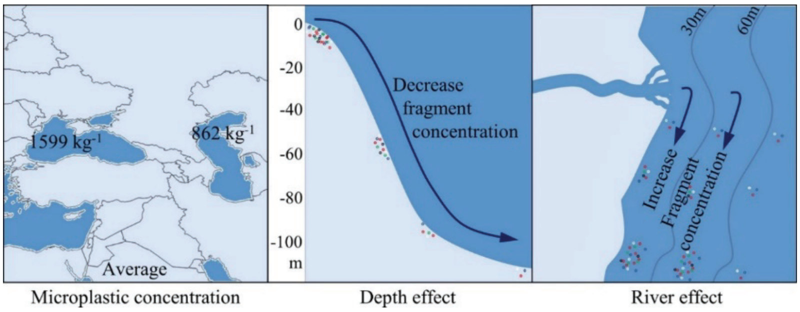

Fig. 7. Dependence of concentration of microplastics on rivers, coasts, cities, etc., in (semi-)closed water bodies.

In some sources, the presence, shape and determination of microplastics in Black Sea sediments taken from different depths (22–2131 m) are described (Fig. 8). The method is used, which includes filtration, followed by FT-IR 2D images to recognize natural and synthetic polymers – polyethylene, polypropylene, acrylonitrile, polyamides and fibres have been identified. MPs were found in 83 % of the sediment samples analysed. The average amount is about 100 pieces/kg. Contamination was found to be the highest in the northwestern shelf (10 times more) than in sediments from greater depths. The authors have also found textile fibres

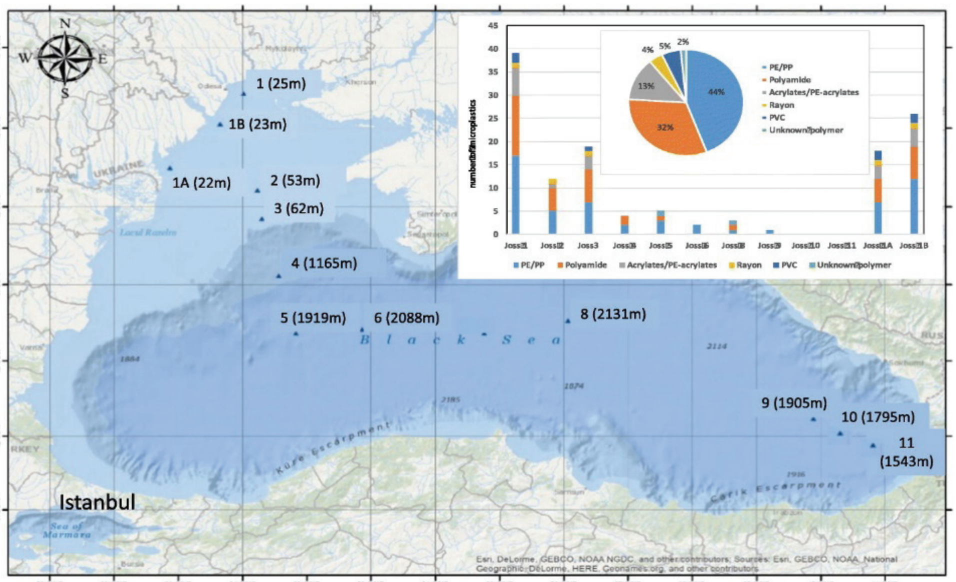

Fig. 8. Identification, morphology and identification of MPs in Black Sea sediments.

on a polyamide and cellulose basis. The most common colours of MPs are black, blue and transparent.[49]

The analytical data from measurements are incomplete and cannot give a clear idea of the current state of the ecosystem and in the Black Sea region. Conducting systematic planning exploratory monitoring will allow tracking the trend of indicators, their interconnectedness, the impact of external pressure, the possibilities for self-purification and sustainable ecological response of the ecosystem.[50]

The transport, distribution and accessibility to biota of MPs in the marine environment depend on their physical characteristics, such as size, shape, density and colour. The size of the MPs is an important factor in how they move in the water column and how it interacts with different types of marine organisms. The shape of the MPs also has significance for their hydrodynamics and potential for adsorption of pollutants. The density of the MPs determines whether they swim on surface, sink or remain in suspension in the water.[51]

The density of the MPs can vary greatly, depending on the type of polymer and the method of production. For example, the density of polystyrene foam is about 0,05 g/cm^3, while the density of polytetrafluoroethylene (Teflon®) is about 2.1–2.3 g/cm^3. Plastic particles have a lower specific density than sedimentary particles (about 2.65 g/cm^3). This means that some types of MPs will be more accessible to filtering or planktonic-eating organisms that live in the upper part of the water column, while other types of MPs will be more accessible to detritophagous or benthic organisms that live in the lower part of the water column or in sediments.[2]

The rate of elevation or sinking of MPs in the marine environment is determined by the difference between polymer density and seawater density, and by the size and shape of microplastics. Studies have shown that MPs can be distributed throughout the water column by turbulent processes, with their concentration decreasing exponentially as the depth increases. The rate of breakdown of MPs decreases in stronger winds, and smaller fragments have a lower rise velocity and are more susceptible to vertical transport.[51]

The colours of marine microplastics are the result of the various additives that are used in the production of polymers. These additives aim to change colour, increase attractiveness, improve mechanical resistance or prevent materials from burning.[52,53] On Fig. 9 are shown some examples of the diversity of MPs colours. Colour can also serve as an indicator of the time of exposure to the sea surface or the weathering process. Yellowing or darkening of plastics is associated with an increase in the carbonyl index, which reflects the degree of photo-oxidation or aging.[2,54] Colours matter, because they can be misleading to some organisms that take them for food.

In the marine environment, MPs occur in two main forms based on origin – primary and secondary (Fig. 10).[55–57] Primary MPs produced for industrial and domestic use enter freshwater bodies by discharging domestic wastewater and eventually make their way into the marine environment.[58] They usually contain waste from cosmetic, pharmaceutical and personal care products, industrial raw materials and microfibers.[14,59–61]

Fig. 9. Examples of the colour diversity of polymer mixtures.

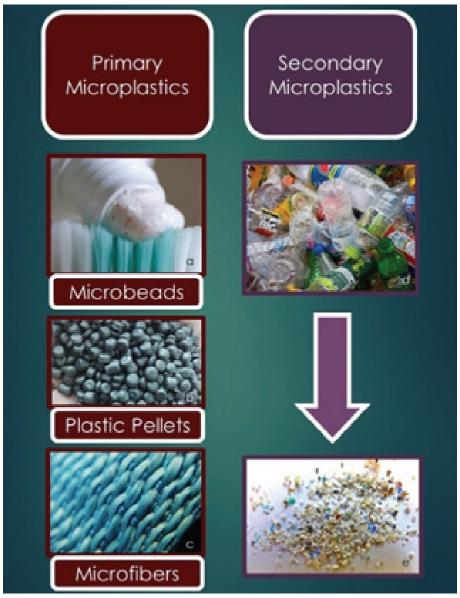

Fig. 10. Primary and secondary MPs.[65]

Secondary MPs are the result of physical, chemical and biological processes that can further degrade to nanoplastics.[62,63] Their degradation in the marine environment into smaller fragments of secondary factors increases the risk of their intake by smaller aquatic organisms.[64]

Various environmental factors influence the distribution of microplastics in ecosystems. These include atmospheric movement and wind directions, meteorological factors such as wave currents, cyclones and tides, river hydrodynamics and water flow and wastewater treatment plants (WWTPs). The WWTPs are a significant source of MPs, but can also contribute to their partial removal. Therefore, it is necessary to study the transport and behaviour of MPs in waste water installations. Authors trace the types and sources of MPs in domestic wastewater, as well as the effectiveness of different treatment processes for their removal and migration. Also considered are biological activities that accelerate the transformation of MPs, and the interrelationships and ecological risks between surface water, soil and atmospheric environment. Finally, possibilities for future research on the influence of wastewater treatment plants on MP pollution are proposed.[66]

Research by Liu *et al*. in 2022 focuses on methods of sampling, extraction (such as flotation, centrifugation, filtration and digesting) and wastewater analysis in treatment plants. The results of the research show that it is essential to remove interfering organic and inorganic constituents in wastewater and sludge samples in order to achieve visualization and identification of MPs using FTIR and Raman analytical methods. This is also important for the integration of FTIR and Raman analysis, spectra mapping and image processing (Fig. 11).[67]

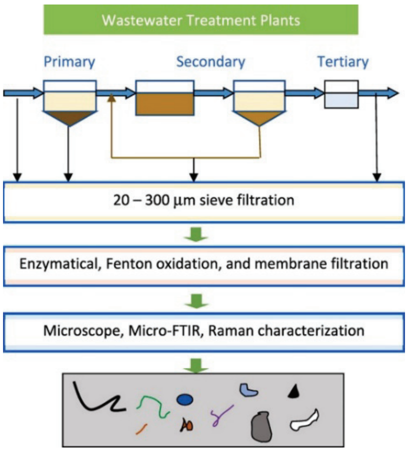

Fig. 11. Methods used to process and identify MPs in WWTPs.

Documenting the distribution of MPs in marine-coastal ecosystems is an important task for assessing ecological status and protecting biodiversity. MPs may contain toxic chemicals that can penetrate the food chain and affect the health of living organisms (Fig. 12). MPs are considered a new type of pollutant that requires special attention and monitoring.[68]

Research has shown that microplastics are present in 93 % of sediment samples in estuaries and are likely to result from deposition processes in these areas. Estuaries are transition zones between freshwater and marine ecosystems that provide habitats for a variety of species, including mussels, fish and birds. MP in estuarine sediments are of different plastics, such as HDPE, nylon (polyhexamethylene adipamide) and PETE. Further research is needed to assess the risk of exposure to microplastics and the potential for bioaccumulation of these contaminants by wildlife species that feed on the surface of tidal flats in estuaries. This is important, as microplastics can have a negative effect on ecosystems and the health of animals and people who consume products produced in these areas.[69–71]

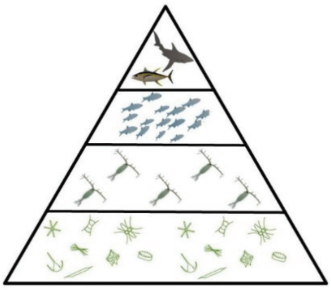

Fig. 12. Example of food chain.

One of the regions where MPs are abundant is the mouth of the Danube. It is the longest river in Europe and passes through ten countries before flowing into the Black Sea. The mouth of the Danube has been declared a reserve of the biosphere by UNESCO and is a unique wetland with rich flora and fauna. Different types of MPs have been found in this zone, such as fragments, fibres, granules and pellets. They originate from various sources, such as textile industry, fishing, shipping and household waste. MPs are found both in surface water and in lower layers and sediments. The composition of MPs is diverse and includes polymers such as PP, PVC, polystyrene (PS) and polycarbonate (PC). Some of these polymers have high persistence and toxicity and may pose a serious risk to animals and plants in the estuary.[72]

In recent years, microplastics have become a serious environmental and potential human health problem.[73] These tiny particles of plastic pollute marine ecosystems and harm marine creatures. In addition, they are a suitable environment for the development of pathogenic microorganisms that form biofilms on their surface. MPs are found in beach sand, seabed, marine flora and fauna. Factors such as fishing, aquaculture and tourism increase the amount of MPs in the sea. They are also generated by the illegal and improper disposal of plastic rubbish. Therefore, it is essential to identify the areas with the highest level of pollution from MPs (Fig. 13). Studies should follow standardised methods of measurement and analysis of microplastics in order to make an adequate assessment of the degree of contamination.[74]

Xue *et al*. (2020) investigated how fishing activities affect the horizontal distribution of MPs in the sediment (Fig. 14).[75] They have found that the main contaminants (polypropylene and polyethylene fibres) were associated with fishing gear wear and formed 61.6 % of the total amount of MPs in surface sediments. MPs can penetrate deep layers of sediment up to 60 cm. The estimate for the stock of microplastics in the deep layers (185 t) is 5 times that in the surface layers.

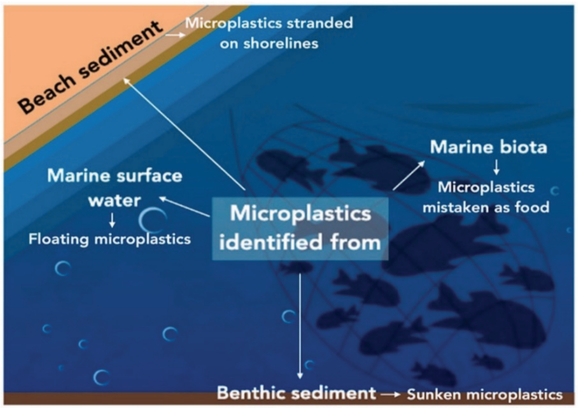

Fig. 13. Distribution of microplastics in marine and coastal ecosystems.

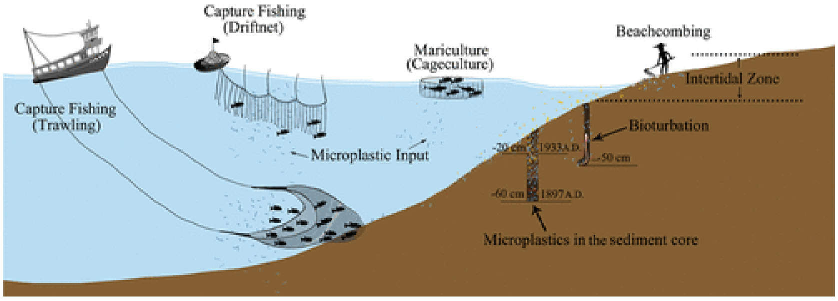

Fig. 14. The horizontal distribution of microplastics in the sediment.

The 2016 paper by Zalasiewicz *et al*. examines the important role of polymers, in particular plastics, in the environment and their geological footprint. The authors argue that plastics are a key indicator of the beginning of the Anthropocene, an era in which human activity is changing the planet. They discuss how plastics become widespread in sedimentary deposits both on land, as well as in the maritime sphere. The possibility of retaining and preserving plastics in Earth's geological layers has been considered as a potential factor that makes them significant to future geologists and archaeologists, as part of the planet's geological history over long periods of time.[72]

The monitoring of plastic microparticles under UV irradiation can lead to the generation of organic matter that is released into the environment. This organic matter can affect the carbon balance and disrupt the global biogeochemical cycle of carbon. The biogeochemical cycle of carbon is a complex process that ensures the transport of carbon between the atmosphere, the hydrosphere, biosphere and geosphere. This cycle includes important processes such as photosynthesis, respiration, degradation of organic matter and geological processes. Disruptions in the global biogeochemical cycle of carbon caused by microplastics can have an impact on the climate in the long term. Changes in the carbon balance can contribute to an increase in the concentration of greenhouse gases in the atmosphere, which can worsen the effect of the greenhouse effect and climate change.[76]

The study of Seely *et al*. (2020) analyse the influence of microplastics on sedimentary microbial communities and biogeochemical carbon and nitrogen cycles. They performed experiments using different types of microplastics (polyethylene, polyvinyl chloride, polyurethane foam and polylactic acid) added to salt marsh sediment. The results show that the presence of microplastics alters the composition of the sedimentary microbial community and influences nitrogen cycle processes. Different types of MPs have different effects on nitrification and denitrification, with polyurethane foam and polylactic acid promoting these processes, while polyvinyl chloride inhibits them. This underlines the importance of investigating the influence of microplastics on global ecosystems and biogeochemical cycling, especially with increasing plastic pollution.[77]

In addition, MPs can alter the chemical balance of the marine environment by transmitting certain chemicals and binding to toxins that can be accumulated in the body of the organisms that consume them. Uptake of MPs has been observed in many species of different size and diet.[78] Soft tissue adherence of organisms is another way of absorption of MPs by bivalve molluscs, crustaceans and algae *Fucus vesiculosus*.[8,79]

In the study published in the journal *Marine Pollution Bulletin*, experts from the Institute of Oceanology at the Bulgarian Academy of Sciences studied the impact of MPs on small crustaceans in the Black Sea. This is the first such study for the region to analyse how MPs are ingested by zooplankton organisms and how this affects the marine ecosystem.

For this purpose, samples were taken from the water column at three places – the mouth of the Kamchia River, the coastal waters of Varna and the open waters of the Southeastern Black Sea. With the help of special methods of processing and analysis of samples, the composition, concentration and size of the MPs, as well as the species and number of crustaceans ingesting them, have been determined.

The results showed that the concentration of MPs in the water column averaged 2.04 counts/m^3, with the highest values recorded at the mouth of the river (5.76 counts/m^3). The most common types of MPs were fibres (66 %) and fragments (28 %), and the most commonly used materials were polyester (40 %) and polypropylene (28 %). The average size of MPs was 0.62 mm, with the smallest particles (0.062–0.100 mm) being most frequently ingested by crustaceans.

The study found that 16 % of crustaceans have MPs in their stomachs, with the species *Acartia clausi* (25 %) and *Oithona similis* (23 %) being the most affected. These species are part of the main food chain in the Black Sea and are food for larger organisms, such as fish and seabirds. The authors concluded that ingestion of MPs may have adverse effects on the health and functioning of zooplankton, also contribute to the transfer of MPs and related toxic chemicals to higher trophic levels, including humans.[80]

MPs are retained in the different layers of the water column, which is the vertical distribution of water from the surface to the bottom. With a supplementary, MPs particles in the water column favour the regular intake of plastic particles by zooplankton (Fig. 15),[81] which is a group of microscopic animals that float or drift in the water. Zooplankton are a major food source for many other aquatic organisms, such as fish and seabirds. In this way, MPs can be carried along the food chain and enter the bodies of larger animals.

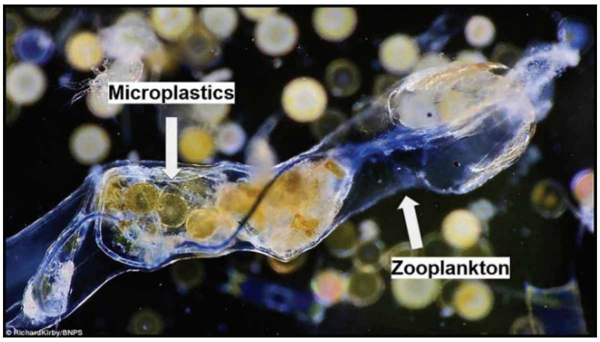

Fig. 15. This planktonic arrow worm, *Sagitta setosa*, has eaten a blue plastic fibre about 3 mm long. Photograph: Dr Richard Kirby.

Among the most vulnerable species to MPs contamination are bivalve molluscs due to their diet.[82] MPs have been found in farmed blue mussels *Mytilus edulis* and Pacific oysters *Crassostrea gigas*, as well as in wild Manila mussels, *Venerupis philippinarum*.[83]

The accumulation and effects of MPs after ingestion in predatory sea crabs (*Charybdis japonica*) were studied. Bioaccumulation (accumulation by consumption of microplastically contaminated mussels) was not observed, likely due to discarding of the plastic particles. Observations show that marine organisms have an innate ability to resist the acute effects of microplastics, but there is a limit beyond which defence mechanisms decrease and physiological functions are impaired.[57]

Aquatic plants can accumulate microplastics in their tissues, thus transferring them to higher trophic levels through the food chain. It is possible that MPs take up several contaminants on their surface due to the high adsorption capacity. There is not much information on developed techniques for efficient removal of

MPs from wastewater. Some authors consider and discuss effective technologies such as flotation, filtration and membrane separation of MPs from aqueous media, given their advantages and disadvantages.[84]

Coral reefs are unique and valuable ecosystems that provide numerous services to humanity, such as food, tourism and protection from the storms. But they are exposed to serious threats from human activities, including microplastic pollution. MP particles can penetrate coral tissues and cause stress, inflammation and death. Some studies, *e.g.*, Reichert *et al*. (2018), have shown that corals have different strategies for dealing with microplastics, such as ejection, ingestion or wrapping with mucus (Fig. 16).[85] But these mechanisms are not enough to protect against the negative effects of microplastics, such as bleaching and necrosis. Therefore, it is necessary to better understand how microplastics affect coral reefs and how to reduce their pollution in the marine environment.[86]

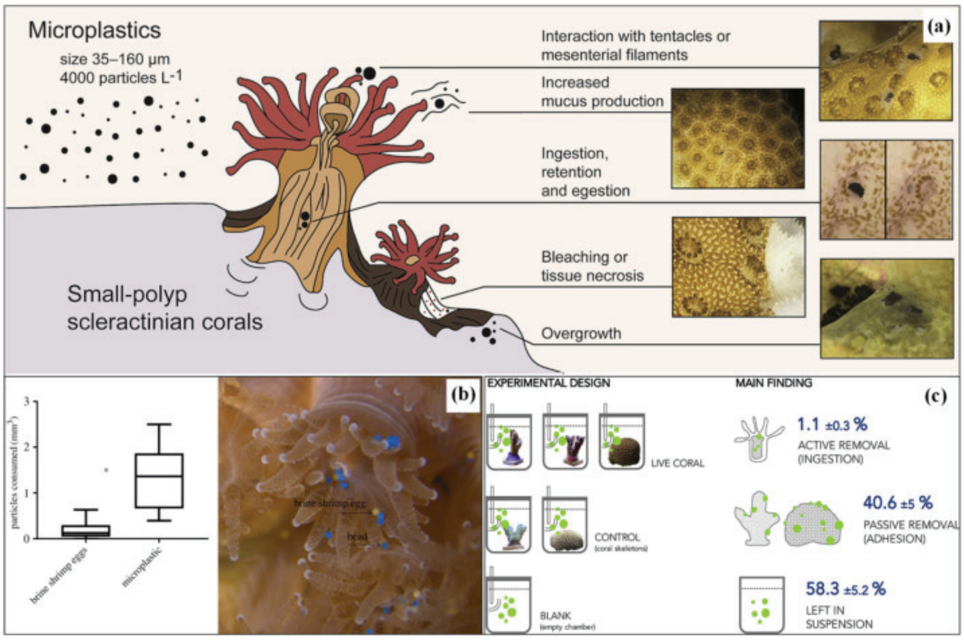

Fig. 16. Influence of microplastics on coral reefs.[85]

MPs have been found in almost all freshwater environments, including remote lakes and rivers.[87,88] MPs, similar in size to those of planktonic organisms, have been found in water columns and sediments of lakes and rivers worldwide. Their number and mass along the river can exceed those of living organisms such as zooplankton and fish larvae. In freshwater sediments, concentrations of MPs reach the same values as in the world's most polluted marine sediments. These particles result from a unique biogeochemical cycle that ultimately impacts on ecosystem productivity, biodiversity and functioning (Fig. 17).[89]

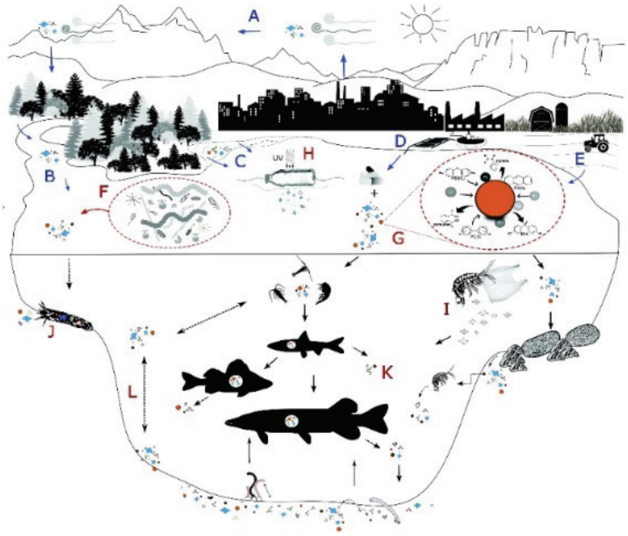

Fig. 17. Biogeochemical cycling of microplastics in inland waters.

Microplastics also act as carriers of toxic substances for invertebrates, fish and waterfowl.[88] The authors argue that MP is an environmentally significant parameter of inland water bodies due to its ubiquity, environmental sustainability, and interactions with key ecological processes. It is necessary to compare spatiotemporal variations in microplastic concentration within and between catchments. These data will allow more accurate modelling of the pollutant cycling and allow to identify sources, distribution and circulation pathways, and retention times.[88] MP can penetrate the food chain and cause hormonal disruptions, cancers or other diseases. According to research, people consume about 70,000 MP of particles per year.[90]

4. IN THE SOIL

Soils are an important element of the natural environment and are of great importance for agriculture, biodiversity and climate. Soils are formed by various factors, such as material, climate, vegetation, animal organisms and human activity. Soils are characterized by a variety of properties, such as mechanical composition, chemical composition, organic matter, moisture, temperature and fertility.

MP particles can contaminate the soil and have an adverse impact on the environment and human and animal health. MP particles can enter the soil *via* different routes, such as from biosolid waste, irrigation, atmospheric deposition or degradation of polymer films for mulching (mulching is a process in which the soil around plants is covered with various materials regulating water and air regimes in the surface layer of the soil (Fig. 18). MP particles can be absorbed by plants through their roots and penetrate their above-ground parts through the conductive system. This can affect plant growth, development and productivity, as well as crop quality. The effects of MP particles depend on polymer type, particle size and shape, plant species and experimental conditions.[91]

Fig. 18. Mulching in agriculture (http://bg.gardenflowerspot.com/).

In agriculture, a large amount of plastic is used for various purposes, such as covering the soil, irrigation, protection from pests and diseases. These products contribute to increase the harvest, but also lead to soil contamination by MPs (50–250 kg/ha). MPs can harm soil life, alter the physicochemical properties of the soil and pose a risk to human health and the environment. Therefore, it is necessary to better understand about the sources, distribution and consequences of MPs in soils and to take measures to reduce their formation and accumulation. Some of the main aspects of the MPs problem in agriculture are how they are distributed and migrated into it, what methods there are for their measurement and analysis, what ecological effects they have on soil life and how they can penetrate the human food chain (Fig. 19).[92]

Some of the most common and used microplastics in the environment are PP, PE, PVC and PET. These MPs can have toxic effects on plants that are important for the food chain and the economy. To investigate their impact, experiments have been carried out with some of the world's most cultivated and consumed crops, such as wheat, rice, maize and soybeans. Plants were exposed to different concentrations of MPs in the soil and various parameters related to growth, photosynthesis and nutritive value were then measured. The results show that all MPs have a negative effect on plants, affecting the root system and leaf surface the most. Also, specific effects were found for each polymer, such as PVC reducing the chlorophyll content and photosynthetic activity the most, and PE being the least toxic. These data suggest that MPs pose a serious threat to plant health and productivity and may affect food safety and quality (Fig. 20).[93]

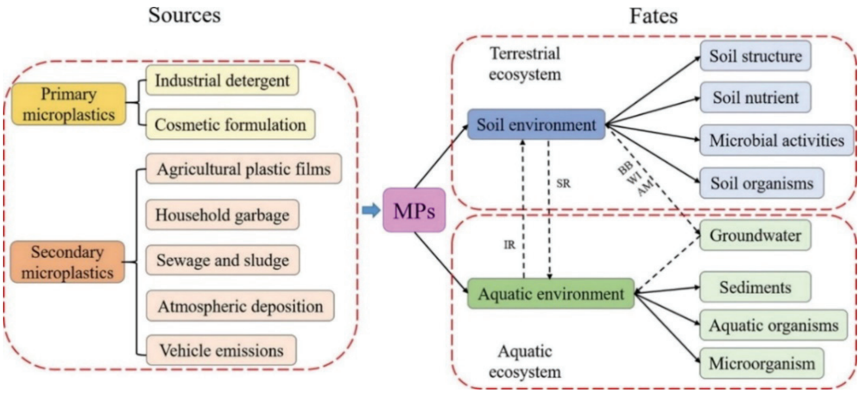

Fig. 19. Distribution and migration of microplastics in soils.

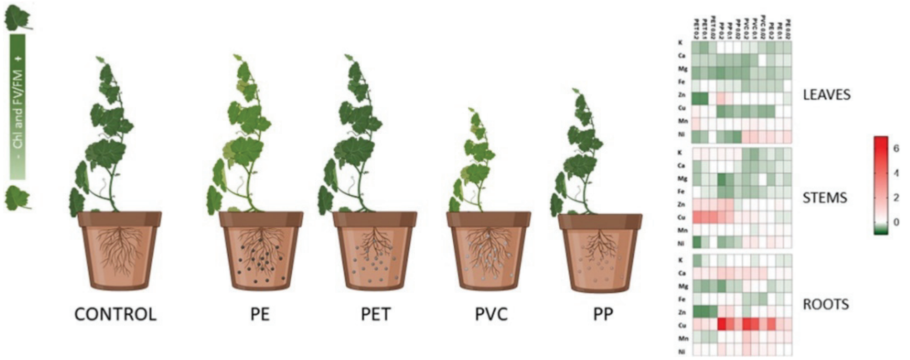

Fig. 20. The toxic effects of some microplastics.

5. FROM THE TRAFFIC

The literature examines the air pollution by MPs caused by motor vehicle traffic (Fig. 21).[94]

The sources of primary microplastics in the urban environment are diverse and complex. One of them is the wear of tires made of synthetic rubber, which are used for cars and other vehicles. These tires contain various additives, such as black carbon, mineral oils and other chemical substances that can have adverse effects on the environment and human health.[95]

When vehicles drive on the roads, they produce tire and road surface wear particles that disperse into the atmosphere or deposit on the surface. The size and quantity of these particles depend on many factors, such as the type and condition of tyres and roads, speed and driving patterns, climatic conditions, *etc.*[96] Tire and road wear particles can be transported by various roads to the environment. Some of them can be inhaled or ingested by humans and animals, which can cause respiratory or digestive problems. Others can be washed away by rain or snow and reach rivers, lakes or oceans, where they can contaminate aquatic ecosystems and enter the food chain.[97]

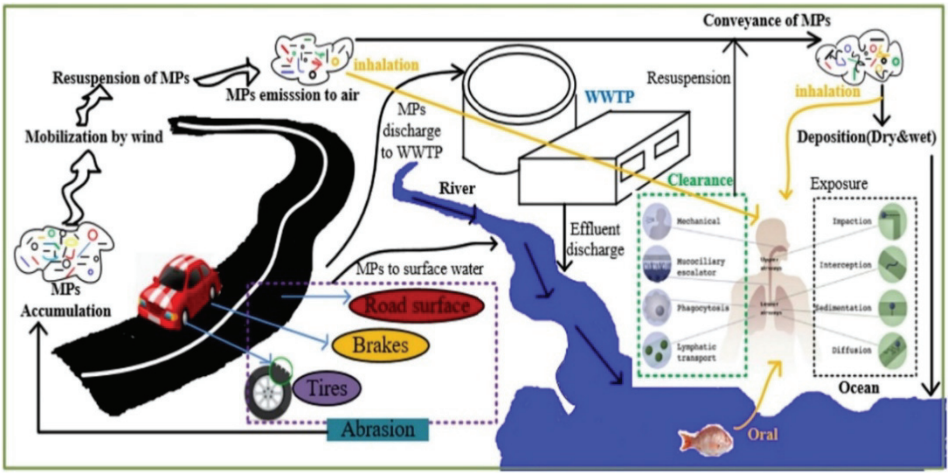

Fig. 21. Air–water exchange of abrasive traffic MPs and human.

The authors indicate that tire and road wear particles contribute substantially to primary MP pollution in urban areas. Kole *et al.* (2017) estimates that these particles make up approximately 0.1–10 % of PM_{10} (fine particulate matter) and 3–7 % of $PM_{2.5}$ in the atmosphere.[96,98] The studies by Panko *et al.* (2013) and Kole *et al.* (2017) reveal that approximately 28–30 % of particulate matter found in the oceans and rivers worldwide originates from tire wear and tearing. These particles, ranging from 15–50 nm in size, consist mainly of mineral oils and black carbon fragments, as documented by Dahl *et al.* (2006).[96,97,99]

After formation, tire wear particles spread to the environment by wind and watercourses. It is estimated that terrestrial sources contribute to about 70–80 % of ocean MPs, mainly transported by rivers.[100]

In Europe, transport sources discharge 42 % of all road pollution vehicles, while textile MPs contribute only 29 %.[101] Larger particles (> 10 μm) are uniquely susceptible to transport in the marine environment due to the gravitational force causing their deposition on the road surface, while small MPs from traffic are subject to direct emissions to the atmosphere and are carried through the air.[102] It has been shown that up to 10 % of the particles generated by tyre wear are carried through the air.

The emitted particles can be transported to a greater distance and subsequently deposited in the ocean.[103] However, the distance to which they can be carried depends on the local conditions and characteristics of the particles. Research has shown that particles measuring 1 to 10 μm can be trapped in the atmosphere for minutes to hours and carried up to 50 km from their source.[96]

6. IN HUMANS

MPs pose a serious threat to life on Earth. They are contained in seafood, salt and mineral water and can get into the human body in various ways – by ingesting contaminated with MP products and inhaling air polluted with MPs. MPs can enter the food chain and cause allergies, asthma or cancer.[104] Inhalation of MPs is especially dangerous because they have a high oxidation potential and can damage the respiratory system and other organs. The effects of MPs on human health depend on their size, shape, chemical composition and concentration. There are not enough regulations to limit emissions of MPs and to monitor their presence in the environment. Research in this area is still insufficient and more data are needed to assess the risk of MPs for human health.[105]

Scientific evidence highlights the role of air as an important source of human exposure to MPs. They have been found in atmospheric samples both indoors (in house dust) and outdoors, and it has been shown that the indoor environment contains a large proportion of these particles.[106] The wide distribution of these particles is due to their rapid transport over large distances, which is facilitated mainly by their small size (from 1 to 5 mm) and their low density.[107]

Studies have shown that airborne MPs consist in particular of fibres between 200 and 600 μm in size.[14,95] These fibres can penetrate human lungs, where fibres up to 250 μm in size have been found that can cause respiratory diseases, especially in vulnerable individuals (Pauly *et al*., 1998). According to estimates by the European Environment Agency (EEA), a person can be exposed to 26–130 MP pieces in the air per day. This is a serious health risk because MPs have pro-oxidative and pro-inflammatory effects, as well as they contain harmful additives, such as plasticizers, which act as endocrine disruptors. In addition, MPs can adsorb hazardous pollutants from the environment, such as persistent organic pollutants (POPs), and carry them into the body when inhaled. Therefore, it is necessary to take measures to reduce emissions of POPs and exposure to MPs in the air.[12,108]

After inhalation, microplastics reach the respiratory tract and are deposited depending on the properties of the particles, the characteristics of the individual and the anatomy of the lungs. Smaller particles of lower density (*e.g.*, polyethylene) are more likely to reach the deep airways. Particles of 5–30 μm are deposited in the upper respiratory tract by impaction in the rhino-pharyngeal walls, while particles of 1–5 μm reach the small airways by sedimentation and diffusion.[109] Particle deposition <1 μm occurs by Brownian motion.[109,110]

Although both MPs and nanoplastics (NPs) can reach the alveolar surface, the latter can pass into the bloodstream, overcoming the pulmonary epithelial barrier (Fig. 22). Despite the low reactivity, the number of atoms per surface per unit mass is large in MPs and NPs, which significantly increases the surface area for chemical reactions with body fluids and tissues in direct contact. This has been demonstrated in workers, working with PVC and a group of people who are prone to persistent inflammatory stimulation leading to pulmonary fibrosis or even carcinogenesis.[111]

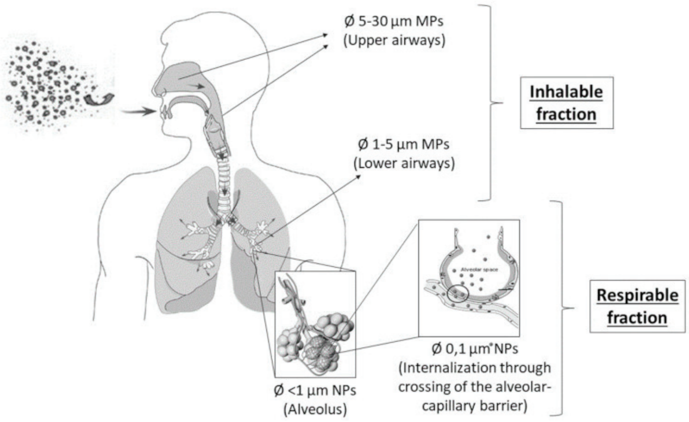

Fig. 22. Size-selective inhalation of airborne microplastics involves specific regions of the respiratory tract: inhalable fraction (upper and lower airways) and respirable fraction (deep airway).

MPs particle exposure by inhalation can trigger an inflammation-related bronchial reaction (similar to asthma), which can lead to toxic effects. The particles are positioned in the bronchi and stimulate immune cells to release substances such as reactive oxygen species, proteases and cytokines to deal with the foreign object. This inflammatory response can cause prolonged inflammation, which can lead to DNA damage and an increased risk of cancer. Inhalation of MPs is considered a more common form of exposure than ingestion and is considered more dangerous.[112]

Intense UV irradiation changes the morphology of airborne MPs, resulting in fragmentation and an increase in their surface area. Air MPs, due to their changed morphology and increased surface area, have a greater capacity to adsorb gaseous polluting chemicals on their surface. This means that MPs can retain a greater concentration of such chemicals relative to their size. This process can increase the potential of MPs to act as pollutant carriers and increase the risk of spreading and affecting these chemicals in the environment and on living organisms.[113]

The chemical toxicity of MPs is related to their hydrophobic behaviour and their ability to attract toxic chemicals. Size, shape, surface charge and ability to adsorb molecules and pathogens, as well as their bioresistance, are factors which may contribute to their toxicity.[114,115] These substances attach to the surface of the particles due to electrostatic forces, biofilm growth and chemical additives in polymeric materials.[116] MPs can adsorb persistent organic pollutants (POPs) like polycyclic arene hydrocarbons (PAHs), pyrene and phenanthrene, as highlighted by Delgado-Saborit *et al*. (2013) and Allen *et al*. (1998).[117,118] Additionally, MPs can also adsorb heavy metals, which are inorganic pollutants, as discussed by Wang and Wang (2018) and Zhang *et al*. (2018).[119,120] Other types of pollutants, such as phthalates and phosphorusorganic esters, have been found to be adsorbed on PS foam and PP microplastics from the marine environment.[121]

Comparisons with well-studied nonpolymeric microparticles in air (asbestos, silica, soot, wood, cotton, hay) allow the identification of putative mechanisms and are the basis for understanding the toxicity of MPs.[122] With the accelerated atmospheric microplastics (SAMP) can be inhaled and deposited in human lungs, where the chemicals and pathogens associated with them can induce infections and other adverse effects. Also, SAMPs can be carriers of heavy metals, which can also be toxic to human health. Research works on phthalates and phenols, show that both they and other components of MPs can cause health problems, such as a shortened gestational period, a decrease in birth weight, a change in gene expression and endocrine disruption.[123,124] According to the research conducted by Wang and Wang (2018), microplastics have the capability to adsorb pyrene and phenanthrene.[119]

A study by Law *et al*. (1990) confirmed that plastic fibres are more durable than vitreous fibres in synthetic extracellular lung fluid over a period of 180 days.[125] MPs can group and stay longer in human lungs. This process can contribute to chronic oxidative damage induced by reactive oxygen forms, which is associated with various diseases and injuries in the body.[125]

Scientists are actively exploring technologies for the separation and identification of microplastics in food products and ecosystems. These technologies include flotation, chemical processing, enzyme processing and other methods that have their advantages and disadvantages. New techniques such as enzymatic degradation in combination with hyperspectral imaging are being investigated to achieve greater separation and characterization efficiency of microplastics with minimal impact on food sample. The choice of standard technology for analysing microplastics in food matrices is challenging, taking into account particle composition, size and shape, data visualization methods and costs (Fig. 23).[126]

Research shows that microplastics spread widely in the fresh and marine aquatic environment and pose a threat to aquatic organisms. Trophic transfer processes (bioaccumulation is the process by which toxins gradually accumulate in certain organs of humans or other organisms) and biomagnification (the process by which toxins steadily increase their concentration as they move up the food chain) are pathways by which microplastics can penetrate the human body. Research focuses on adverse effects of microplastics on aquatic organisms, such as neurotoxicity, behavioural changes, histopathological damage, ignition, oxidative stress, biochemical and haematological changes and embryotoxicity. Also discussed are the main food sources contaminated with microplastics that can enter the human food chain – sea salt, drinking water and seafood (fish, shells, crustaceans).[127] After administration, they can enter the gastrointestinal tract by endocytosis from M-cells, pass into tissues by paracellular transport, and then determine systemic exposure.[128] There is evidence that synthetic particles with a size of less than 150 μm can pass through the gastrointestinal epithelium of mammals. However, it is assumed that only 0.3 % of these particles are absorbed and only 0.1 % of particles that are larger than 10 μm should be able to reach organs and cell membranes.[129] Although no study has reported toxic effects of MPs in the human body, in several studies it has been suggested that large concentrations of these pollutants can produce toxic effects in various *in vitro* systems.

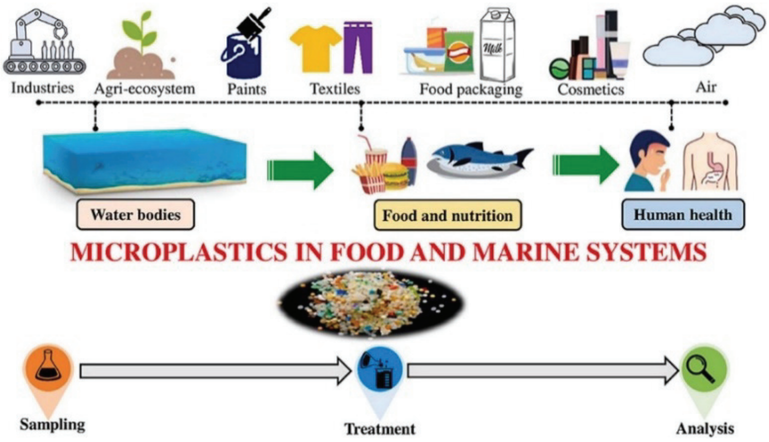

Fig. 23. Microplastics in food and marine systems.

6.1. *To the digestive system*

In their study on gastric adenocarcinoma cells, Forte *et al.* (2016) have found that unmodified polystyrene nanoparticles of sizes 44 and 100 nm were internalized by clathrin-mediated endocytosis.[130] This internalization process could potentially trigger inflammatory responses and induce morphological changes in the cells. Studies have demonstrated that high concentrations of polystyrene (PS; known as PS-MPs), with a diameter of 1 μm, increase cytotoxicity in three different *in vitro* systems.[131]

Other authors provide a probabilistic lifetime exposure model for children and adults, which accounts for intake via eight food types and inhalation, intestinal absorption, biliary excretion and plastic-associated chemical exposure *via* a physiologically based pharmacokinetic submodel.[132]

6.2. *To respiratory system*

According to Paget *et al.* (2015), only positively charged polystyrene nanoparticles (PS-NPs) exhibited cytotoxicity in a dose-dependent manner. For certain cells, the LC_{50} (lethal concentration 50) was found to be 31 μg/mL, while for specific macrophages, it was 75 μg/mL.[133] The cytotoxic effects observed could be attributed to the ability of PS-NPs to induce DNA double-strand breaks and cause significant depletion of glutathione (GSH) in both cells and macrophages. Additionally, researchers suggest that PS-NPs could potentially contribute to impairment and functional disorders in the respiratory system of humans and mammals.[134]

6.3. To the nervous system

In order to better understand the cytotoxicity of MPs at the cellular level with respect to oxidative stress and cell viability, brain human cells (T98G) were exposed to several concentrations (50 μg/mL to 10 mg/L) of PE-MPs and PS-MPs.[135] According to their results, none of the MPs resulted in a significant decrease in cell viability, suggesting that cytolysis was not induced. However, reactive oxygen species were significantly increased in T98G cells after exposure to both types of MPs. These results suggest that oxidative stress may be an important mechanism by which MPs exert their toxicity at the cellular level.

6.4. To the placental barrier

In a study conducted by Grafmueller *et al*. (2015), it was demonstrated that microplastics have the ability to cross the human placental barrier. The researchers utilized an *ex vivo* model of human placental perfusion to analyze the transport mechanisms involved in the placental transfer of PS-NPs ranging from 50 to 300 nm in size.[136] Their results showed that PS-NPs accumulate in the syncytiotrophoblast of placental tissue. Thus, syncytiotrophoblast has been suggested to be a key player in regulating the transfer of PS-NPs through the human placenta. Moreover, the underlying mechanism underlying this relocation can be based on an energy-dependent transport pathway. These results highlight the need for further research to help in the overall understanding of the mechanism of NPs transport across the placental barrier, as NPs can induce embryotoxicity. Lithner *et al*. (2011) conducted a study where they developed a comprehensive ranking of hazards associated with plastics. They based their ranking on internationally agreed criteria used to identify risks related to physical, environmental, and health factors.[137]

Apart from the chemical nature, there are other factors inherent in polymers which may also affect toxicity. Free radicals are generated in the polymerisation process and subsequent processing of plastics which act as a common factor in promoting the production of reactive oxygen species (ROS).[112] Moreover, these free radicals easily increase their concentration in the particles due to the dissociation of C–H bonds induced by light exposure or interaction with transition metals during the weathering process.[138] It is therefore worth noting that photodegradation and biodegradation in the environment induces surface changes affecting their functional groups (*e.g.*, –COOH, $–NH_2$) which alter toxicological profiles.[139] Other properties of the particles, such as shape or surface charge, have also been identified as potential toxicity factors for MPs.[140]

7. SEPARATION, IDENTIFICATION AND CHARACTERIZATION OF MICROPLASTICS

Despite the advanced stage in the areas of MP pollution, there are still no widely accepted and uniform standards for sample collection, laboratory analyses, quality control (QA/QC) and reporting of MPs in ecosystem samples. Based on a comprehensive assessment of MPs in water, sediments, fish, binary molluscs, rainwater and wastewater, some authors have developed and recommend best practices for collecting, analysing and reporting MP in the environment. They also recommend the factors to be considered in the design of the study for MPs, especially with regard to site selection and sampling methods. First emphasize the need for standard QA/QC practices, such as collection of field and laboratory samples, then use of methods outside microscopy for partial composition identification and standardized reporting practices, lastly proposal for a glossary for particle classification (Fig. 24).[141]

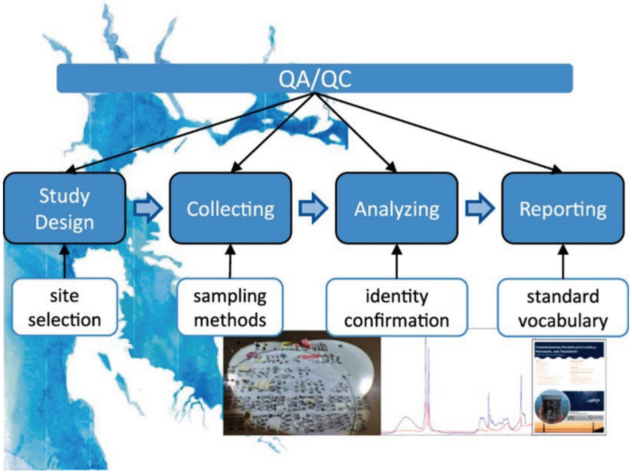

Fig. 24. Quality assurance/control (QA/QC).

Microplastics <5 mm in size are very difficult to remove from water bodies, sediments and air with available techniques. NPs are less than 1 μm. Methods suitable for collecting MPs include sieving, filtration, visual sorting, grinding, density separation. Their isolation can be carried out by various physical, chemical and biological methods. In practice, the techniques for identification and characterization of MPs in the environment are SEM-EDS, FTIR, NIR, Raman, NMR spectroscopy, *etc*. NMR spectroscopy can also be used to find concentrations. There is still a need for the development of similar more economical and portable techniques (Fig. 25).[142]

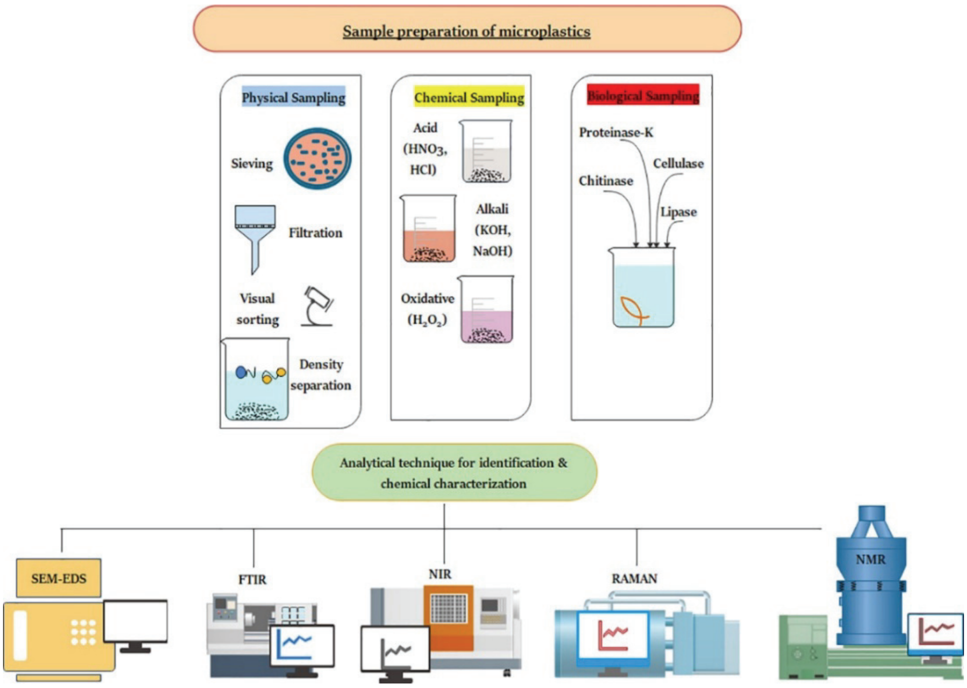

Fig. 25. Methods and techniques for the identification of microplastics in samples.

One way to quantify and classify microplastics of diverse chemical composition and shape is by scanning electron microscopy. It offers greater depth and finer detail, over a wider magnification range, than visible light microscopy or the digital camera, and allows further analysis of chemical composition. For the quantification of MPs, the authors propose two deep learning models with neural networks (U-Net and MultiResUNet) for semantic segmentation. To classify the shapes, they use a finely tuned VGG 16 network, which classifies microplastics based on their shapes with a high accuracy of 98.33%. With the trained models, only seconds are needed to segment and classify with high accuracy, which is remarkably cheaper and faster than manual labour.[143]

In other studies, stable carbon isotope ratio mass spectrometry (IRMS), attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) and micro-Raman spectroscopy (μ-Raman) were investigated as complementary techniques for characterizing common MPs.

The polymer articles selected by the authors for comparative analysis include food packaging, containers, straws and polymer pellets. The ability of the

IRMS to discriminate between weathered samples was also investigated using simulated weathering conditions with ultraviolet (UV) light and heat. IRMS results show a difference between $\delta\ {}^{13}C$ values for polymers of plant origin and petroleum-based polymers. Differences were also found between plastic products composed of the same polymer but from different countries, and between some recycled and non-recycled plastics. In addition, there was an increase in $\delta\ {}^{13}C$ values after exposure to ultraviolet light. The authors discuss the results, advantages and disadvantages of the three techniques (Fig. 26).[144]

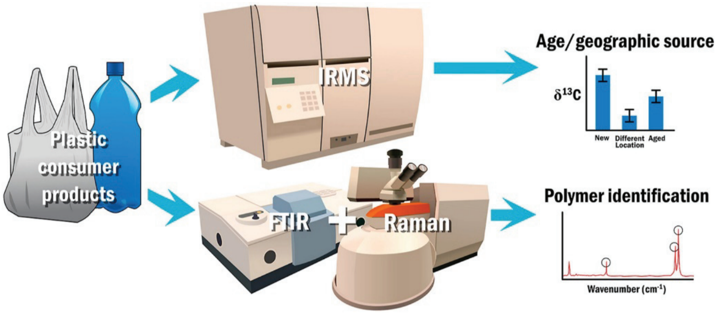

Fig. 26. Spectroscopic techniques for the characterization of microplastics.

Other authors consider and analyse the strengths and weaknesses of the different instrumental methods for separation, morphological, physical classification, chemical characterization and quantification of MPs. This is due to the complex transformation, cross-contamination and heterogeneous properties of MPs in size and chemical composition (Fig. 27).

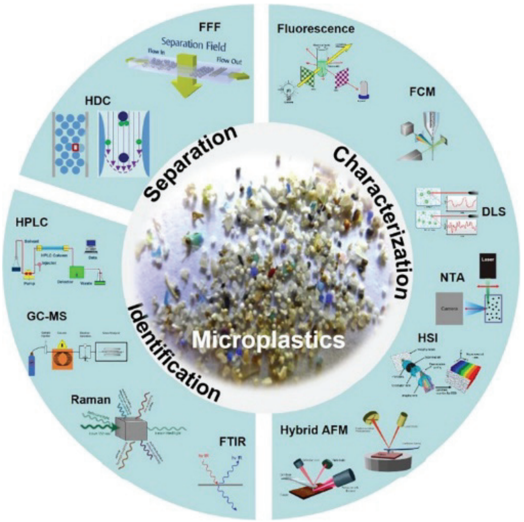

Fig. 27. Separation, characterisation and identification of MPs and NPs in the environment.

It is pointed out that future research efforts should be focused on the development and implementation of new analytical tools and combinations of technologies to complement detection constraints and provide reliable information for the characterization of MPs.[145]

Different analytical techniques can be used to measure the levels of MPs and NPs in different matrices. The application of thermal analysis is also promising. The authors consider the importance and advantages of thermal analyses for assessing exposure to such plastics in ecotoxicological and toxicological studies.[146]

Microplastics contained in food salts (marine, stone) may pose a potential hazard to human health. A visual assessment is performed for the identification of the shape, size, number and colour of the particles using light and fluorescence microscopy. The composition of the sample is analysed by Raman spectroscopy. A relatively large number of MPs are found in sea salts. The most common are PE, PP, PET) nylon and PS, effectively removed from seawater by microfiltration membranes. The membrane backwash technique is used to improve membrane efficiency.[147]

Research teams are working on the use of near-infrared hyperspectral imaging (HSI-NIR) to automatically identify microplastics (Fig. 28).

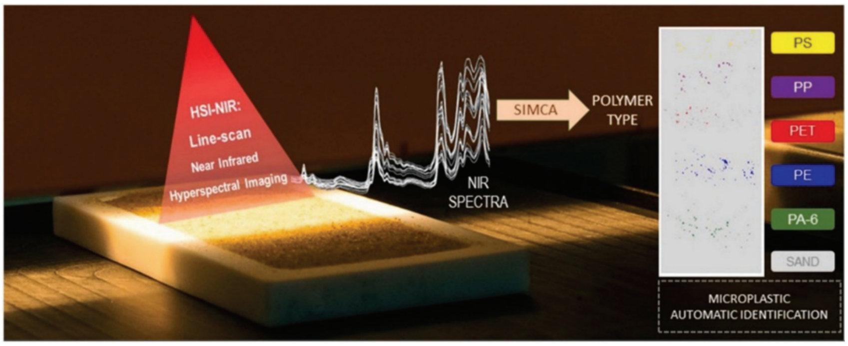

Fig. 28. A comprehensive and fast microplastics identification based on near-infrared hyperspectral imaging (NIR-HSI).

A high-throughput screening method utilizing near-infrared hyperspectral imaging (NIR-HSI) has been developed for the automatic identification of MPs in beach sand with minimal sample preparation. The method can analyse the whole sample or a fraction (150 µm to 5 mm) after sieving. It can detect small, colourless MPs (<600 µm) that may be difficult to identify through visual inspection or manual collection. Unlike conventional infrared spectrometers, no spectroscopic subsampling is required due to the high-speed analysis capability of the linear scan toolkit, allowing simultaneous evaluation of multiple MPs.

The NIR-HSI method investigates a scan region of 75 cm^2 in less than 1 min, with a pixel size of 156 µm×156 µm. A proprietary comprehensive spectral data set, which includes weathered microplastics, is used to construct multidimensional supervised classification models using class analogy modelling (SIMCA). These chemometric models have been validated for hundreds of microplastics collected from the environment, taking into account particle size, colour and weathering. The models exhibit high sensitivity and specificity (over 99 %) for identifying specific types of MPs such as PE, PP, polyamide-6 (PA), PET and PS.

The method has been successfully applied to a sand sample, identifying 803 particles without prior visual sorting. This indicates the stability and reliability of automatic identification, even when analysing weathered microplastics alongside other matrix constituents. The NIR-HSI-SIMCA method is also applicable to MPs extracted from other matrices after sample preparation.

Comparisons have been made between the principles of NIR-HSI and other commonly used techniques for the chemical characterization of MPs. The results highlight the potential of using NIR-HSI in combination with classification models as a comprehensive screening approach for characterizing different types of MPs.

In the context of the marine environment being a major sink for MPs, there is an urgent need for monitoring methods that can detect synthetic particles in various marine components and sample matrices. Previously, the direct characterization of MPs in real marine matrices using near-infrared hyperspectral imaging (NIR-HSI) has not been explored. However, a study by Piarulli *et al.* (2022) introduced a fast NIR-HSI method coupled with a customized data processing strategy using normalized image differences (NDI). This method was utilized to detect MPs up to 50 μm in environmental matrices.[148]

The proposed method is highly automated, eliminating the need for extensive data processing. It enables the successful identification of different polymer types in surface water, mussel soft tissue samples, and real field samples containing MPs in the environment. NIR-HSI is directly applied to filters, eliminating the requirement for pre-sorting of particles or repeated sample purification. This approach saves time, prevents air pollution, and avoids particle degradation and loss.

With its temporal and financial efficiency, the large-scale application of this method could facilitate comprehensive monitoring the presence of MPs in natural environments, allowing for the assessment of ecological risks associated with this form of pollution (Fig. 29).

One of the developing, environmentally friendly and clean technology for the reduction of MPs and NPs is microbial degradation. It is influenced by several biotic and abiotic factors, such as enzymatic mechanisms, concentration of substrates and co-substrates, temperature, pH, oxidative stress, *etc*.

Therefore, it is crucial to recognize the key pathways adopted by microbes to use polymer fragments as the sole source of carbon for the growth and development. Some authors critically discuss the role of different microbes and their enzymatic mechanisms involved in the biodegradation of MPs and NPs in the wastewater stream, municipal sludge, municipal solid waste and composting, starting with biological and toxicological impacts of MPs/NPs.[149] The implementation of various MPs/NPs recovery technologies, such as enzymatic, advanced molecular and biomembrane technologies to promote their bioremediation from the environment, along with their pros, cons and perspectives, is also considered.

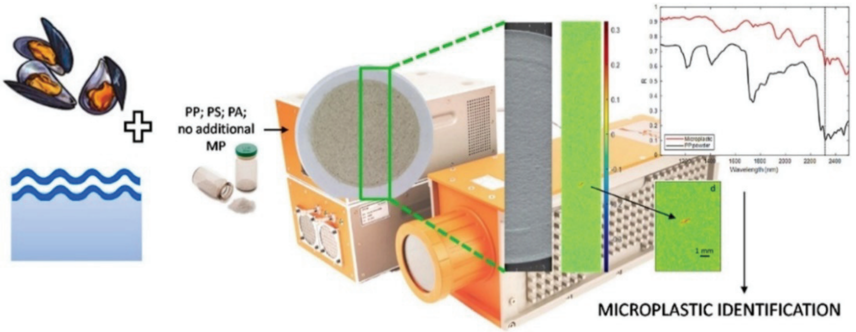

Fig. 29. A comprehensive and fast microplastics identification based on near-infrared hyperspectral imaging (HSI-NIR).

Therefore, it is crucial to recognize the key pathways adopted by microbes to use polymer fragments as the sole source of carbon for the growth and development. Some authors critically discuss the role of different microbes and their enzymatic mechanisms involved in the biodegradation of micro- and nanoplastics in the wastewater stream, municipal sludge, municipal solid waste and composting, starting with biological and toxicological impacts of MPs/NPs.[149] The implementation of various MPs/NPs recovery technologies, such as enzymatic, advanced molecular and biomembrane technologies to promote their bioremediation from the environment, along with their pros, cons and perspectives, is also considered.

8. CONCLUSION

We looked at where plastic waste comes from, where it goes and what its effect is on seas, living organisms and on us, humans. We have also shown available techniques for identifying plastic waste and how to prevent or reduce it. Knowledge of the consequences of plastic waste is constantly improving.

All types of organisms suffer consequences from the ingestion of plastic particles. Drifting waste can interfere with both the surface and the bottom of the ocean when it settles. Plastic particles concentrate on their surface both toxic substances disrupting a number of human systems and other persistent synthetic compounds, which are then collected in the natural way of life at different trophic levels.

Our study and other research of this type, especially those of a regional and local nature, can be part of training campaigns and efforts planned to reduce plastic waste around the world. Although ocean cleanup is probably one of the most outstanding ventures at present, the countless smaller and private shoreline cleanup activities around the world are contributing fundamentally to much needed change.

The circular economy is seen as the most promising path towards a more sustainable use of polymers. It aims to reduce resource consumption by keeping materials in the value chain for longer periods than traditional linear material flow.

MPs are a serious environmental and potential health problem. Therefore, it is necessary to take measures to reduce the production and disposal of plastics waste, as well as to better manage and process this waste. Raising general awareness and achieving a positive effect through cleaning and prevention activities can continue to develop. Institutional research strategies would ensure similarity of results in order to be able to form an increasingly stable picture of plastics pollution around the world. We will most likely tackle this problem if the contribution of new plastic junk is stopped in the long term or reduced radically earlier. Like this we should be able to protect biological systems and not cross any major natural boundaries.

Life on Earth depends on us!

ИЗВОД

МИКРОПЛАСТИКА – ЗАГАЂИВАЧИ ЕКОСИСТЕМА

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Присуство микропластике у различитим екосистемима интензивно се проучава од почетка 21. века, и од тада се налазе у свим деловима животне средине, као и у бројним организмима. Микропластика (MP) је термин за честице чија је величина 1 μm–5 mm која се формира током деградације већих пластичних производа или се производе у микро-величинама за различите индустријске и козметичке производе. Дистрибуција ових честица последица је њиховог брзог транспорта на великим раздаљинама, а углавном је олакшана њиховом малом величином и ниском густином. Још увек не постоје уједначене методе и стандардизоване процедуре за узорковање и анализу. Стога чињенице о појављивању, дистрибуцији и претњама екосистемима и људском здрављу од MP још увек нису у потпуности схваћене. Овај преглед литературе је широка презентација стања знања о расподели MP у атмосфери, води, земљишту и организмима. Поред тога, овај документ описује најраспрострањеније методе за раздвајање, идентификацију и карактеризацију микропластике.

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