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Plastic oceans

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Abstract: With annual global production of artificial polymers (plastics) exceeding 400 million tonnes, the oceans are among the areas most affected by plastic pollution. The distribution of plastics in these oceans is influenced by human activities. Plastic pollution is found on beaches, on the surface and, for more than 90%, on the seabed worldwide. Plastic degrades at sea into microplastics or nanoplastics, constituting, together with industrial pellets or primary microplastics, a heterogeneous group of particles, varying in size, shape, colour, chemical composition and density. Little is known about the extent of the impacts caused by marine litter and microplastics. Some of the most important are the entanqlement of organisms, ingestion by organisms, release of contaminants and long-range transport of species. There are also impacts on certain sectors of the economy, including tourism and fisheries, but also risks to navigation and health impacts. In addition to reduction measures based on circular economy, recycling, water purification, selective cleaning and education, global initiatives (United Nations Environment Assembly, G7 and G20), establish a framework within which states must take management measures to achieve a better state of the environment. However, the risks remain high, environmentally, socially, economically and for human health.

Keywords : *Marine litter, plastic pollution, microplastic, social and ecological damages*

1. Introduction

With around 4 billion tonnes of waste including plastics generated worldwide each year and annual plastic production reaching 400 million tonnes by 2021, the world's ocean receives around 20 million tonnes each year, of which 8 million tonnes is plastic from the continents. No sea, no ocean is spared and the most remote areas, beyond the polar circles, also receive some. For specialists, marine litter consists of all materials or objects that are directly or indirectly, voluntarily or involuntarily, discarded or abandoned in marine aquatic environments or connected to the seas and oceans. This definition covers a very wide range of sizes from mega-waste (> 1 m), to microplastics (1–5,000 µm: Fig. 1) and even nanoplastics (< 1 µm). They are classified according to the nature of the material, such as plastic, metal, glass, rubber or wood, or according to sources or uses, such as fishing gear, industrial pellets, sanitary ware and single-use plastics.

According to the United Nations Group of Experts (GESAMP, 2019), plastics consist of

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polymers synthesised from hydrocarbon or biomass molecules with thermoplastic or thermoset properties. It is the main component of marine litter and has a wide range of properties, shapes and compositions. Depending on the area, these materials can account for up to 100% of marine litter and their increase in the marine environment has long been ignored, reinforced by economic policies that favour single-use, disposable and non-repairable products. In a few years, the problem has become global.

The problem of litter pollution is not really new. In chapter 11 of his famous book "Twenty Thousand Leagues Under the Sea" (VERNES, 1870), published in 1870, Jules Vernes describes in Chapter 11 the accumulation of debris in the Sargasso Sea, an accumulation attributed to the circular currents that allow boards and other floating ropes to be concentrated. However, the share of plastics, which was non-existent at the beginning of the 20th century, has become very important in recent years. Although the first descriptions of plastic floating on the surface of the oceans date back to the 1970s, in the Atlantic and Pacific Oceans, all compartments of the marine environment are now affected. It is estimated that 1–5 trillion plastic bags are consumed globally each year (UNEP, 2018). At sea, about 40% of the waste is single-use plastic packaging, made to be light and strong, but unfortunately persistent in the environment.

Marine litter is present in all habitats, from densely populated areas to remote regions (BARNES *et al.*, 2009), from beaches and shallow waters to deep ocean trenches (PIERDOMENICO *et al.*, 2019). Sources are often diffuse and mainly land-based. Wastes come from rivers, sewage, sewage overflows, inappropriate or illegal discharges or dumping and runoff, and directly from some human activities such as tourism. It is estimated that more than one million tonnes of plastic waste enter the ocean each year from the 20 most polluting rivers, mostly in Asia, accounting for a significant percentage, between 60 and 80% of the world's total plastic at sea (GALGANI *et al.*, 2021b).

Through degradation and fragmentation, plastic waste is transformed into microplastics. The diversity of polymers that form these plastics and their properties makes understanding their fate very complex, some sinking immediately, others, of low density such as polyethylene and polypropylene, moving on the surface with the currents. Primary microplastics such as industrial granules or microbeads used in cosmetics are designed to be small and represent a significant fraction of microplastic inputs, but the vast majority of these, known as secondary, are derived from the fragmentation and degradation of larger debris. The most recent work has shown the importance of certain sources such as textiles, via washing cycles in machines or emission of fibres into the atmosphere, tyres, from rubbing or on tarmac, or fragments from boat paints. Plastic pollution also enters the marine environment due to deficiencies in treatment infrastructure, including water treatment. For plastic microparticle streams alone in water from wastewater treatment plants in Europe, concentrations can reach up to 10 million particles/m^3 (GALGANI *et al.*, 2021b).

Other sources of marine litter can be attributed to shipping, industrial exploration and offshore oil platforms, fisheries and aquaculture (GESAMP, 2015; 2019), as well as to the intentional loss or disposal of, for example, containers, ballast weights and cargoes. Fishing waste (Fig. 1) is most characteristic, particularly in the Western Pacific and Indian Ocean where it is not uncommon to see buoys or pieces of net accumulating on isolated archipelagos where they have been transported. In some fishing areas, marine litter consists entirely of abandoned, lost or discarded fishing gear (Pham *et al.*, 2014). The amount of such litter is not well known, although some estimates are available. About 640,000 tonnes per year, according to Macfayden *et al.* (2009), and about 70% (by weight) of floating macroplastics in the high seas are fisheries-related (Eriksen *et al.*, 2014). It is also estimated that 5.7% of all fishing nets, 8.6% of all traps and 29% of all lines are lost globally each year (Richardson *et al.*, 2019).

On a more local scale, microplastic granules, which are synthetic industrial products lost during production or shipping, become plastic waste before they are even used. These inputs constitute a risk of future accidental pollution, as illustrated by recent events such as the stranding of plastic microbeads on the Sri Lankan coastline in 2021 following the loss of containers (The Washington Post https://www.washingtonpost.com/world/2021/06/01/nurdles-sri-lanka-ship-wreck-plastic-pellets/ accessed on 1 October 2021).

Inputs from extreme events and natural disasters, such as hurricanes, floods, earthquakes and tsunamis, as well as accidents, can reach millions of tonnes each year and match the magnitude of regular inputs from the land (Carlton *et al.*, 2017). The tsunami in Japan in 2011 is the most representative and recent example of massive accidental waste inputs, this event generated about 5 million tonnes of waste discharged into the sea (Ministry of the Environment of Japan, 2012), some of which drifted to the surface towards the convergence zones and the eastern coasts of the Pacific Ocean (Murray *et al.*, 2018).

The nature of the litter varies greatly depending on whether it is beach, surface or seabed based, and on the activities in a region. Observation, trawling, aerial surveys, plankton collection, aerial photography, use of submersibles or scuba diving are the various possible approaches to assessment, each corresponding to a particular site, region or biotope. Numerical modelling completes the methodological approaches. It allows the location of likely accumulation areas and the prediction of the fate of objects at sea, including indications of transboundary transport.

At sea, the duration of degradation is subject to external factors such as luminosity and the presence of oxygen, which is less at depth, or the possibility of abrasion, particularly on beaches. Thus, the lifespan of waste is very variable, from two weeks for newsprint, a few years at least for fine plastics and several hundred years for certain polymers such as telephone cards (1000 years) or fishing lines (600 years). Glass, considered inert, can persist for thousands of years.

In the coastal environment, at the surface of the sea, plastics are mainly made up of polyethylene, polypropylene and expanded polystyrene. But in addition to these three types of resins, there are a dozen other polymers in lesser proportions. These are all polymers that are less dense than sea water and can therefore remain on the surface. In the open sea, still at the surface, we still find mainly polyethylene (90%) and polypropylene (10%), the polymers most produced in industry and probably the most persistent in the open sea. The water column has been much less explored than the sea surface. It seems that from a few metres down in the water column, microplastics are distributed differently. They are mainly small microplastics and synthetic fibres, which are only a few hundred or even tens of micrometres in size, whereas at the sea surface, the particles detected measure several hundred micrometres to a few millimetres.

In the sediments, denser polymers such as polyesters or polyacrylics are found (77% on

Fig. 1 Plastic pollution affects all areas of the marine environment: (A) Microplastics collected on the surface, Mediterranean Sea, (B) Beach litter, Northwest Atlantic, (C) Fishing litter, Northwest Atlantic, (D) Accumulation of plastic litter on the bottom, Mediterranean Sea, Ramoge campaign, 2200M.

average) but surprisingly, fragments of polymers less dense than seawater are also found (Galgani *et al.*, 2022), which have therefore undergone vertical transport from the surface to the bottom via processes that are very poorly understood. These processes could include colonisation by micro-organisms or integration into aggregates made of organic matter and responsible for the normal process of transferring this organic matter to the bottom.

2. Beach litter

Most work on plastics at sea has focused on coastal areas due to proximity to sources, ease of access/assessment and for aesthetic reasons. Data is most often based on measurements of quantities or flows of waste categories, on transects of varying width and length. This makes it difficult to build up an overall quantitative picture of beach litter. In addition to scientific work, beach clean-ups are important sources of data, sometimes providing information on the number of items, their weights; types of materials, and even their use or origin. These assessments reflect the long-term balance between inputs, land-based sources or strandings, export to the sea, burial, degradation and clean-ups. Certain factors largely influence densities, including storms, rainfall, tides, and hydrological changes.

The most common scientific approach is to conduct regular post-cleanup surveys to reveal long-term patterns and cycles of accumulation, while not requiring a lot of time. In particular, this approach allows the assessment of flows. It mainly concerns the space between the sea and the upper submerged limit of beaches, at sites most often chosen for their ecological relevance, accessibility and particular anthropogenic activities and sources. Beach shape, location and nature of debris are also important selection criteria (TURRA *et al.*, 2014). In addition, most surface sediment counts do not take into account the overlay and burial of debris, grossly underestimating the quantities present. It appears that glass and hard plastics accumulate more easily on rocky shores (GALGANI *et al.*, 2015). Waste often washes up on beaches without strong prevailing winds (Fig. 1), which can carry it offshore (GALGANI *et al.*, 2000). Furthermore, the abundance and composition of litter often varies between different parts of an individual beach, with the highest amounts frequently found at high tide or storm lines. For this reason and because of beach topography, patchy distribution is a common distribution pattern on beaches, particularly for smaller, lighter items that are more easily dispersed or buried. High concentrations range up to 78.3 items/m^2 or even more than 5,000 items/m^2 in the case of extreme events such as typhoons or floods (GALGANI *et al.*, 2015). In general, the results indicate the prevalence of plastics, with higher loads near urban areas and tourist regions (BARNES *et al.*, 2009). However, other types of waste may also be important in some areas, in terms of type (wood) or use (e.g., fishing gear). The lack of large-scale trends (GALGANI *et al.*, 2021b) in many beach studies is probably due to the heterogeneity of sources and factors that may influence the small-scale distribution.

3. Litter on the seabed

The seabed remains the least known part of the oceans. Litter has been observed on almost all types of seabeds, but the highest concentrations have been observed in canyons and trenches (GALGANI *et al.*, 2022), due to their physical and geomorphological characteristics. Recent work has assessed human impacts on deep-sea environments, determined temporal trends, shown the presence of characteristic objects or sources, and evaluated the effectiveness of measures. Some studies have even covered the deepest areas, such as the Mariana Trench (CHIBA *et al.*, 2018). However, with a poorly described distribution and circulation of water different from surface currents, one of the major issues of the coming years, a real challenge of the 21st century, will be to discover these remote and deep areas where large amounts of debris probably accumulate.

Generally speaking, average densities range from 0 to more than 7, 700 items/km^2. The highest densities of plastic litter are found in coastal areas, in enclosed bays, including coral reef lagoons, fjords and at the heads and upper slopes of marine canyons. They very often end up at the bottom of canyons or in areas of low circulation where sediments can accumulate. High densities have been found in the Barents Sea, the North Sea, the Bay of Biscay and the Western Pacific. In addition to canyons, the presence of deep, converging currents, leading to high sedimentation rates, accounts for accumulations at great depths. Distant regions such as the Arctic regions can receive substantial amounts of waste (5,351–8,082 items/km^2; TEKMAN *et al.*, 2017), probably due to deep and converging currents (GALGANI and LECORNU 2004; TEKMAN *et al.*, 2017). However, the quantities are much smaller in the Antarctic region.

Piles of several tonnes of waste have been demonstrated in some underwater areas, sometimes several tens of miles offshore. In the abyssal plain, high densities are the result of populated areas and intense maritime activities（Morales-Caselles *et al.*, 2021）. Extreme average values, above 10,000 items/km^2, have been found in Sardinia, Malta, California and the South China Sea. In some areas of the Mediterranean, densities of up to 10,000 items/km^2 have even been identified（Fig. 1）. This is mainly heavy waste, metal, glass, plastics or dense packaging（Harris, 2020）. This situation is linked to the high population density on the coast, the high volume of maritime traffic, the presence of large rivers（Nile, Po）and the intensive tourist activities around this closed basin（UNEP, 2015）.

Finally, the accumulation of microplastics on the seabed is still very poorly documented, even though it is known that many macro-waste products are stored in the seabed away from light and therefore have extremely slow degradation kinetics. In general, microplastics in deep-sea sediments are present in greater quantities than in surface waters, which supports the hypothesis that they constitute a reservoir of microplastics（Harris, 2020）.

These microparticles have been found in sediments all over the world（Galgani *et al.*, 2022）with higher average concentrations in fjords, estuarine environments, and in shallow coastal environments. Unlike macroplastics, microplastic concentrations are generally not associated with local sources of contamination. Of particular interest are the high densities observed in the Arctic; up to 6,595 items/kg of sediment, comparable to those observed in populated areas and even higher than the amounts reported by many other studies, including marine canyons. These densities are likely related to atmospheric transport and deposition, a now-recognised pathway for microplastics in remote areas（Bergmann *et al.*, 2019）. Finally, several studies have highlighted the importance of fibres, most of which account for more than 50% of microplastics, often reaching 70–90% of total microplastics（e.g. Harris, 2020）.

4. Floating litter

It is estimated that there are 24 trillion floating microplastics on the surface of the oceans（Isobe *et al.*, 2021）. Although the coasts are generally the most affected, transport at sea can take place over long distances, sometimes from one continent to another. Imagine the massive arrival of several dozen species fixed on floating waste and acclimatising in an area, disrupting interspecific relations and in particular the organisation of ecosystems. This situation is demonstrated by the arrival of 289 new species of macro-fauna and macro-flora counted on the coasts of North America, without regard for microorganisms, on plastic objects that crossed the North Pacific Ocean within 6 years of the 2011 Japanese tsunami（Carlton *et al.*, 2017）.

At sea, the main principles of geostrophic current dynamics condition the 'journey' of waste. Due to the trade winds at the equator, the mean residual surface circulation, dependent on interactions with the atmosphere, is oriented westward in the three ocean basins of the Pacific, Atlantic and Indian Oceans. The inflow of water to the west of these three basins causes water to flow north or south, generating significant water movements. Five major currents for each of the North and South Atlantic, North and South Pacific and Indian Ocean basins flow back and forth at high latitudes towards the east, as a result of the Coriolis force, and bring the water masses towards the eastern coasts and then partly back to the equator, closing the oceanic vortex which functions like a vortex or, more graphically, like the draining of water from a sink. At the centre of these moving water masses are areas of low dynamism, known as 'convergence zones' or ocean gyres. All floating objects and living organisms are then moved by the currents to these areas of weak circulation. Floating piles of plastic waste in these areas have been in the news recently because of the convergence zones, which have been exaggeratedly described as plastic continents that exist in all ocean basins. In the Western Pacific, for example, the waste arrives with the equatorial current and bifurcates towards Australia, via the Australian Current, or towards Japan in the north, via the current known as the Kuro Shio. Before heading back eastwards where they will create, through the giant gyre, these famous concentration zones.

Together with the oceanic gyres, these zones alone should receive between 35 and 60% of all plastic waste at sea within thirty years. The collective imagination is very sensitive to this information. However, while the image is spectacular, as is that of plastics concentrated in a plankton net after collecting samples from several thousand square metres, the quantities of plastics are greater in certain coastal areas such as the Mediterranean, the Bay of Bengal and South-East Asia are the most affected areas (ERIKSSEN *et al.*, 2014), and the actual quantities in the gyres represent only a few thousand tonnes. In coastal areas, the problems can be even greater due to massive inputs and lack of dilution.

5. Long-term trends

In a comprehensive article on the evolution of quantities in the different compartments of the marine environment, a number of realities have been mentioned (GALGANI *et al.*, 2021a). While the production and input of plastics in the sea has increased since the 1950s, several modelling studies predict a further increase in these respective quantities in the coming years. The compilation of scientific literature on marine litter trends is mainly based on monitoring programmes. These are very often partial, very diverse, and frequently focus on limited components of the marine environment in different regions, covering a wide spectrum of marine litter types, with limited standardisation. Increasing amounts of plastic are found in some regions, especially in remote areas, but the large number of studies does not demonstrate a consistent temporal trend. The observation of a steady state of plastic amounts in many marine compartments, as well as the fate and transport of plastic in the marine environment, remain areas that require further research.

Most studies indicate constant amounts of litter in coastal marine ecosystems in recent years until 2019. The increase in the amount of plastic observed in remote areas over time could therefore be interpreted as a long-term transfer of litter from directly affected areas to areas with little or no human activity. Nevertheless, while the total amount of plastic waste predicted globally is increasing, as models suggest, the apparent steady state of plastic amounts observed in coastal systems calls into question our ability to predict the sources and fate of plastic. More standardisation and coordination are needed before we can reliably report on plastic waste trends. A reduction in marine temporal trends is possible for some types of plastics, subject to societal reduction measures, as is the case for industrial granulates, which have received much attention in regional action plans following changes in industrial practices. Until there is a better understanding of the mechanisms behind the apparently stable amounts of plastics recorded in marine surveys, identifying possible trends will remain a challenge. There are still many gaps and uncertainties in the rates of degradation, burial and transport of plastics in the marine domain.

6. Impact of litter on ecosystems

Throwing waste into nature is not without consequences as it can remain there for a long time. In recent years, the known number of species impacted by waste has reached 1,400 species (Claro *et al.*, 2019). The impacts of plastics at sea can be presented in two main types (Galgani *et al.*, 2020): global impacts at the ecosystem scale mainly related to species transport and impacts at the organism and population scale.

In terms of ecosystems, plastics constitute a new habitat for many species at sea, particularly benthic macro-organisms such as arthropods, molluscs, hydrae, bryozoans, and many micro-organisms, bacteria, viruses, fungi, micro-algae of the dinoflagellate genus and diatoms (Fig. 2). These species will rapidly colonise plastic waste at sea, attaching themselves to it and even developing. Not only do they encourage the colonisation of new environments, sometimes thousands of kilometres away, but the alteration of the balance of ecosystems, caused by the transport of species, also represents a major risk. There is also clear evidence of the presence of invasive, toxic or pathogenic species that can alter the marine organisms of the regions to which they are transported.

At the individual level, the impacts of plastic waste at sea are particularly visible on large marine animals, including seabirds (Fig. 2), mammals and turtles trapped in large plastic waste such as ghost nets. The ingestion of microplastics by plankton or certain fish or even whales are other examples of effects. The most significant case is that of sea turtles, so common in the tropics, where up to 100% of individuals, depending on the region of the world, have waste in their stomachs. However, compared to macroplastics, microplastics are far more numerous and affect the entire marine food chain more widely. Because of their small size, they are easily ingested by a very large number of species. Once ingested, these microplastics can either obstruct the digestive system or simply pass through it, the primary route observed in the laboratory. However, the smallest particles, such as nanoplastics, can also pass through the digestive membranes and migrate into the circulatory system or even into other organs, as has been observed in fish. In any case, even a simple transit of microplastics through the digestive tract (Fig. 2) induces major changes in the biology of the animal that has ingested them: changes in digestion that disrupt energy input via the diet, a direct source of cellular stress, with disruptions in the major physiological functions of growth, immune defences and reproduction. In addition, the additives contained in plastics can also be released in the particular conditions of the digestive tract during transit and cause chemical disruption, with associated endocrine disruption for example. The entire life cycle of an organism can thus be affected with trans-generational repercussions. The interactions between prey, predators, the environment and microplastics require a complex approach, on a community scale, taking into account the diversity of plastic waste, as this has a strong influence on its fate and behaviour at sea and therefore on its toxicity.

Because of the adsorption properties of microplastics, particularly persistent organic pollutants which can be attached to their surface thanks to their hydrophobic properties, contaminants can be carried. Polychlorinated biphenyls or polycyclic aromatic hydrocarbons, heavy metals (Hg, Cd, Pb...) and pesticides can be found on their surface. However, even if the accumulation of persistent organic pollutants has

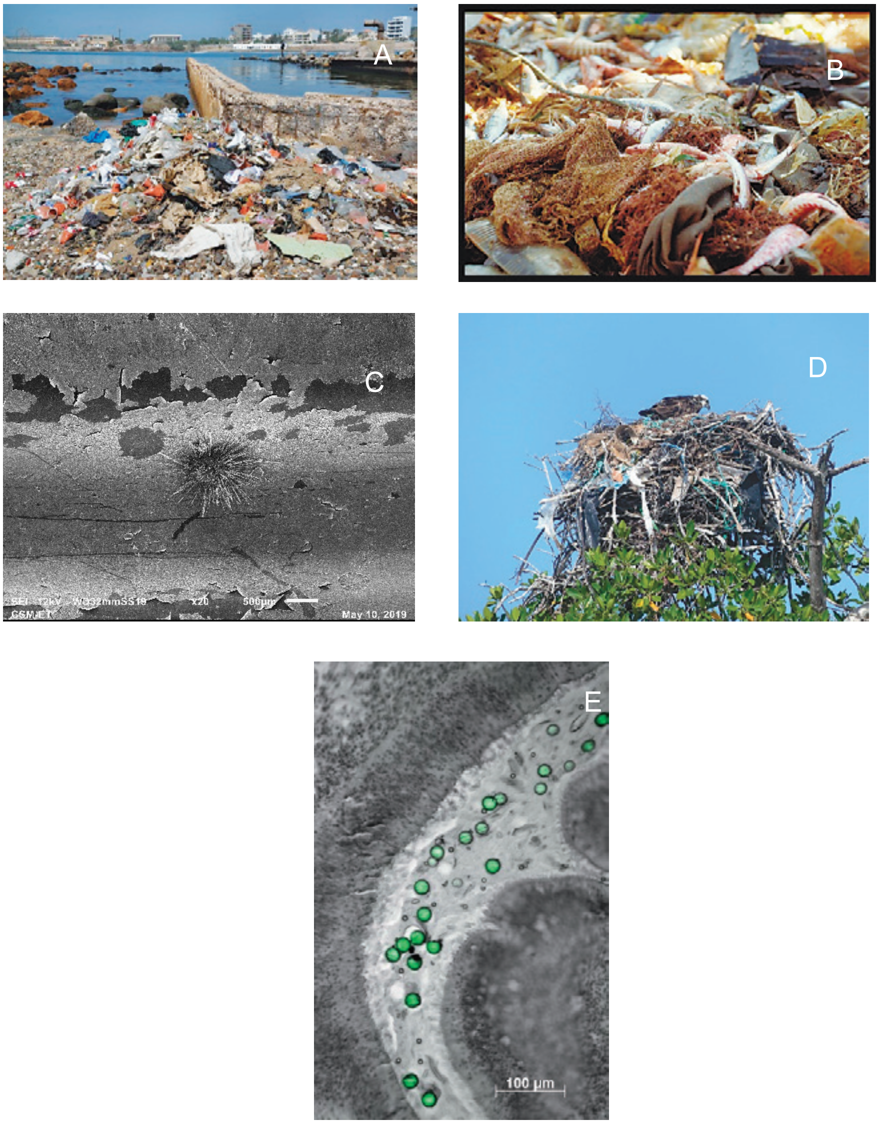

Fig. 2 Impacts caused by plastic are environmental, social, economic and can affect human health: (A) Aesthetic impact in an equatorial beach of eastern Atlantic, (B) Bycatch of litter in bottom trawl fisheries affecting fishermen's community in the Mediterranean Sea. (C) Radiolaria colonies formed on a bottle submerged at depths of several hundred metres (Mediterranean Sea, RAMOGE cruise, 2018). Transport of invasive species, with or without risk, may affect biodiversity and in some cases human health. (D) Fish-eating bald eagle nest buit with a mix of wood and plastic (Pacific coast of Mexico). The mixing of litter has significant impacts on marine species. (E) Experimental ingestion of microplastic fluorescent polyester particles accumulated in the digestive gland of an oyster (Ifremer/A. Huvet). The ingestion of plastic by marine organisms may have environmental costs, and impact on human health.

been demonstrated in certain organisms, microplastics are apparently not the main vectors compared to other particles suspended in the seas and oceans. Furthermore, the effect on bioaccumulation in marine organisms does not seem to be predominant in human food. Indeed, from a chemical point of view, despite an identified risk, the levels of polymer constituents and/or their additives (phthalates, bisphenol A) in the sea remain well below toxicity thresholds and if plastics play a role as vectors of pollutants, this remains a minor route of contamination of the marine environment, much less important than traditional pollution, particularly in urban or industrial areas.

7. Socio-economic impacts

The costs generated by plastics at sea are most often linked to human activities (Table 1). These costs amount to millions of euros each year for some communities and in some regions of the world, they affect a significant percentage of fishing fleets (Fig. 2). The first obvious economic impact is related to the consequences of the pollution of coastal areas, particularly beaches and foreshore areas, by plastic. The heritage value of the sites is largely affected, and the economic stakes linked to tourism can be strongly affected (recent closures of very touristy beaches for example). These impacts are often of an aesthetic nature (Fig. 2) and are reflected and quantified by the significant costs of cleaning.

Along the coastline, aquaculture activities can be the cause of significant inputs of plastics to the marine environment, particularly in shellfish production areas (oysters, mussels and other shellfish) due to losses of material, whether unintentional or not. Socio-economic impacts also concern underwater interventions on the bottom of ports or along the coastline as well as environmental awareness and education programmes. The most bulky waste also poses risks to shipping and in some countries, such as Japan, can account for up to two thirds of the damage paid by insurance companies to fleets. In addition to transport, these impacts are also significant for fishing vessels, with additional costs for cleaning and repairing nets or lines, as well as indirect costs related to the alteration of fish stocks due to unintentional catches of lost or abandoned nets. This issue of ghost nets is particularly critical in certain regions of Europe (South Brittany, North Adriatic, Gulf of Lion) where stock losses can reach 2 to 3% of an entire population of certain species (GALGANI *et al*., 2020). More generally, the costs associated with the socio-economic impacts are still poorly known, with costs estimated at around 260 million euros for marine litter in European waters alone. For the world's oceans as a whole, the financial damage is estimated at around 12 billion euros per year (UNEP, 2021). Finally, this economic pressure also affects recreational boating due to the frequent accidents caused by plastic nets or sheets caught in boat propellers or cooling systems.

Whether they are mainly washed up or sometimes floating, it should never be forgotten that waste can have effects on human health, including pieces of glass, syringes and medical waste that can cause injury or even contamination. It is now a fact that microplastics are present in all compartments of our environment and have entered our food. In particular, their presence has been shown in commonly consumed seafood products such as mussels and other shellfish, with quantities varying according to geographical location. Microplastics have also been found in crustaceans, and also in many species of fish, mainly in their digestive systems. The presence of significant quantities of microplastics in table salt should be highlighted. Moreover, human

Table 1. Summary of the impacts of marine litter on the economic sector with an estimation of their respective importance (modified from UNEP, 2015). += Low; ++= moderate; +++= high,; ?= unknown

SECTOR	IMPACT	IMPORTANCE
	Health risks	++
	Legal action	+
	Hidden cost	?
Municipalities	Removal of waste	++
	Beach cleaning	+++
	Negative publicity	++
	Cost of bad labelling	+
Tourism	Cost for beaches	+
	Negative publicity	++
	Promotion de the region	++
	Reduced income	+++
	Reduced recreational opportunities	++
	Loss of aesthetic appeal	++
Industry	Damage to equipment	+
	Increased maintenance	+
	Time lost per facility and staff	+
	Removal of waste	+
Aquaculture	Manual removal of waste	+
	Damage to vessels and time lost by staff	+
	Cleaning of nets	+
Navigation	Damage to vessels	+
	Cost of rescue operations	+
	Legal obligation	+
	Negative publicity	+
	Cleaning and dredging of ports	+
	Labelling for ports	+
Non-governmental organisations	Operational costs	++
	Financial support	++
	Volunteers' time	+++
Fisheries	Repair of damage to fishing gear	++
	Replacement of lost gear	++
	Reduction/contamination of catches	++
	Reduced fishing time	+
	Cleaning of gear	+
Ecosystem services	Costs of degradation	+

exposure to microplastics is not limited to the food chain, but can also occur through inhalation of microplastics and airborne fibres. This route of entry may be even more important than food, but it varies greatly depending on the environment and is often associated with certain work environments. Concerning the impact on the health of consumers of products containing microplastics, there is still relatively little knowledge and several questions are currently being asked about the composition of microplastics, polymers and additives, mainly phthalates, bisphenol A, brominated flame retardants and nonylphenols, which are known to be potentially toxic.

8. What measures?

Limiting the input of plastic waste into the environment is the first solution to improve the state of our seas and oceans. Reduction, Reuse and Recycling must be developed by all manufacturers, retailers, communities and consumers. This requires joint efforts and improvement of collection and processing infrastructure: increasing the performance of materials kept in the system and finally, reducing the negative impact of plastic packaging. Wastewater treatment plants are also strategic investments in the fight against marine pollutants, enabling the removal of pollutants. In addition to the removal of macro-waste in sewage systems, usually by screening, sewage systems must take into account micro-particles, which have recently become a significant source of pollution. Wastewater treatment plants are not specifically designed to retain them, but can nevertheless play an important role in limiting the input of microplastics into the marine environment. However, the varying concentrations, nature of the discharges, different materials, shapes and sizes make it difficult to implement homogeneous processes. The purification capacities depend on the degree of elaboration, but specific modules are needed to achieve almost 100% elimination in the most elaborate systems. Moreover, abatement does not mean the disappearance of particles but their trapping, most often in sewage sludge. Therefore, the reuse of sludge, especially in agriculture, poses the problem of its return to the natural environment, as no current "post-treatment" allows for their total elimination. In the end, the current approach remains mainly useful for water purification, for reuse by humans, including for everyday consumption, rather than a real solution for preventing pollution of the natural environment.

For several years, research has focused on the development of sustainable biobased polymers, *i.e.*, polymers obtained from renewable resources, while being both persistent and therefore difficult to degrade. Examples include developments in bio-based polyethylene, polyamides and polyurethanes, and even polyethylene terephthalate (PET). Thus, substituting fossil carbon with biosourced carbon, known as renewable or "short cycle" carbon, can be considered a relevant strategy for limiting greenhouse gas emissions, whose repercussions on climate change are now real. Nevertheless, obtaining sustainable bio-based materials is far from neutral. From an environmental point of view, competition for resources and the potential for deforestation and water depletion remain a problem. In addition, the substitution of petrochemical plastics by their biobased counterparts does not solve the problems of pollution and accumulation of plastics in the terrestrial and aquatic environment.

Numerous studies have been initiated in the research world to develop new polymers with a biodegradation resistance time equivalent to the time of use. Plastic waste from these so-called "biodegradable" materials would thus have the advantage of being able to biodegrade *in situ* (water, soil, compost), which appears to be a particularly relevant strategy in the case of plastic waste, which is becoming uncontrolled waste at the origin of the contamination of all ecosystems, and the marine environment in particular. These new materials, biodegradable and biosourced (at least in part), will have to meet certain requirements in terms of functional properties and use. All studies today tend to develop models to help design 'tailor-made' (bio) degradable polymers whose (bio) degradation could be controlled by playing on previously identified physical and chemical factors intrinsic to the polymer. Designing a rapidly biodegradable material in an environment as complex and constraining as the marine environment implies, however, being able to evaluate and demonstrate this property in a repeatable, reliable and unequivocal manner using a set of standardised methods and analytical conditions.

Cleaning the seas or oceans can only be justified when the waste has value. This value can be direct, such as lost fishing nets that could be repaired or recycled, or it can be indirect, such as in the case of coastal clean-up where the recovered plastic itself has little value but its absence maintains the heritage value of a site. It is this reason and the economic aspect attached to certain places such as beaches that justify the significant expenditure on clean-up.

The case of a large-scale organised clean-up, particularly in oceanic convergence zones, presents problems in terms of implementation costs linked to the distance of these zones, the risks of failure of the systems operated and the associated repair costs, and the accidental capture of marine organisms with passive behaviour such as floating plastics (plankton, young turtles, small fish). The heterogeneity and non-recyclability of plastics that have been at sea for a long time demonstrate the hypothetical nature of this approach, which is nevertheless supported by the public. In the same way, it is inconceivable to imagine collecting waste on the seabed because of the costs involved. Thus, in general, apart from valuable objects, cleaning up at sea will not provide the necessary solutions to the problem. It is only justified locally, in tourist or urban areas, on the basis of citizens' initiatives or locally for economic reasons.

The management of plastic pollution at sea is exceptionally complex and requires an integrated approach encompassing scientific, legislative, economic and social aspects. New technical approaches, using tools such as automated sensors, remote systems, or new indicators, should be able to support the acquisition of new knowledge. In terms of understanding the effects of plastics on wildlife and the environment, risk assessment, including assessment of the spatial extent of interactions between animal species and plastics, holds great promise.

The main knowledge gaps for scientists and managers also relate to accurate counting using standardised methods, the degradation of plastic in the various compartments of the marine environment and the measurement of the smallest particles and their effects. More studies are also needed to determine the transfer of contaminants to organisms, including the transfer of additives, and the role of plastic debris as a vector for the transport of pathogens, or more generally of species at risk. More generally, the need for a better understanding of the links between marine litter flows and their costs for targeted measures is very important in order to propose more adapted and targeted means of control. These include the generalisation of more sustainable production and consumption patterns, as well as conditions for the scaling up of alternative, more environmentally friendly products.

Other, more recent avenues, show the importance of research, particularly in solving problems related to the recyclability of materials. The scientific community has recently proposed more sustainable technical solutions, allowing for the permanent and total recyclability of plastics, thus opening up a way to give value to polymers at the end of their life. In the field of social sciences, research is still scarce, and knowledge on the link between economic and social activities and the presence of plastics in the oceans is still mainly built by actors involved in the fight against waste, most often locally. The fate of plastics in the sea therefore remains an emerging research topic that raises many questions for the scientific community. These questions can currently be divided into different areas, including the actual state of contamination, the long-term impacts of such quantities of plastics on organisms and on the functioning of ecosystems, and the risks for human societies, particularly on health.

9. Future actions

As a result of a more global approach, international agreements provide a legal framework for coordinated action. The UN's 2011 "Honolulu Strategy", supported by industry, the actions of the regional seas conventions under the UN Environment Programme or the recent G7 initiative for global action are the best examples of coordinated initiatives. Of course, the success of these initiatives will be measured over time. Successive management and fiscal measures since the 2000s in favour of limiting and banning checkout bags have led to a reduction in the quantities of packaging bags in the retail sector in many countries. However, there are still many unanswered questions, particularly about the extent of the problem, the sources, the methods of dissemination and the mechanisms of degradation. The future should bring new materials that are more environmentally friendly and there should soon be a better understanding of the social or economic impact of marine litter. Probably the most important environmental issue is that of environmental education, which is necessary to better deal with the diversity and complexity of individual behaviour that is a major cause of the problem of marine litter.

It seems that not all actors in society are yet fully aware of the urgency of the situation and the efforts required to emerge from this era marked by "all plastic" with its waste that is becoming our main and unique marker in geological time. Industrialists, politicians, NGOs and scientists must join forces to advance knowledge and promote its dissemination to the general public in order to raise awareness of this issue throughout society. This is the meaning given to the global approach underway within the United Nations General Assembly for the Environment (UNEA), whose ongoing negotiations should make it possible to reach a global treaty by 2024, which will make it possible to coordinate significant actions.

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