STUDY

Requested by the PETI committee

European Parliament

The environmental impacts of plastics and micro-plastics use, waste and pollution: EU and national measures

Policy Department for Citizens' Rights and Constitutional Affairs
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Abstract

This study, commissioned by the European Parliament's Policy Department for Citizens' Rights and Constitutional Affairs at the request of the Committee on Petitions (PETI), focuses on the pervasive use of plastics and reviews the rising consensus on the potential eco-toxicological impacts of these materials, in particular of smaller plastic particles, dubbed microplastics. It discusses possible mitigation strategies aimed at curtailing the prevalence of (micro)plastics, as well as emerging alternatives and their environmental adequacy.

Propelled by increasing awareness of the impacts of plastics and by public opinion, in recent years a multitude of norms, regulations, laws and recommendations have been proposed and/or implemented. These vary greatly across local, national, regional and international levels, and it is not clear what the beneficial impacts of these tools are. This study assesses these existing instruments, analyses whether they are based on sound scientific data, and discusses foreseeable challenges that could restrain the relevance and suitability of existing and future legislative proposals

This document was requested by the European Parliament's Committee on Petitions.

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LIST OF ABBREVIATIONS

ABNJ	Areas Beyond National Jurisdiction
CBD	Convention on Biological Diversity
CH	Switzerland
CO	Carbon monoxide
CO2	Carbon dioxide
COVID-9	Coronavirus Disease 2019
DDT	Dichlorodiphenyltrichloroethane
ECHA	European Chemicals Agency
EPS	Expanded polystyrene
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
GDP	Gross Domestic Product
GES	Good Environmental Status
GPA	Global Program of Action
GPML	Global Partnership on Marine Litter
HDPE	High density polyethylene
HELCOM	Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area
IMO	International Maritime Organisation
IOC	International Oceanographic Commission
IUCN	International Union for Conservation of Nature
MARPOL	International Convention for the Prevention of Pollution from Ships
MSFD	Marine Strategy Framework Directive
NO	Norway
NOAA	United States National Oceanic and Atmospheric Administration
NOx	Nitrogen oxides
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PA	Polyamides
PAHs	Polycyclic aromatic hydrocarbons
PBDEs	Polybrominated diphenyl ethers

PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PC	Polycarbonate
PCBs	Polychlorinated biphenyl
PE	Polyethylene
PET	Polyethylene terephthalate
PETI	Committee on Petitions of the European Parliament
PHA	Polyhydroxyalkanoate
PLA	Polylactic acid
PM	Particulate matter
POPs	Persistent Organic Pollutants
PP	Polypropylene
PRF	Port Reception Facility
PS	Polystyrene
PTT	Polytrimethylene terephthalate
PUR	Polyurethane
PVC	Polyvinyl-chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RSC	Regional Seas Conventions
SAICM	Strategic Approach to International Chemicals Management
TPC-ET	Thermoplastic polyester elastomers
UNCLOS	United Nations Convention on the Law of the Sea
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UV	Ultra-violet
VOCs	Volatile organic compounds

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EXECUTIVE SUMMARY

Plastics are a modern marvel, they have benefited society across all sectors, including in the health and food sectors, saving countless lives. Since the industrial production of plastics began in the 1950s, the volumes of plastics produced have outpaced those of almost any other material. However, the same characteristics that render plastics highly desirable are also those that render them ubiquitous in the environment, especially as a large fraction of plastics is designed to be discarded almost immediately following their use. Society's ability to cope with the sheer amounts of plastic produced and discarded is vastly overwhelmed, and only 9% of all the plastic ever manufactured has been recycled. Most of the plastic waste ends up in landfills and, ultimately, in the environment.

Most plastics do not degrade. Instead, they slowly fragment into smaller particles, referred to as microplastics, and, probably, nanoplastics. These particles, whether in the form of larger or smaller plastics, have profound detrimental consequences for ecosystems, biota, and the environment, but also for the economy and human health. Plastics have been found in the stomach contents of numerous organisms, including earthworms, birds, turtles, dolphins and whales. Smaller particles may be even more pervasive, as these may be ingested by organisms that are at the basis of different food webs. One such example is the recently discovered new species *Eurythenes plasticus*, an amphipod found at a depth of 6,900 meters and named after the plastic found to contaminate its gut. Before we even knew it, we had already contaminated it.

Hydrophobic and exhibiting high surface area-to-volume ratios, smaller plastic particles can adsorb other contaminants and act as either sinks or sources of contamination in organisms. In addition, chemicals used to improve the characteristics of plastics - known as plasticisers - can leach into the environment and constitute new routes of exposure to organisms, potentially leading to bioaccumulation phenomena.

The inherent economic impact due to plastic waste is also vast. Studies suggest an economic damage to the global marine ecosystems surpassing € 11 billion. In Europe, € 630 million are spent every year to clean plastic waste from coasts and beaches while the failure to recycle costs the European economy € 105 billion.

In January 2018, China banned the import of waste in order to stop the crushing flow of low-grade plastic waste. This ban had a profound impact throughout the world, as Western nations were suddenly confronted with vast amounts of such waste with no management strategies to deal with them. This highlights the urgent need to restructure existing recycling systems and policies on the production of plastic and its disposal. Additionally, the announcement of the Chinese ban led to a sharp fall in EU export prices for plastic waste in 2016. From over € 320/tonne, the extra-EU export price has fallen to € 244/tonne in 2019.

The environmental, health and economic reasons to act are clear. Consequently, there is a growing international determination to reconsider and evaluate the use of plastics at all stages of their life-cycle. This not only includes design and manufacture, but also use, reuse, and end of life management, with a special focus on the inputs and removal of plastics from the environment.

A variety of regulatory and legislative tools exists, aimed at controlling, reducing and managing the use of plastics, with a particular emphasis on single-use plastics. Existing legislation consists mainly of levies, bans, and voluntary efforts through the 3R rule: *reduce*, *reuse* and *recycle*. However, these regulatory instruments have had a limited impact, in volume, scope, or both, especially when considering the exponential yearly increase in production and use of plastics, including the growing synthesis of new materials with new applications.

Moreover, recycling of plastic waste remains problematic because of the inherent difficulties with the collection and separation of the feedstocks used in the recycling process. Alternative solutions, such as energy conversion (incineration) have severe environmental impacts and detrimental consequences for the climate. Improvements on plastic legislation are therefore needed to be able to better consider and address environmental and human health impacts. Importantly, most of the existing tools are designed to address plastic waste at the end of its life-cycle, i.e. following its manufacture. Upstream legislative approaches are needed to stimulate a zero-waste target, which will undoubtedly improve the feasibility and efficacy of future plastic policies.

Key findings

Plastic production has exponentially increased and presently surpasses the 359 million tonnes mark. Of this, nearly 40% is intended to be used as packaging, i.e. destined for immediate or near immediate disposal.

Approximately two-thirds of all plastic ever produced has been released into the environment, where it continues to impact ecosystems as it fragments and degrades.

In the form of debris, micro- and nanoplastics, these materials are found in the oceans, the air and soils. Some of these materials (e.g. nanoplastics) are intentionally added to various types of products and are therefore present in water supplies and even in the human body.

Uncertainties and knowledge gaps undermine the full understanding of the ecological, toxicological and environmental impacts of plastics.

Reducing toxic exposure to plastic waste, in all its forms, requires a plethora of solutions, both voluntary and legislative.

Ideally, production, use and disposal of plastics should be dealt with at a global level, as existing supply chains cross and re-cross borders, continents and oceans.

"Stick and carrot" legislative approaches are needed, aimed at rewarding those – consumers, producers and suppliers – working towards a zero-waste strategy, while highly punitive actions should be developed for offenders.

1. THE PLASTIC AGE

KEY FINDINGS

- "Plastics" is a generic term that includes a wide range of materials which may also contain substances to improve their characteristics – plasticisers/additives.
- The versatility of plastics allows them to be used in a continuously increasing range of applications.
- The latest estimates point to 359 million tonnes produced worldwide, of which 40% were meant for packaging, i.e. for immediate discard.
- Most plastics end up in the environment, in the form of larger or smaller particles (microplastics) which have been found across the globe.
- The highly pervasive plastic particles can cause entanglement, may be ingested and inhaled. They may also constitute added routes of contamination for other chemicals, including organic pollutants.
- Exposure to microplastics may have numerous physical and chemical effects on biota and, ultimately, human health.

1.1. Plastics and microplastics

Historians and archaeologists define periods in history by the materials or technologies that most affected humankind – such as the Stone, Bronze or Iron Ages. Given the prevalence of plastics in our society, it is not surprising that some researchers have called our present day the "Plastic Age". [1, 2] Named ages should not be confused with geological divisions of time, such as the present Holocene (11,650 years ago – present [3]) or the proposed Anthropocene[4], a geological epoch characterised by humans as a geological force and process, ushered in by the nuclear age and perpetuated by plastics[5].

"Plastic" is an umbrella term that encompasses a wide range of materials made of semi-synthetic or synthetic organic compounds. The International Union of Pure and Applied Chemistry (IUPAC) defines plastics as "polymeric materials that may contain other substances to improve performance and/or reduce costs"[6]. These highly malleable materials may be moulded into solid objects of a multitude of shapes and sizes. In fact, the main feature of these materials is reflected in their etymology: the word plastic originates from the Greek words *plastikos* (πλαστικός) meaning "capable of being shaped", and *plastos* (πλαστός), meaning "moulded". Typically synthetic, plastics are most commonly derived from petrochemicals and exhibit high molecular mass and plasticity.

Thus, plastics are polymers, long chains comprised of linked repeated units, named "monomers". One way to visualise this is to picture a polymer as akin to a pearl necklace in which the monomers are the individual pearls. The process through which these monomers are linked is called polymerisation and, therefore, plastics can be classified according to the chemical process used in their manufacture, namely, condensation, poly-addition, or cross-linking, or according to the chemical structure of the polymer's backbone and side chains. Among these, the most important groups are silicones, acrylics, polyesters, polyurethanes and halogenated plastics.[7]

However, quite frequently plastics are also categorised according to key characteristics that are of relevance to manufacture, product design and end-use. Examples include thermoplastics and thermosets. Thermoplastics are plastics that can be melted when heated and hardened when cooled. These characteristics are reversible and may theoretically be carried out indefinitely, meaning that these materials can be reheated, reshaped, cooled and re-used repeatedly. Thermosets, on the other hand, are a family of plastics that undergo a chemical change when heated that creates a three dimensional network that cannot be re-melted and reformed.[8] Thermoplastics include Polyethylene (PE), Polyamides (PA), Polypropylene (PP), Polycarbonate (PC), Polystyrene (PS) and Expanded polystyrene (EPS), Polyethylene terephthalate (PET) and Polyvinyl-chloride (PVC). Examples of thermosets are Polyurethane (PUR), Silicone, Epoxy and Phenolic resins, as well as Acrylics.

Box 1: Plastic Pollution Facts

- Daily, **8 million** pieces of plastic reach the oceans.
- Yearly, this translates into between **4.8** and **12.7** million tonnes.
- It is the equivalent of a garbage truck full of plastic dumped into the ocean every **minute**
- Of the total amount of plastics sent to landfills, 79% is transported to the oceans, **less than 10% is recycled** and 12% is incinerated.
- **25 trillion macro**- and **51 trillion microplastics** litter the oceans.
- Of these, **269,000 tonnes** float on the surface.
- This equates to **1345 blue whales** and **500 times the number of stars** in the Milky Way.
- Plastic has been found throughout the Globe, including in remote and isolated locations
- Plastic in expected to increase 10 fold in the next 5 years

Due to their ease of manufacture, low cost, impermeability, and their resistance to chemicals, temperature and light, plastics are used in a wide range of products and have replaced and displaced many other materials, such as wood, paper, stone, leather, metal, glass and ceramic. In the modern world, plastics can be found in components ranging from stationary items to spaceships.[9]

Given this versatility, it is not surprising that the last detailed report (2018) on the annual global production of plastics showed it to exceed 359 million tonnes[10]. In Europe, nearly 40% of plastics was intended for packaging, i.e. for immediate or near immediate disposal (see Figure 1). While the benefits of plastics are undeniable, their widespread use as well as their inherent resistance to (bio)degradation, ultimately leads to their accumulation in the environment. Presently, it is estimated that plastic waste constitutes approximately 10% of the total municipal waste worldwide[11] and that 80% of all plastic found in the world's oceans originates from land-based sources[12], which translates into harrowing statistics (see Box 1).

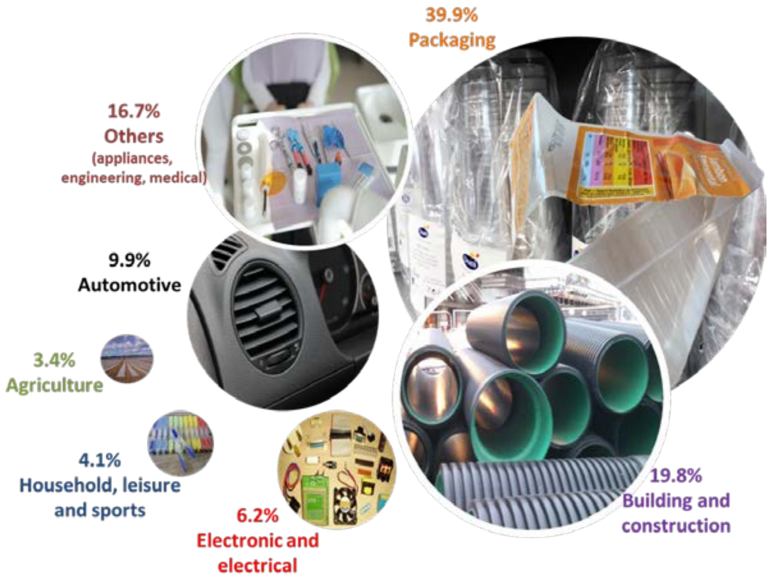

Figure 1: European (EU28+NO/CH) plastic converters demand by segment in 2018, totalling 51.2 Mt, according to Plastics Europe.[8]

The fate of these plastic debris, in particular the larger fragments known as "macroplastics", has long been the focus of environmental research, particularly in the oceans, where they tend to accumulate in specific regions, owing to the convergence of surface currents, as is the case of the Great Pacific Garbage Patch. Also commonly referred to as "Pacific trash vortex", this is a gyre of marine debris materials, mostly plastics, in the central North Pacific Ocean. It was discovered in 1985 and it is located roughly between 135°W to 155°W and 35°N to 42°N[12], covering approximately 1.6 million square kilometres. This floating debris is incessantly mixed by the concerted actions of waves and wind. It is dispersed over huge surface areas and across the top portion of the water column. The plastic concentration in the Great Pacific Garbage Patch is estimated to be up to 100 kg/km^2 in the central area, gradually decreasing to around 10 kg/km^2 in the outer parts of the patch.[13] Despite the common public perception of giant islands of floating garbage, this low density prevents detection by satellite imaging or even by casual divers or boaters.

In fact, a more apt description of the Garbage Patch would be that of a "soup" that consists mostly of suspended, dispersed, often small plastic particles. These larger and smaller particles may cause entanglement and smothering, may be ingested and may even constitute new routes for invasive species.[9] Remarkably, it has been reported that species found associated with these plastic materials, referred to as the Plastisphere, sometimes differ greatly from the free-floating surrounding microbial communities commonly found.[14]

The predicted tonnage of all these materials surpasses the 79 thousand mark, but possibly reaches nearly 130 thousand tonnes. Over three-quarters of this mass may be attributed to debris larger than 5 cm, with at least 46% being comprised of fishing nets. However, although pieces smaller than 0.5 cm only account for 8% of the total mass, they correspond to over 94% of the estimated 1.8 (1.1–3.6) trillion pieces floating in the area.[15]

These smaller particles, frequently classified as particles <5mm, are known as microplastics. They have become a source of increasing concern both by scientists and the general public because they are a threat to the environment. Also colloquially referred to as "mermaid`s tears"[16], perhaps due to their size and the vast array of colours they show, microplastics may be defined as primary or secondary, depending on their source.

Primary microplastics are deliberately manufactured within the millimetric or submillimetric size, and can be found in numerous household items, including personal hygiene products, such as facial cleansers, toothpaste and exfoliating creams. These products are of special concern, as it has been estimated that approximately 6% of all liquid skin-cleaning products sold in the EU, Switzerland and Norway contain microplastics, of which more than 93% consist of polyethylene (PE).[17] Another key source of primary microplastics are the raw materials used in the manufacture of plastic items. Inadequate handling, accidental loss, run-off from processing facilities and residues from the production process can lead to the accumulation of primary microplastics. Present in air-blasting media, microplastics are also used, to a smaller degree, in medicine, namely as drug vectors.[9] After their use, microplastics are discharged in domestic wastewaters and may reach the environment.[12, 18] Sources of primary microplastics as well as their specific origins can be identified and therefore mitigation actions to reduce their input into the environment can be developed.

Secondary microplastics result from the breakdown of larger plastic particles. When exposed to the elements, physical, chemical and biological processes can lead to reduction of the structural integrity of these plastics, leading to their fragmentation.[19] However, this breakdown can also take place before these materials enter the environment, as is the case of synthetic fibres from clothes released during washing cycles[20] or the wear-and-tear of car tires, which generates minute polymeric fragments.[21]

When transported in drain and wastewaters, these materials may be efficiently removed in more advanced wastewater treatment facilities, and some mechanical processes have been shown to be considerably well capable of removing microplastics.[22] However, this is not the case for less advanced wastewater treatment plants or in locations where such facilities are either inexistent or inadequate, as is the case in some developing countries. Additionally, this efficiency is highly dependent on the nature of the materials present and their load, as well as on the characteristics of the treatment facility influent.[12]

The multitude of sources of microplastics is illustrated in Figure 2. In Table 1 the main sources of primary and secondary microplastics are summarised and the wide range of sources of these materials and how easily they can enter the environment are emphasised.

Figure 2: How microplastics are generated. Primary sources and secondary sources are identified. Image available at https://www.grida.no/resources/6929. Credit: Maphoto/Riccardo Pravettoni.

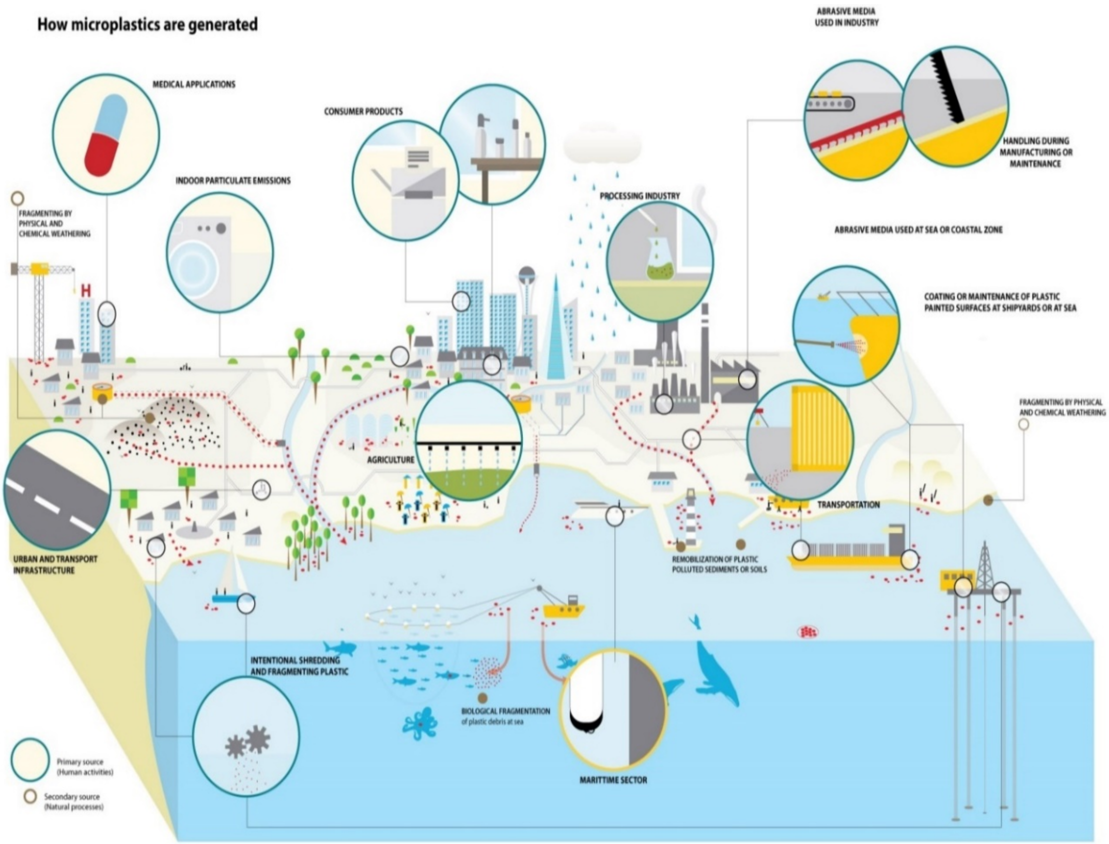

Table 1: Main sources of primary and secondary microplastics. Adapted from Duis et al. (2016)[23] and da Costa et al. (2019).[24]

Primary microplastics	Industrial abrasives
	Specific medical products (e.g., dental tooth polish)
	Personal care products/cleaning products
	Drilling fluids
	Raw materials (*nurdles*[a])/process sub-products
	Improper handling/disposal
Secondary microplastics	General littering; plastic waste dumping
	Discarded fishing gear
	Abrasion in landfill and recycling sites and facilities
	Fibres released from synthetic textiles
	Ship generated litter
	Fibres from hygiene products
	Plastic material from organic waste
	Abrasion during paint removal; use of paint with synthetic
	Polymers found in compost additives

[a] Nurdles are plastic resin pellets, commonly used as feedstock in the production of plastic products.

Smaller microplastics, called nanoplastics, can also be present in the environment, but their definition remains controversial. Nanomaterials exhibit specific properties that differ from their bulk counterparts. They display colloidal[b] behaviour and are generally considered to be materials of less than 100 nm in at least one dimension.[6] However, for nanoplastics, a consensus classification is yet to be reached and different proposals have been put forth.

Nanoplastics have been classified as particles of less than 1 μm[9, 25]. The European Commission in particular has suggested the use of the standardised definition for engineered nanomaterials, referring to them as particles smaller than 100 nm.[26] Other size definitions for nanoplastics have been suggested, including the size threshold of 20 μm, as this is the classification used by ecologists to classify plankton as nanoplankton.[27] Although such debates may be construed as merely semantic in nature, these definitions have profound consequences in both research and the development and implementation of regulations, directives and guidelines.

Owing to its role in legislation and regulations, the EU Commission's size definition of nanoplastics has gained track. Although the use of this categorisation may seem reasonable from a practical perspective as it minimises any potential confusion with the field of nano-environmental health and safety, and benefits from the existing regulatory mechanisms in place for engineered nanomaterials, it fails to "encompass the environmental interactions, implications and impacts of slightly larger particles within biomes at a more biologically significant level"[24]. Therefore, defining nanoplastics as particles smaller than 1 μm may be sensible, given that this is the size below which there is a *de facto* biological and environmental impact. It should be noted, however, that until now the occurrence of these materials in the environment remains theoretical, as no such nano-sized plastics have been successfully isolated from any environmental matrix.

Similarly to microplastics, nanoplastics may be released into the environment directly or form due to the fragmentation of larger particles. Hence, nanoplastics may be also classified as primary or secondary nanoplastics. Primary nanoplastics include particles found in products such as paints, adhesives and electronics. Also, activities such as thermal cutting of polystyrene[28] (PS) or polyvinylchloride[29] (PVC), as well as the increasingly popular and affordable 3D printing, which has been shown to result in the release of particles as small as 11.5 nm[30], can result in the release of these minute particles into the environment.

Secondary nanoplastics form from the fragmentation of larger plastic particles, such as microplastics. However, the exact mechanism through which this occurs is still unclear, though the formation of these small materials has been experimentally demonstrated using bulk PS in the form of disposable coffee cup lids. In their experiment, the authors showed that particles with an average size of 224 nm were formed in less than 60 days, due to the action of UV radiation, thermal oxidation, mechanical abrasion, and hydrolysis.[31] Hence, given the existence of these conditions in the environment and the concerted action of these factors, the formation and persistence of nanoplastics in the environment is not only possible, but a near certainty. Therefore, a clear understanding of the potential impacts of (micro)(nano)plastics in the environment, including biota, is of the utmost importance.

[b] A colloid is a mixture in which one substance is suspended throughout another substance. Unlike a solution, whose solute and solvent constitute a single phase, a colloid has two phases: the suspended particles and the suspension media. Typically, colloids do not completely settle or take very long to settle completely. Milk, for example, is a colloid made of liquid fat globules dispersed in a water-based solution.

1.2. Environmental impacts of plastics and microplastics

"End of life" does not equate "end of impact". In fact, because plastic materials persist and pollute long after their intended use, it has become clear that there is no such thing as "end of life" for plastics. Depending on how plastic is handled, it may pose a significant threat to the environment and to the climate when it reaches the waste phase of its life-cycle.[32] According to a 2019 report, the global plastic waste management by 2015 broke down as illustrated in Figure 3.

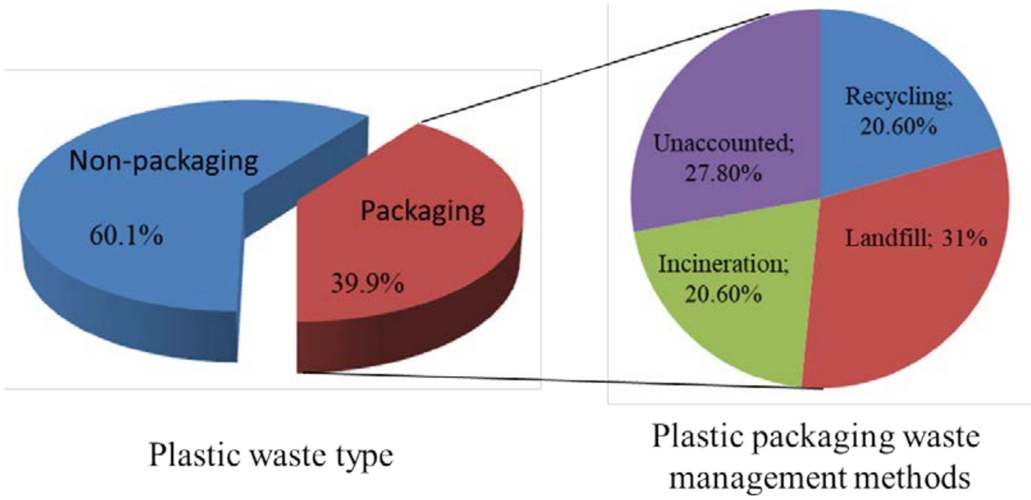

Figure 3: Global plastic waste management, 2015. Adapted from Hamilton et al., 2019.[32]

The last figures indicate that in Europe (inside and outside the EU) 7.2 million tonnes of plastic post-consumer waste were landfilled, while 9.4 million tonnes were collected for recycling and approximately 12.4 tonnes were incinerated.[8]

Only a fraction of plastic waste is recycled and is an expensive process owing to the inherent separate collection, transportation, processing, and re-manufacture. These considerable costs in combination with the low commercial value of recycled plastic on the one hand and the low cost of virgin polymers on the other seldom renders the recycling process profitable and often requires onerous governmental subsidies.[32] Furthermore, a recent report by DS Smith Packaging showed that 44% of Europeans are unclear as to what materials may or may not be recycled, and in which recycling bin some plastic waste products should go.[33] The same report highlighted that, owing to the COVID-19 pandemic and the associated exponential increase in online shopping, the amount of plastic packaging waste significantly rose. By inappropriately discarding potentially recyclable materials, Europeans may incur in a loss of 1.9 billion euros to the economy.[33] Considering all these factors, it is not surprising that less than 10% of all plastic produced since 1950 has been recycled, while only 12% has been incinerated[34] - a process that is not without its hazards.

While incineration of plastic is often euphemistically dubbed "energy recovery", the truth is that when plastic is burned it emits greenhouse gases, mainly CO_2. However, plastics also often contain additives which are hazardous when released into the environment during incineration, a long known issue.[35] The types, quantities and concentrations of these chemicals vary, depending on the type of plastic waste and on how the incineration process takes place, but there is little doubt that such chemicals impact human health (see Figure 4). In Europe over the past years efforts have been made to divert plastic waste, especially plastic packaging, from landfills to incineration, a trend more evident in countries that have implemented bans on landfilling recyclable waste.[8]

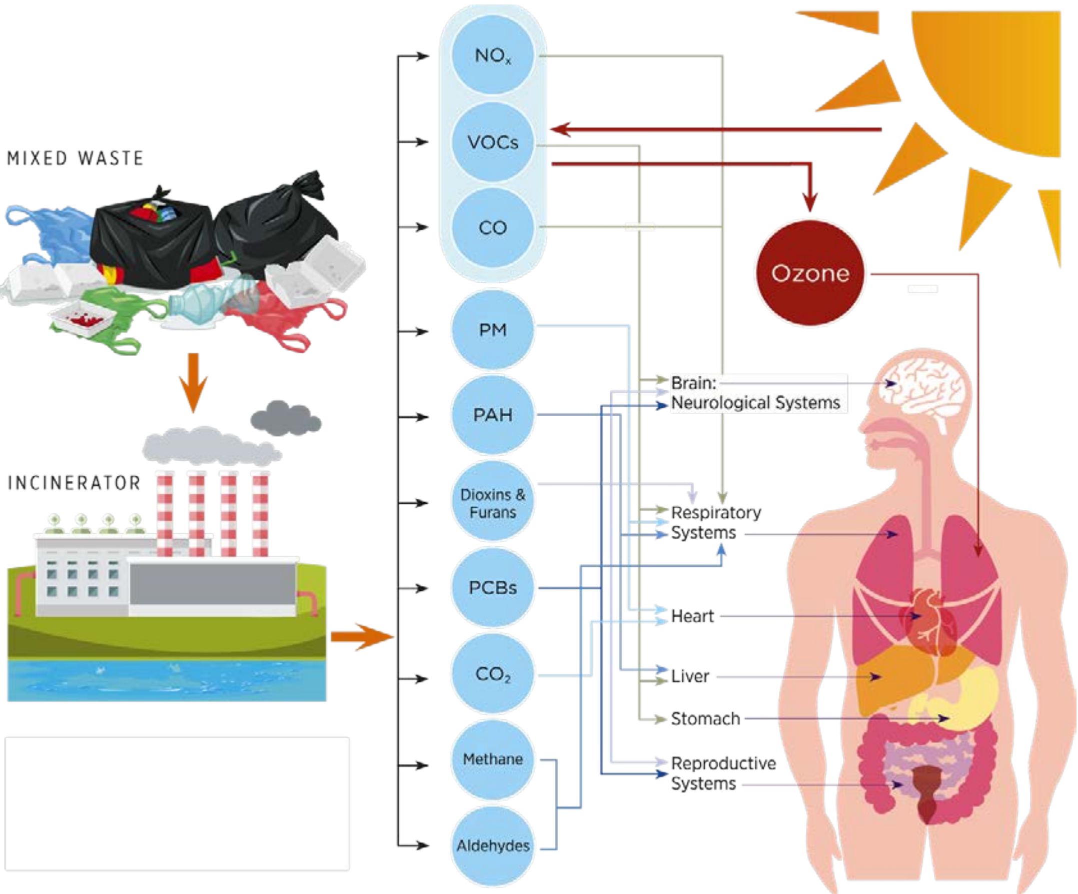

Figure 4: Toxic exposure from incinerated mixed waste, containing plastic. NOx – nitrogen oxides; VOCs – volatile organic compounds; CO – carbon monoxide; PM – particulate matter; PAH – polycyclic aromatic hydrocarbons; PCBs – polychlorinated biphenyl. Image credit: Nonprofitdesign.com. Adapted from Azoulay et al., 2019.[36]

A high proportion of the remaining plastic waste (see Figure 3) ends up in the environment, in dumping sites, oceans and other waterways, scattered across natural and human landscapes worldwide, unconstricted by political or natural borders. Regardless of the disposal method, all discarded plastic waste constitutes a risk to the environment and organisms, including humans.

1.2.1. The fate of plastics in the environment

Determining the fate of (micro)(nano)plastics in the environment is inherently difficult. This is mostly due to the multiplicity of sources and routes of entry into the environment and the timescales necessary to determine their degradation pathways. For smaller particles, this is due to their size as well (see Figure 5). As such, the quantification of these materials is rather difficult, particularly given that, especially for smaller sized plastics, there is a lack of standardised methods for their sampling, unit normalisation, data expression and quantification, as well as identification. In addition, there is the absence of a unified definition for these materials, in particular, for nanoplastics.

Microplastics have been identified across the globe, including in remote locations, from the Arctic[37] to the Antarctic[38] and throughout the water column, from surface[39] to the depths (benthos).[40] But microplastics are also found in rivers[41] and lakes[42], in agricultural soils[43], sediments[44] and even in the atmosphere, both in indoor[45] and outdoor[46] environments. Figure 5 shows the multitude of pathways through which plastics enter the environment, particularly the marine environment.

Once in the environment, plastics can undergo degradation through abiotic and/or biotic processes. The former is an essential first step that precedes the latter. In other words, biodegradation mechanisms require an initial abiotic degradation process. This yields materials of diminished structural and mechanical integrities, resulting in particles with higher surface area-to-volume ratios, amenable to microbial action.[47]

Abiotic degradation pathways may be separated into two distinct types of processes, which depend on the polymer type. More concisely, it depends on whether the polymer consists solely of a C–C backbone, as is the case of PP, PS, PVC and PE, or if heteroatoms are present in the backbone, such as PET and PU. In the first case, the process is initiated by a random photolytic cleavage of a C–H bond, while in polymeric materials containing heteroatoms, hydrolysis is usually the initiating step.[48]

However, these mechanisms refer to unadulterated materials, and polymers are rarely used and therefore rarely occur in the environment in their pure form. Consequently, the described mechanistic pathways of degradation may be incomplete and products are released during (bio)degradation[49]

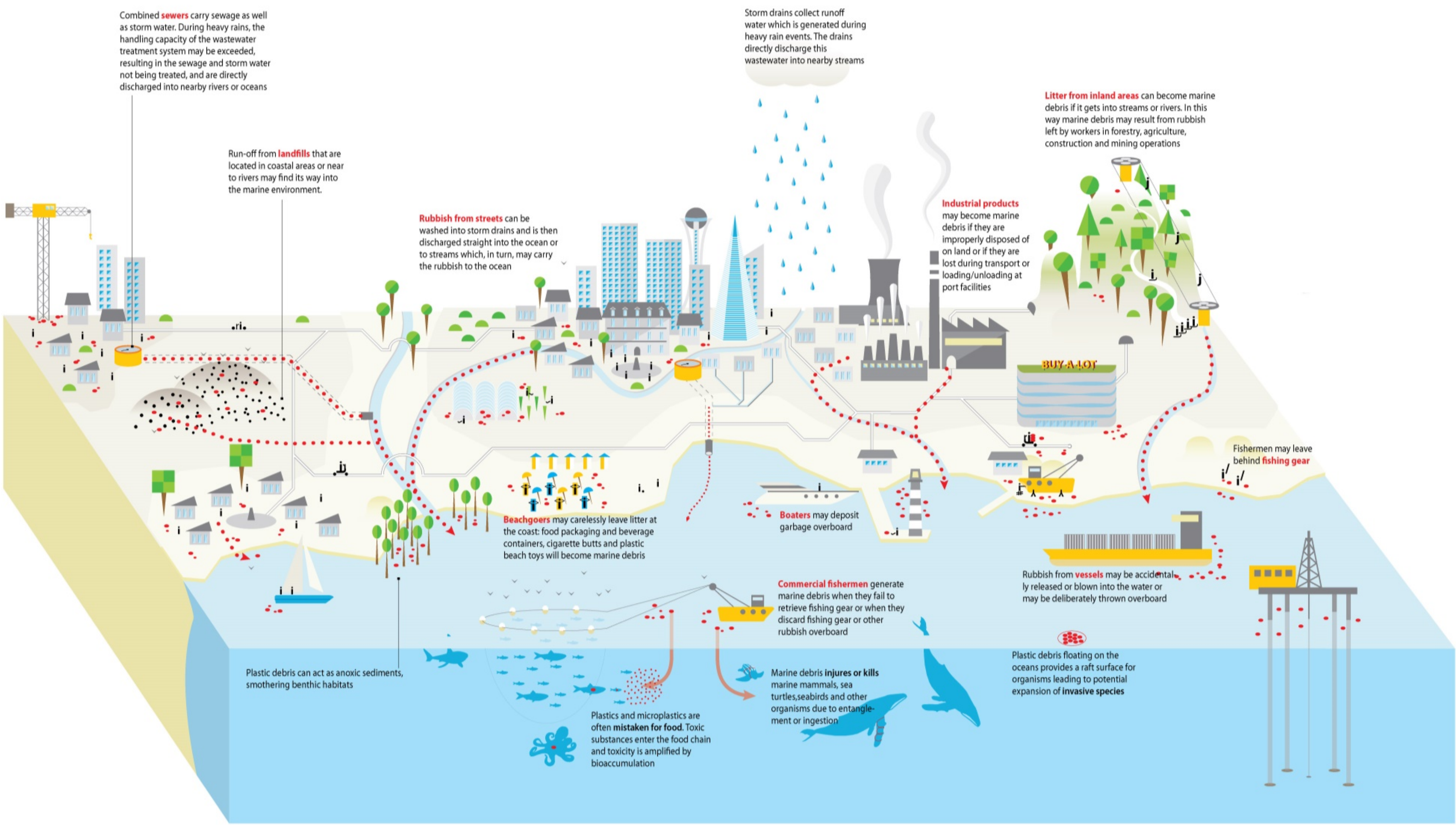

Figure 5: The multitude of sources and pathways through which plastics enter the environment. Image available at https://www.grida.no/resources/6922. Credit: Maphoto/Riccardo Pravettoni.

Such products include un-polymerised monomers and additives and plasticisers used to modulate and optimise the characteristics of plastic products. The complexity of the degradation pathways is further enhanced by other factors, such as the density of the polymers, which may vary due to phenomena such as formation of biofilms and heteroaggregation[9, 12]. This affects their bioavailability in the water column. Consequently, the type of plastics ingested by organisms may vary, depending on their occurrence.

The biological mechanism of plastic degradation usually initiates outside of the cells due to enzymatic activity. This results in the cleavage of the main polymeric chain through hydrolytic pathways[9], irrespective of the media. Groups susceptible to be used by the organisms are then formed[50], which contributes to the continuous process of polymer degradation[51]. Eventually, water-soluble oligomers and monomers are generated, ultimately leading to mineralisation. Nevertheless, pre-exposure to UV radiation appears to be a key factor affecting the rates of biodegradation, both in soils and aquatic environments.[52]

However, the presence of plastics in different environmental matrices will undoubtedly contribute to alterations in the physical, chemical and biological interactions taking place, which may entail environmental and ecotoxicological implications.

1.2.2. Effects of plastics

Plastic pollution represents one of the major perceived threats to biodiversity. Due to its abundance, durability and persistence in the environment, it is a cause of special concern. In the oceans, plastic debris accounts for over 90% of all encounters between debris and individuals.[53] By comparing the listed encounters with the International Union for Conservation of Nature (IUCN) Red List, at least 17% of species affected by entanglement and ingestion were listed as threatened or near threatened.

The interaction of organisms with plastic debris results in a wide range of consequences, both direct and indirect, including the potential occurrence of sub-lethal effects, which, owing to their uncertainty, may be of considerable concern. Broadly, the presence of larger plastic materials in the ocean may result in entanglement and ingestion, potential creation of new habitats, and dispersal *via* rafting, including transport of invasive species. Entanglement and ingestion frequently causes harm or death, although gathered data appears to suggest that entanglement is far more fatal (79% of all cases) than ingestion (4% of all cases).[53] Debris may also constitute new habitats, and derelict fishing gear, for example, has been shown to cause not only death by "ghost fishing", but

also to constitute new habitats for invertebrates.[54] The dispersal of species in the marine environment, particularly species with no pelagic larval stage, has increased in recent decades. Highly dependent on oceanic currents, numerous species have always rafted on natural materials such as wood, but industrialisation and the continuous increase of the presence of plastic debris in the oceans suggests that rafting is playing an active role in their scattering.[53] This holds true for invasive species as well. A clear example is the detailed presence of a ciliate, Halofolliculina, a pathogen that may be the culprit of the skeletal eroding disease that has affected Caribbean and Hawaiian corals.[55]

Less attention has been paid to the effects of plastics in freshwater systems, in spite of the fact that rivers are the dominant source of plastic pollution to oceans, as well as a significant sink accumulating plastics originating from multiple sources.[56] It is therefore reasonable to assume that the potential effects are identical to those described for plastic debris found in the marine environment.

Far less documented are the potential effects of polymeric materials in terrestrial environments, although their presence has been documented in home gardens[57], areas of higher population density or points of convergence of anthropogenic activity, such as urban environments or in the vicinity of waste processing facilities.[58] Larger debris are also commonly found in agricultural soils[59], owing to the increased usage of plastics in traditional agricultural practices (*plasticulture*), such as plastic mulching, for increased productivity and lower consumption of water[60], or the use of plastic films in tunnels or for wrapping hay bales. Hard plastics are also frequently present as containers for numerous products used in agriculture, and the sewage sludge used for fertilisation or soil conditioning, may also contain pieces of plastic that are deposited in the soil.[58] Yet, in spite of the reduced body of research pertaining to the (biological) effects of larger plastic materials in terrestrial environments, it is again conceivable that some animals may ingest and, at least partially, become entangled, in these materials. In fact, this has been reported for some ruminants, with plastic debris found in the stomach contents of sheep and goats.[61]

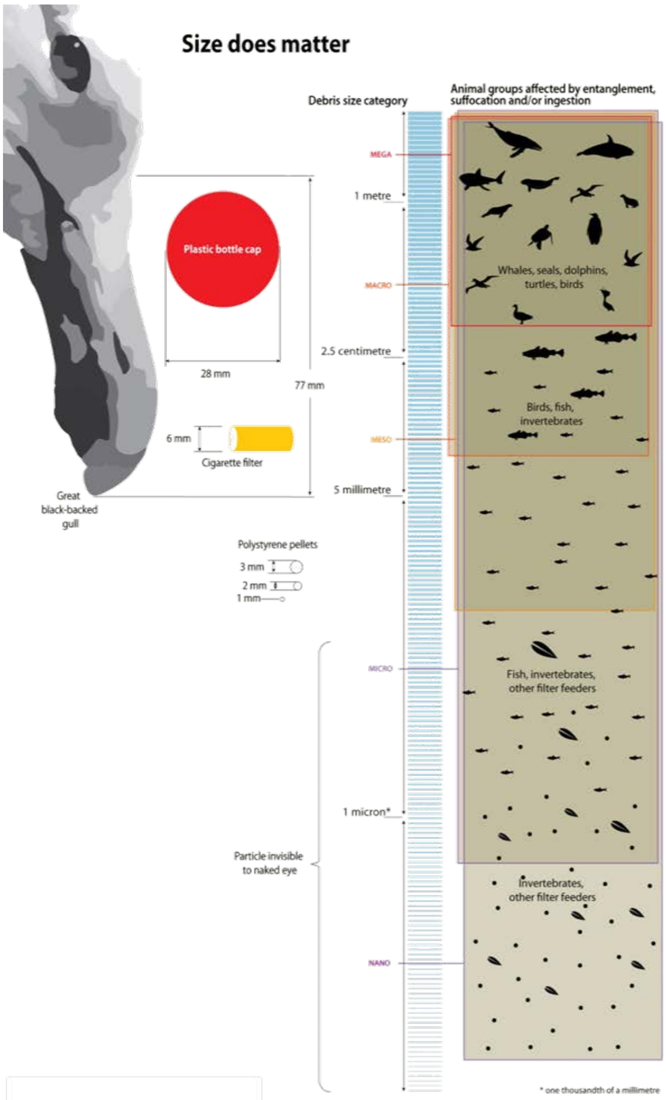

Figure 6: Size matters. Size of plastic debris affects the organisms that ingest, suffocate or become entangled in these materials. Image available at https://www.grida.no/resources/6924. Credit: Maphoto/Riccardo Pravettoni.

In turn, for smaller plastic pollutants, such as microplastics, pollution has been described in freshwater, marine, terrestrial and atmospheric ecosystems.[62] Although the increased awareness and focus of research has led to significant advances in the understanding of the behaviour of microplastics in the environment, there is still much that is undetermined, in particular with regard to the ability to accurately forecast the exposure scenarios and predict exposure hotspots. The already described complexity of the (bio)degradation processes contributes to a higher degree of intricacy, as do biofouling, ingestion and egestion (which may occur far from the location of exposure) processes. This introduces randomness in the distribution of these materials, as well as changes to the properties of the microplastics, with concomitant unpredictability on their environmental fate.

Owing to their small size, microplastics may be ingested by multiple organisms, such as planktonic and higher organisms (Figure 7), including mammals, birds and fish. Although the exact mechanisms of toxicity of these materials are still ill understood, the effects are potentially due to either (1) ingestion-induced stress, such as physical blockage, energy expenditure for egestion and false satiety; (2) leakage of chemicals, such as additives, from plastics and; (3) exposure to contaminants adsorbed (and subsequently released) by microplastics such as persistent organic pollutants (POPs).[12] Cnidarians, annelids, ciliates, rotifers, copepods, amphipods, euphausiids, mussels, barnacles, tunicates, birds and fish have all been demonstrated to ingest these small sized polymers within laboratorial settings.[23, 24, 63]

Interestingly, results showed that the uptake of microplastics depends not only on their shape and size, but, perhaps less intuitively, also on their colour, with the preferential ingestion of yellow particles. This is likely due to their similarity to prey.[64] The direct consequences of the ingestion of microplastics include obstruction of the digestive tract and internal injury, frequently leading to reduced food consumption and concomitant decreased nutrition. This potentially results in starvation and death. In air-breathing organisms, microplastics have been described to lodge in gills, which may translate into reduced respiration rates. Works focusing on the effects of these highly pervasive materials in terrestrial settings remain limited. Yet, although soils greatly differ from aquatic environments, the features that are essential to biota are identical, as many organisms thrive in small bodies of water that exist at or just below the surface, rendering them essentially aquatic organisms.

Microplastics can also be ingested by earthworms and mites, likely leading to their presence and accumulation throughout food webs.[12] For example, significant reductions in the growth rate of the earthworm *Lumbricus terrestris*, accompanied by higher mortality rates[65], were observed. These earthworms also carried microplastics from litter in their burrows[66] and effectively size-selected and downward transported these materials into the soil. It was also observed that only the smaller particles to which the earthworms were exposed to were egested, which could have profound implications on the fate and risk of microplastics in terrestrial ecosystems, given the preponderant role earthworms play in shaping the physical properties of soils.


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Plastic materials, nonetheless, do not constitute a danger solely in isolation, or, in other words, by themselves. Researchers have recently begun to use a new classification of these materials, based on the use of an ever-growing list of additives added to commercial plastics, the so-called plasticides. In essence, plastics are biochemically inert. However, these additives, frequently of low molecular weight and not chemically bound to the polymers, may elicit biochemical effects. Residual monomers, found in polymers due to incomplete polymerisation reactions, can also migrate away from the matrix, as can solvents and other organic pollutants adsorbed by plastics from the surrounding environment. These substances are then able to leach from the plastic materials and, because most of them are frequently lipophilic, have an inherent affinity for cell membranes. They can transverse the membranes and then actively participate in biochemical reactions.[12, 24] PVC, PS and polycarbonate (PC) have all been shown to release toxic monomers associated with the development of reproductive abnormalities, as well as cancer in invertebrates, rodents and humans.[9] The measured toxicological consequences have also been attributed to some of the most widely used plasticisers found in plastic products, listed in Table 2.

Table 2: Common plastic additives used in the manufacture of plastic products. Adapted from da Costa et al., 2017[67] and Nerland et al., 2014.[68]

Additive/Function	Examples
Plasticizers[c] - Esters - Aliphatic esters - Polyesters - Phosphates - Phthalates	Benzyl butyl phthalate Di-isoheptylphthalate Di-isobutyl phthalate Dibutyl phthalate Bis (2-ethylhexyl)phthalate Bis(2-methoxyethyl) phthalate Tris(2-chloroethyl)phosphate
Flame retardants	Boric acid Brominated flame retardants Tris(2-chloroethyl)phosphate Short and medium-chain chlorinated paraffins
Stabilizers - Antioxidants - Preservatives - Absorbers - Biological stabilizers - UV stabilizers	Arsenic compounds Triclosan Organic tin compounds Barium-cadmium-zinc-epoxy-phosphite Bisphenol A (BPA) Octylphenol Nonylphenol compounds Cadmium compounds Lead compounds
Colorants	Titanium dioxide Cadmium compounds Cobalt(II) diacetate Chromium compounds Lead compounds
Curing agents	Formaldehyde 4,4′ -Diaminodiphenylmethane 2,2′-dichloro-4,4′- methylenedianiline
Antistats	Amines Quaternary ammonium compounds Organic phosphates Polyoxyethylene glycol esters
Processing aids - Lubricants - Flow controls - Other aids	Calcium, zinc and lead stearates Fatty esters Amides Petroleum and polyethylene waxes

[c] Plasticisers are used to render plastics softer and more flexible, to increase their plasticity and to decrease both their viscosity and friction during handling in manufacture.

Among such organic contaminants, many are of special environmental relevance, including PCBs, PAHs and organochlorine pesticides (e.g. dichlorodiphenyltrichloroethane, or DDT), owing to their persistence in the environment. The risks of these substances become of even greater concern when associated with microsized particles, as these particles exhibit high surface area-to-volume ratios. Consequently, they can constitute new sources of exposure to chemicals when ingested in considerably high concentrations. Nonetheless, it has also been advocated that such characteristics make microplastics *de facto* sinks for these highly pervasive environmental chemical contaminants,[69] although the biological consequences of these remain undetermined.

Hence, overall, the effects of different sized polymeric materials may be summarised in a conceptual model (see Figure 7).

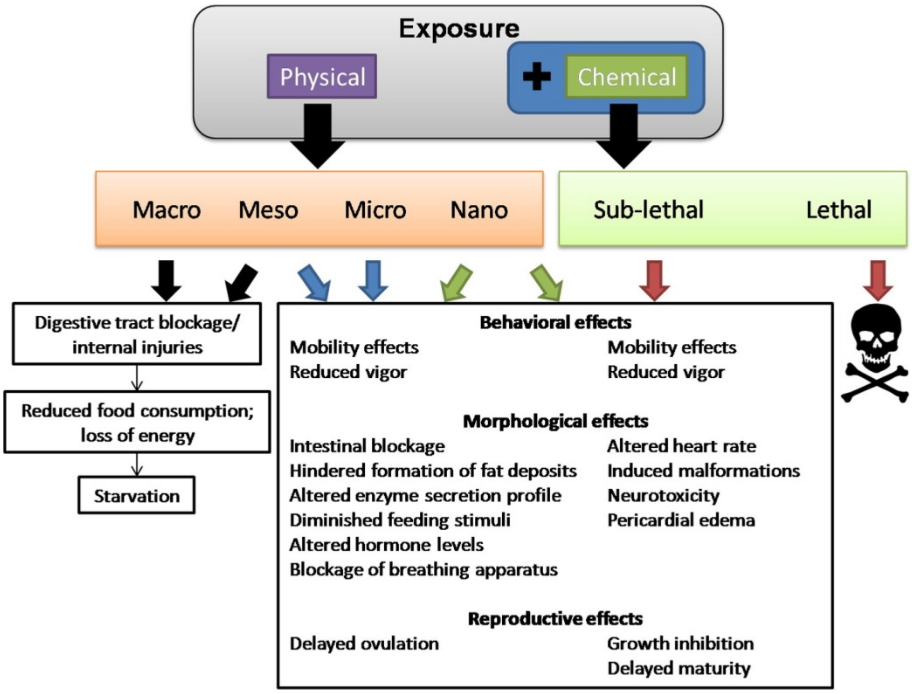
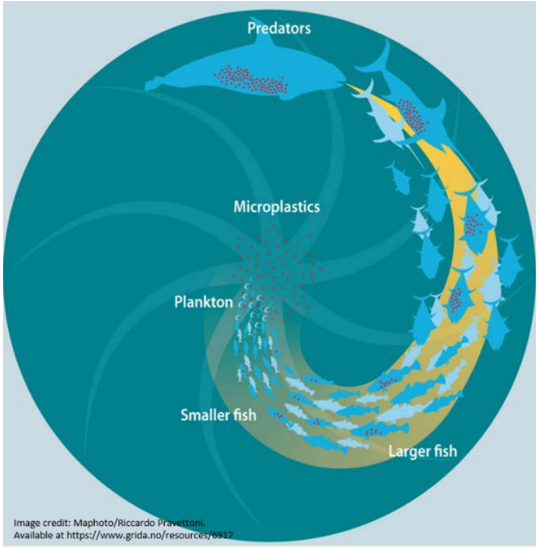


Figure 7: Conceptual model illustrating the potential biological effects of different sized plastic materials. Note that the effects of macro- and mesoplastics may also be observed in smaller organisms and that exposure to chemicals alone may yield the listed effects. In this model, macroplastics correspond to plastic particles >1cm, mesoplastics range between 1mm to 1 cm in size, microplastics measure between 1mm and 1 m and nanoplastics are plastic particles <1 m. Reprinted with permission from Elsevier.

Most of the effects listed in the conceptual model in Figure 7, however, stem from laboratorial observations in which pristine materials were used, often in concentrations that far exceed those found in the environment.[9, 67] Nevertheless, the described results certainly demonstrate the need to more accurately ascertain these effects, as they demonstrate the potential widespread ecotoxicological impacts of these materials.

These effects are further exacerbated by the potential bioaccumulative effects of plastic particles in the environment. Some studies have aimed to demonstrate a positive correlation between plastic debris and the bioaccumulation of hazardous chemicals, showing that the concentrations of PCBs and trace-metals in seabirds and higher brominated polybrominated diphenyl ethers (PBDEs) were positively related with plastic debris (e.g., Rochman *et al*., 2014[70]). Yet, correlation does not mean causation and multiple unaccounted environmental factors may contribute to explain the observed results.



More recently, detailed results have yielded contradictory findings. In fact, while there is abundant evidence on the accumulation of POPs by microplastics, there is scant indication that microplastics are significant transfer vectors of these organic contaminants into animals. Mussels, for example, have been shown not to accumulate fluoranthene when microsized PS particles were present at different rates than those observed in the absence of these materials[71], although tissue alterations and anti-oxidant marker levels changes were noted. Other studies have highlighted that co-exposure of earthworms to both microplastics and hydrophobic organic contaminants actually resulted in lower bioaccumulative effects of PCBs and PAHs when higher rates were tested. Under realistic conditions, however, such effects may be negligible.[72] This is not surprising, as numerous factors affect the mechanisms of sorption, in particular hydrophobic and electrostatic forces, which vary greatly in the environment. Moreover, particle properties undergo many modifications when exposed to the elements and these may lead to an unpredictable environmental fate.

Hence, although the volume and quality of the data available on microplastic concentrations and organic pollutants in different environmental compartments and species has increased significantly, the number of studies specifically reporting these impacts remains relatively small. Smaller sized plastics, in particular nanoplastics, appear to typically elicit more pronounced effects on organisms, particularly at the cellular and sub-cellular levels. The underlying mechanisms, however, are as yet quite unclear, as studies rarely include considerations on the potential role of any additives.

Additionally, exposure studies, in both field and laboratorial studies, usually focus on a limited number of individuals. Consequently, no current understanding on the effects of microplastic exposure at a population level and subsequent implications for food webs exist. Nanoplastics, however, appear to display a greater potential to cross biological barriers, including the blood-brain-barrier, a highly selective permeable membrane.[24] Such findings require corroboration, and must, therefore, be further investigated, considering the perceived toxicological risks.

Although exposure to (micro)(nano)plastics has resulted in a wide range of observed impacts across a vast array of species, interpretation and comparison of data remains challenging. Frequently, researchers assume a 100% constant exposure for the duration of the experiment, but the distribution of both micro and nanoplastics in suspension is unlikely to remain even and constant, as phenomena such as settling, aggregation, and loss occur. Therefore, the bioavailability of these materials is not homogeneous and must not be assumed as such. Studies must also steer away from the customary use of commercially available, spherical, pristine materials. Micro and nanoplastics (likely) found in the environment display different morphologies, degrees of degradation and even colours, all factors that may affect how these materials impact biota. Future studies investigating the toxicity of plastic additives should benefit from the expanding knowledge on the leaching, bioavailability and biological effects of these chemicals and incorporate an improved characterisation of both the materials and exposure conditions. Considering the evidenced toxicity of these organic compounds, their presence in plastic materials when subjected to an assessment of toxicological effects is essential for understanding the underlying sorption mechanisms.

2. LAWS, NORMS AND REGULATIONS GOVERNING (MICRO)PLASTICS

KEY FINDINGS

- Whether at the international, regional or national level, multiple regulatory instruments specifically or parenthetically addressing the issue of plastic pollution exist.
- However, legislative gaps exist and compliance remains an issue, especially for international and regional accords.
- At the national level, most of the existing restrictions are based on levies or bans, but many limits on the emission of plastic litter persist. A broader and more holistic perspective is needed.
- The currently rising public concern and goodwill towards the protection of the oceans constitute a unique opportunity for closing these gaps and to create stricter policies and regulations to combat plastic pollution.

The growing perception of the global pervasiveness of plastics in the environment, together with the pronounced potential ecological and toxicological consequences – both known and unknown – has drawn the interest not only of scientists but of the general public and policy makers as well. This interest has arisen from the increasing number of public reports in the news and on social media, detailing the visible and less evident effects of plastic pollution, mostly on marine life. This has led to the implementation of a wide range of guidelines and policies of varying degrees of strictness.

Yet, the efficiency of such regulations remains undetermined and no single policy solution currently exists that may solve the problem of plastic pollution, and no integrated and unified mechanisms for the regulation and control of plastics in the environment exist.[73]

This is not only due to the inherent difficulties in developing targeted transversal policies applicable worldwide, but also to the intrinsically limited information on the occurrence, behaviour, fate and effects of plastics. For example, a recently published study (August 18th, 2020) in which three types of microplastics were sampled in the Atlantic at varying depths of up to 200m, suggests that by extrapolating their concentrations for all depths until the bottom of the ocean, microplastic concentrations can be as high as 10 times those previously estimated.[74] Hence, it is inherently difficult to develop strategies aimed at combating a contaminant whose prevalence is as yet undetermined.

Considering that some plastics are mutagenic and/or carcinogenic (polyurethanes, PVC and epoxy resins) and that some plastic-associated chemicals are hazardous[75, 76] it is clear that - in spite of the aforementioned difficulties - there is a need to create, develop, implement and enforce legislation aimed at curtailing the continuously growing threats of plastics. Such legislation may exist at different levels, including national, regional or international levels. However, given that plastics are a contaminant unconstrained by political borders, only a concerted global effort will provide a credible and viable route for reducing and potentially eliminating the continued release of plastic waste into the environment.

2.1. International level

At the world stage, perhaps the most widely known regulatory tool available is the colloquially described "Constitution of the Oceans", the United Nations Convention on the Law of the Sea (UNCLOS).[77] Opened for signature in December 1982, UNCLOS came into force on November 16th,1994. UNCLOS constituted an unparalleled attempt to regulate "all aspects of the resources of the sea and uses of the ocean, and thus bring a stable order to mankind's very source of life", as described in the final version of the signed document. Composed of 320 articles, UNCLOS focuses on an extensive array of subjects, ranging from navigational rights, economic and territorial jurisdiction, legal status of resources on the seabed beyond national jurisdiction limits, to binding procedures for settlement of disputes between states. It also applies to marine resources management and conservation as well as protection and preservation of the marine environment, to which 46 articles are devoted (Articles 192-237, Part XII). Article 210, for example, mandates that all signatory states must develop frameworks to "prevent, reduce and control pollution of the marine environment by dumping". Concurrently, any state "has the right to permit, regulate and control such dumping after due consideration of the matter with other States which by reason of their geographical situation may be adversely affected thereby".[77]

Hence, owing to the fact that plastic litter is not circumscribed to national jurisdiction and the sources of marine debris are difficult to identify, the detailed principles and measures foreseen in UNCLOS are of limited efficacy. This is further complicated by inherent limitations that derive from historic regional and economic conflicts, such as the Aegean dispute in which Turkey challenges the extension of the Greek territorial waters foreseen in UNCLOS. Additionally, and perhaps more glaringly, the United States of America, a pivotal regional player in maritime security and in environmental protection as well as major producer of this type of waste, is not a signatory state.[78] Unfortunately, non-compliance

with the principles and norms enshrined in the UNCLOS Convention is recurrent. Flag states[d] often do

[d] The jurisdiction under which laws the vessel is registered or licensed, considered as the nationality of the vessel.

not fulfil their responsibilities, frequently owing to grievances stemming from the added duties that coastal states incur in, among others, search and rescue operations, pollution prevention and remediation, and the need for international navigation information systems and infrastructures, whose compensation is not envisioned in UNCLOS. Nevertheless, UNCLOS established a source of dialogue and communication between signatory states and served to initiate a process that in time may actively contribute to cooperative efforts between states aiming for reduction of plastic litter into the environment.[73]

In turn, the Marine Debris Program of the U.S. National Oceanic and Atmospheric Administration (NOAA) and the United Nations Environment Programme (UNEP) jointly developed a global agenda specifically developed for and aimed at the prevention, reduction and management of marine debris. Known as the Honolulu Strategy, it is a framework for a "comprehensive and global collaborative effort to reduce the ecological, human health, and economic impacts of marine debris worldwide (…). It is organised by a set of goals and strategies applicable all over the world, regardless of specific conditions or challenges".[79]

However, owing to its non-binding nature, the Honolulu Strategy does not supersede or supplant national, municipal, industrial or international organisational activities and is therefore restricted to the will of participating states and stakeholders. Rather, it provides a central point for improved coordination and higher degrees of collaboration between all interested parties concerned with marine debris. The successful implementation of the goals described in the strategy document requires active and voluntary participation at multiple levels – international, regional, national and local – from stakeholders within the government, inter-governmental organisations, the private sector and the entire spectrum of civil society. This result-oriented framework comprises three distinct goals, each of which contains different sets of strategies for:

a) reducing the amounts and the impacts of land-based sources of marine debris introduced into the sea;
b) reducing the amounts and the impacts of sea-based sources of marine debris, including solid waste, lost cargo, abandoned, lost, or otherwise discarded fishing gear, and abandoned vessels, introduced into the sea;
c) reducing the amounts and the impacts of accumulated marine debris on shorelines, in benthic habitats and pelagic waters.

Developed by the International Maritime Organization (IMO) with the objective of reducing pollution of the seas and oceans, including dumping, oil and air pollution, the Convention for the Prevention of Pollution from Ships (MARPOL (73/78)) Annex V, revised in 2012, is the main international convention aimed at the prevention of pollution from ships.[80] Created in 1973, a 1978 Protocol was developed in response to a series of tanker accidents in 1976-1977 and subsequently incorporated into the parent Convention. The combined regulatory instrument entered into force in 1983, yielding the common designation MARPOL 73/78. The Convention requires all ships to dispose of the generated waste at land-based wasted facilities. As of January 2018, 156 states (see Figure 8) are parties to the Convention, all of which are flag states responsible for over 99% of the total global shipping tonnage.[81]

Complementary to MARPOL 73/78 guidelines for the survey and monitoring of marine litter, as well as on lost, abandoned or discarded fishing gear have been formulated by the International Oceanographic Commission (IOC) and the Food and Agriculture Organization (FAO).[82] However, although only flag states have the authority to enforce restrictions on marine pollution in international waters, they often either lack the resources or the will to fulfil their duty, or both.[83] Additional efforts are required to help close such enforcement gaps and extend the ability of the Convention to achieve the vital goal of protecting the marine environment, which also includes expanding coastal and port state authority and extending the regulatory requirements to track cargo, including oil, from "cradle to grave" in smaller vessels. It is possible, however, that other multi or trans-national agreements, such as Free Trade Agreements, could heighten MARPOL 73/78 compliance, through active public participation in trade and dispute resolutions.[84]

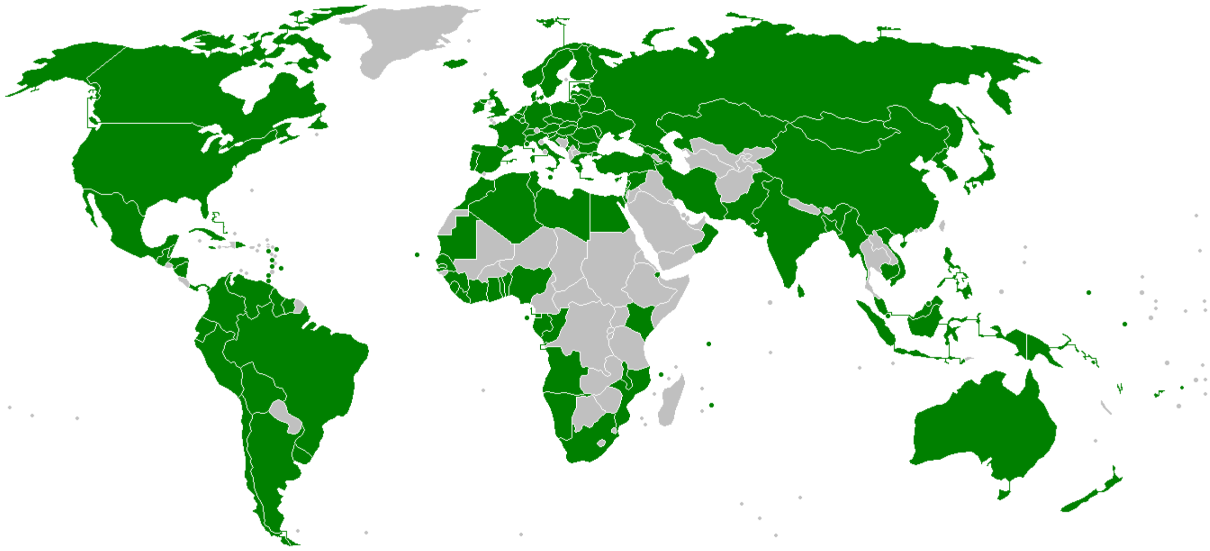


Figure 8: Signatory parties to the MARPOL 73/78 Convention on marine pollution.

In 2017, UNEP's Environment Assembly gathered in Nairobi (Kenya) and passed a draft resolution specifically dealing with marine litter and microplastics.[85] In general, this document recognises the existence of multiple challenges "addressing marine plastic pollution in the face of increasing production and consumption of plastic in products and packaging". The text also urges "all countries and other stakeholders to make responsible use of plastic while endeavouring to reduce unnecessary plastic use, and to promote research and application of environmentally-sound alternatives".[85] The participation and initiatives of both public and private entities are acknowledged and encouraged. In light of this call to action, some cross-industry agreements have been reached and some enterprises have also independently developed efforts in this direction.[73]

In Europe, this is exemplified by the agreement to prevent the release of microplastics into the aquatic environment during the washing of synthetic textiles. This agreement was proposed by EURATEX, a textile confederation representing around 160.000 companies.[86] Also, some internationally recognised companies are developing efforts towards reducing their emissions themselves by phasing out single-use plastics (IKEA)[87], by reducing the use of plastic in their products (planned by Unilever)[88], or by actively replacing plastic products with e.g. refillable recipients, as is the case in some McDonald's restaurants.[89].

Also in 2017, the United Nations proclaimed the Decade (2021-2030) of Ocean Science for Sustainable Development.[90] This initiative encompasses broader goals for combating pollution and, more specifically, plastic litter. It focuses on the creation and fostering of active interfaces of science and policy aiming at enabling and boosting sustainable management of coastal areas and oceans. Under the banner "the science we need for the ocean we want", this process, which is still in its preparatory phase (2018-2020), is motivated by the will to reverse the cycle of decline of the health of the oceans. The current increasing awareness and goodwill towards protection of the oceans and the development of adequate science-based policies resulting from integrated areas of research, constitute a unique opportunity that may culminate in the creation of efficient measures successfully directed to the preservation of the marine environment.

The issue of plastic pollution has also been addressed from a more economically intergovernmental perspective. The Group of 7 (G7) and the Group of 20 (G20) have devised specific action plans.[91, 92] These emphasise the need to promote resource efficiency, waste reduction and sustainable waste management. However, currently most of the reported achievements are reduced to workshops, which have, nonetheless, highlighted the need to identify improved solutions for dealing with (marine) litter.

2.2. Regional level

As of mid-2019, the EU has in force Directive (EU) 2019/904, aimed at reducing the impact of certain plastic products in the environment.[93] This Directive demands that all Member States should "ensure environmentally sound waste management to prevent and reduce marine litter from both sea and land sources". The document envisions different strategies for different plastics, for example in the form of market restrictions, reduction of consumption and promoting the transition – albeit gradual – to a circular economy of plastic materials to be achieved by fostering the advancement and implementation of original and sustainable business models, materials and products.

Perhaps the most important EU Directive related to the issue of marine pollution is Directive 2008/56/EC[94], referred to as the Marine Strategy Framework Directive (MSFD). Adopted on 17 June 2008, it is an ambitious integrated policy to reach Good Environmental Status (GES) of the European marine environment by 2020. This is to be measured through a set of detailed criteria and methodological standards recently revised (2017).

The objective of GES is to be achieved by protecting "the resource base upon which marine-related economic and social activities depend" and maintaining biodiversity as the cornerstone of its goals. The Directive therefore contains a total of 11 descriptors to be used for defining and establishing GES in which marine litter broadly and microplastics, specifically, are covered. GES, defined as "[t]he environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive", is covered in all European aquatic ecosystems by the Water Framework Directive[95] which has been in force since 2000 and was consolidated in 2014. The WFD impacts directly on marine litter pollution, as it encompasses estuaries as well as coastal waters up to one nautical mile (≈1.85 km) from mainland. Nonetheless, and in spite of the formal definition and of the established descriptors, Member States are free to interpret what GES means in practice. In a subsequent revision, the Commission included a revised definition of both the criteria and the methodological standards for assessing these parameters. However, the language used remains open to interpretation, resulting in some discrepancies between the definitions used and methodologies applied by Member States.

Following MARPOL's Annex V, the European Union developed detailed laws aimed at reducing and enforcing ship-generated litter. These laws are canonised in Directive 2000/59/EC, entitled the Port Reception Facility (PRF), and are broadly based on the "polluter pays" principle.[96] Yet, both the MSFD and the PRF are not without limitations. In addition to its already described limitations, the MSFD leaves the responsibility of developing the required tools for implementing the detailed marine strategies to the parties. This could potentially result in inherent difficulties when comparing assessments carried out by different Member States. In the case of the PRF, recently proposed changes have sparked controversy and increased concerns over its applicability. A specific example is the suggested policy of introducing a 100% fixed fee for garbage and for passively collected waste in fishing nets. This may lead to the delivery of vast quantities of litter - including dangerous waste - for a fixed fee. This would, as noted[97], be a divergence from the "polluter pays" principle. Presently, however, the following provision exists: "no direct fee shall be charged for such waste, in order to ensure a right of delivery without any additional charges based on the volume of waste (…); passively fished waste shall be covered by this regime".[98]

Another statutory instrument, signed and ratified by the EU and 15 states is OSPAR - the Convention for the Protection of the Marine Environment of the North-East Atlantic. The name of the Convention reflects the merger (and update) of the 1972 Oslo Convention and the 1974 Paris Convention (Oslo and Paris).

OSPAR promotes and regulates cooperation with the ultimate goal of protecting the environment. From this initiative, specific guidelines for monitoring marine litter on beaches have been developed. These include practical advice, photographic guides and standardised methodologies for the detailed and accurate quantification and identification of the sampled litter.[99] OSPAR contains a series of Annexes, each for specific areas:

1) Prevention and elimination of pollution by dumping or incineration.
2) Prevention and elimination of pollution from offshore sources.
3) Assessment of the quality of the marine environment.
4) Protection and conservation of the ecosystems and biological diversity of the maritime area.

Conceivably the most comprehensive set of efforts aimed at protecting coastal and marine environments are UNEP's Regional Seas Conventions (RSC). Launched in 1974, these Action Plans cover 18 regions of the world - Antarctic, Arctic, Baltic, Black Sea, Caspian, East Asian Seas, Eastern Africa, Mediterranean, North-East Atlantic, North-East Pacific, Northwest Pacific, Pacific, Red Sea and Gulf of Aden, Persian Gulf, South Asian Seas, South-East Pacific, Western Africa, and Wider Caribbean.

The first RSC was the Barcelona Convention (1976), an essential part of the Mediterranean Action Plan of 1975. This Convention pioneered the "framework" model for environmental treaties that underpins other regional sea conventions and is present in several global environmental conventions. The Action Plans are not all administered by UNEP, but all engage neighbouring nations in extensive and specific activities aimed at protecting the regional marine environment through a "shared seas" approach.[100] Actions are comprised of multi-sector approaches to both coastal and marine areas, spotlighting the existing identified environmental challenges.

Because of the active involvement of regional governments, the participation of all stakeholders is encouraged - from design to inception to evaluation of the implemented actions - as they are the greatest beneficiaries of the successful implementation of the plan. Moreover, parties to 14 out of the existing 18 programs have adopted legally binding frameworks, and while some of these regional instruments have proven to be extraordinarily effective – such as the Barcelona Convention, which has always been highly active and visible – others struggle with funding and lack of participation and engagement by local governments.[73]

The Baltic Sea is governed by HELCOM, the Helsinki Convention on the Protection of the Marine Environment, signed in 1992. It includes ten members – Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, Sweden, and the EU – and was signed in 1974 to address the increasing environmental challenges stemming from human activities, in particular industrialisation. Updated in 1992, HELCOM entered into force in 2000 with the declared goals of preventing and eliminating pollution, thus paving the way to the complete ecological restoration of the Baltic Sea. The Convention also promotes the use of Best Environmental Practices and Best Available Technology, and applies the polluter-pays principle. Its text underlines that the implementation of HELCOM should not cause transboundary pollution outside the Baltic Sea Area.[101]

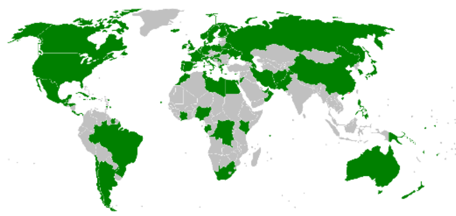
Under HELCOM's purview, several guidelines have been devised and made publicly available on a wide range of topics, from the periodical compilation and reporting of waterborne pollution to determination of "heavy metals" in sediments or even on the monitoring of radioactive or reprotoxic substances, i.e. substances that may induce reproductive toxicity.[102]

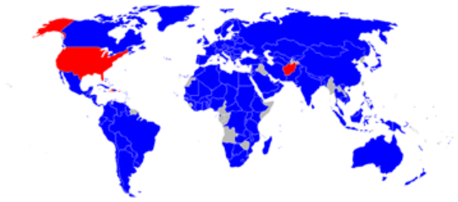
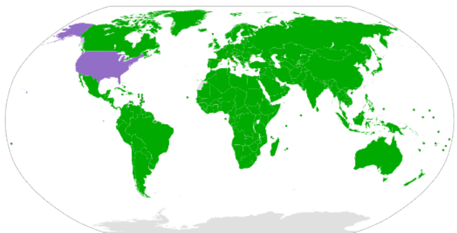
Figure 9: Regional coverage of action plans on marine litter. These may vary in features and extent of actions. For example, while the Barcelona Convention includes legally binding measures, the Baltic and North Atlantic Conventions are based on sets of essential principles. Adapted from da Costa et al., 2020.[73]

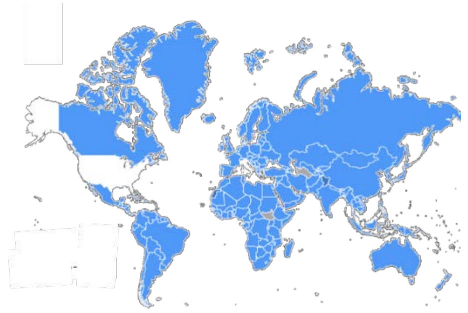
RSCs and Action Plans are essential tools that support and allow for the implementation of the Global Program of Action (GPA) at the regional/national levels. In spite of containing and consisting of identical approaches, each action plan is developed considering the regional specificities, including specific environmental challenges. Therefore, strategies may differ in terms of legal structure, scope and efficacy.

Additional international treaties, agreements and conventions for the management of marine litter and pollution are listed in Table 3. A brief description of each accord is included, but it should be noted that the list does not purport to be exhaustive. It is merely indicative of the numerous and varying regulatory initiatives in place.

Table 3: Additional international treaties, agreements, conventions or initiatives aimed at the management of pollution and conservation. A brief description of each accord is included, as well as the international coverage of signatories. The list does not purport to be exhaustive. It is merely indicative of the numerous and varying regulatory initiatives in place. Adapted from da Costa et al., 2020[73]*.*

Accord	Description	Coverage (when available)
London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	The main objective is to promote control over all sources of marine pollution. In force since 1975, it is signed by 87 States. The Convention predicts regional cooperation based on mechanisms of action that "allow for the full and open exchange of information".	 Signatories are highlighted in green.

Accord	Description	Coverage (when available)
Basel Convention on the Control of Trans-boundary Movements of Hazardous Wastes and Their Disposal	Presently signed by 187 countries, the Convention entered into force in 1992. The main goal is reducing the production and toxicity of hazardous wastes, promoting environmental management and enforcing restrict and highly regulated transboundary movements. It was amended (BC-14/12) in May 2019.	 Signatories are highlighted in blue. In red, countries that have not ratified the Convention.
Global Partnership of Marine Litter (GPML)	GPML is a multi-stakeholder partnership launched at the UN Conference on Sustainable Development Rio+20 under the auspices of UN Environment. Its declared objective is to "by 2025, prevent and significantly reduce marine pollution of all kinds".	Not directed at individual nations or governments, any entity can become a member of the GPML.
Code of Conduct for Responsible Fisheries	Developed by the UN's Food and Agriculture Organisation, this voluntary code of conduct was adopted in 1995. The accord seeks to promote long-term fisheries by setting a set of principles and standards for the responsible practice of fisheries to ensure the conservation, management and development of all living aquatic resources. The Code includes the principle that fisheries should be conducted in manners that reduce the generated waste and minimise the negative impacts on the environment. The voluntary nature of the accord has, however, resulted in limited compliance by the signatory parties [53].	The Code is not just aimed at the FAO's 194 members, but also to non-member nations, fishery managers, fishing operators and non-government organisations. They can adopt the Code and some have adopted it. However, owing to the fact that the FAO has no legislative authority and because of the voluntary nature of the Code, even those who have publicly embraced this Code cannot be forced to implement measures to successfully achieve any of the detailed objectives.
Convention on Biological Diversity (CBD)	The CBD entered into force in 1993 and was signed by 168 countries. It is devoted to biological conservation. In 2016 the Conference of Parties urged members to implement within their national jurisdictions measures to prevent and mitigate the impacts of marine debris on marine and coastal biodiversity.	 Signatories are highlighted in green.
Strategic Approach to International	Non-binding policy framework adopted in 2006 to promote chemical	Includes a program encompassing a voluntary, time-limited trust fund,

Accord	Description	Coverage (when available)
Chemicals Management (SAICM)	safety. Presently, SAICM is assessing whether to consider plastics and additives materials of concern.	administered by UNEP as well as multilateral, bilateral and other forms of cooperation for all interested stakeholders.
Stockholm Convention	Legally binding agreement adopted in 2001 and entered into force in 2004. Requires parties to take measures to eliminate or reduce the release of POPs into the environment	 Signatories are highlighted in blue.

From the previous paragraphs, it emerges that there is a large number of regulations, recommendations and laws pertaining to the prevention of pollution, particularly in the marine environment, and to the promotion of the conservation of ecosystems and the environment. However, for most of these instruments, the main issue remains compliance, even for tools that have full strength of law.

One key example is Areas Beyond National Jurisdiction (ABNJ).[103] These correspond to over 40 percent of the earth's surface and make up nearly two thirds of the oceanic surface and 95 percent of its volume. ABNJs are colloquially referred to as "high seas", areas in which no nation has the responsibility for policing, monitoring and management. UNCLOS does include an international regime governing the ocean, but it does not include any detailed process or mechanism through which enforcement can be reached in ABNJs. Negotiations to include an "Implementing Agreement" in UNCLOS are currently underway. If successfully added, it may provide a way to close the existing governance gaps in ABNJs, but that will greatly depend on the agreement and compliance of the involved parties.

Regional initiatives are also insufficient to address the issue of pollution, as local or regional (eco)systems are interconnected to wider and larger networks such as ocean currents and migratory pathways. Inter-regional cooperation is thus essential. Strengthening cooperation and coordination are key steps to develop efficient ecosystem-based management strategies.

Hence, whether at international or regional level, existing and future accords must be based on legally-binding effective measures implemented firstly at the national level. These tools and instruments are the key catalysts for the development of more aware and participating societies in combating pollution.

2.3. National level

At the national level, there have been multiple legislative initiatives focusing on litter and on plastic in particular. Wales was the first country in the UK to introduce a 5 pence (just under 0.06€) plastic tax per bag. Soon thereafter, the Scottish legislature drafted the Marine Litter and the National Litter Strategies, in response to the EU's MSFD. The main goal of the Scottish bill is to reduce or completely eliminate the incidence of litter by directly reaching out to citizens. To be fully implemented by 2020, the proposed approach aims mostly at educating the public to the dangers posed by plastic debris, especially in aquatic systems. The bill also envisages the creation of infrastructures, enforcement measures and deterrence mechanisms. England also developed legislation focusing specifically on microplastics but the document is yet to be subjected to a vote.[73] The most emblematic legal instruments – perhaps owing to their direct impact on everyday activities of citizens – are the well described and amply adopted measures concerning lightweight plastic bags - in the form of bans or levies or both - and the widely publicised bans on plastic straws.

Ireland introduced a levy in 2002, which resulted in a reduction of over 90% of the consumption of plastic bags, with a concomitant decrease in littering and visible landscape improvements.[104] Denmark was among the first countries in the world to adopt such measures, and a 66% reduction in usage was observed. In Portugal, a single-use plastic bag levy has existed since February 2015. Nonetheless, two years later, in spite of a reduction of plastic bags by 74%, a rise of 61% was noted for reusable plastic bags and an increase of 12% in the consumption of garbage bags.[105] This was not surprising given the fact that many consumers re-used these lightweight plastic bags subsequently as garbage bags.

However, the most dramatic and evocative example of these policies and their unintended consequences comes from outside the EU. In Kenya, the local government implemented a complete ban on plastic bags. The ban was accompanied by sanctions of $40,000 or imprisonment of up to 4 years for the production, sale or use of plastic bags.[106] This measure was emulated by Rwanda. In Kenya, the ban resulted in the creation of a black market for carrier bags. Smuggling from neighbouring nations, in particular Uganda[107], is frequent, which threatens the efficacy of the measure.

Table 4 summarises the countries that have introduced some form of ban, tax, levy or otherwise general regulations on single-use plastics.

Table 4: Summary of European countries, alphabetically listed, that have in place regulations on single-use plastics. When available, impacts of the regulations are detailed. Adapted from Giacovelli, 2018.[108]

Country	Year	Policy	Description
EU	2015	Directive (EU) 2015/720[109]. Member States must ensure that by the end of 2019 no more than 90 lightweight (<50μm) bags are consumed per person per year. By the end of 2025 that number should be down to no more than 40 bags per person/year. Member States can choose whether to introduce bans, taxes, or other policy tools.	
Belgium	2007	Levy – in force	Levy on consumer. A bill on carrier bags has been drafted but is yet to be adopted. Consumption of carrier bags decreased by 80% over the following decade.
Bulgaria	2011	Levy - in force	Levy on supplier of PE bags (<15μm). Impact: drastic reduction in the use of plastic bags according to the Bulgarian Ministry of Environment and Water.
Croatia	2014	Levy – in force	Levy on supplier.

Country	Year	Policy	Description
Cyprus	2018	Levy - in force	Levy on consumer for plastic bags >15µm. Retailers determine the price, but charge covers the production cost of the plastic bag.
Denmark	1994	Levy - in force	Levy on supplier for plastic bags. Fee passed on to retailers, who in turn pass it on to consumers. Impact: decrease from around 800 million bags to half of that.
Estonia	2017	Levy - in force	Levy on consumer on plastic bags <50µm (exemption of very lightweight bags used for hygiene and prevent food waste). Avoidance of sale or free of charge oxo-degradable plastic carrier bags.
France	2016	Ban - in force	Ban on lightweight single-use carrier bags (<50 µm and <10 litres). Expanded in 2017 to all other plastic bags except compostable bags.
	2015	Ban - approved	Ban on all disposable tableware not made from at least 50% biologically-derived by 2020.
Greece	2018	Levy - in force	Levy on consumer (€0.04) for non-biodegradable plastic bags (<50µm). Businesses allowed to charge customers for thicker bags (up to 70µm) Impact: after the first month consumption decreased by 75-80% and sales of reusable shopping bags increased sharply.
Hungary	2012	Levy - in force	Levy on supplier. The introduction of the fee obliged producers and distributors to pay the fee, which was incorporated into the products' price. Retailers voluntarily added a fee on plastic bags.
Ireland	2002 (revised in 2007)	Levy - in force	Levy on consumer for plastic bags (initially, €0.15, later, €0.22). Legislation allows the levy to be amended, not exceeding €0.70 per bag. Impact: one year later, the consumption of plastic bags decreased by more than 90%.
Italy	2011	Ban - in force	Ban on non-biodegradable plastic bags (<100µm). Exemption for reusable plastic bags. Impact: reduction of plastic bag consumption by approximately 55%.
	2018	Levy - in force	Levy on consumer for plastic bags in supermarkets and grocery stores. Only biodegradable and compostable lightweight bags are allowed to be provided or sold.

Country	Year	Policy	Description
Latvia	2009	Levy - in force	Levy on retailer for plastic carrier bags. Most supermarkets charge for plastic carrier bags. Impact: plastic bag consumption dropped. The use of reusable bags increased, but stabilised after the first year.
Lithuania	2016	Levy - approved	Levy on consumer. Free lightweight plastic bags with a thickness between 15 and 50 µm are forbidden.
Malta	2009	Levy - in force	Levy on consumer for all plastic bags (€0.15).
Netherlands	2016	Levy - in force	Levy on consumer. Very lightweight bags for packaging are exempt. Businesses are officially suggested to charge €0.25 per bag, but they can decide how much to charge. Impact: number of plastic bags found in litter decreased by 40% in one year.
Portugal	2015	Levy - in force	Levy on supplier, but the fee (€0.10) was largely passed onto the consumer. Impact: following implementation, consumption of lightweight plastic bags decreased by 74%. Consumption of reusable plastic bags, exempted from the levy, increased by 61%.
Romania	2009	Levy - in force	Levy (€0.05) on consumer on non-biodegradable plastic bags.
	2018	Draft law - approved	Ban on plastic bags <50µm in supermarkets and 15µm on national markets.
Slovakia	2018	Levy - in force	Levy on consumer for plastic bags between 15 and 50 µm.
Spain	2020	Draft Law - approved	A tax of €0.45 per kilogram of plastic waste. Also includes a ban on straws. To be levied on the manufacturing, import or intra-EU acquisition of the non-reusable plastic packaging
Sweden	2017	Law - in force	Requires supermarkets to educate customers on the environmental effects of plastic bags.
United Kingdom (England)	2015	Levy - in force	Levy on consumer (£0.05, around €0.06) for plastic bags. Charged by companies with >250 employees. Voluntary basis for smaller retailers. Impact: single-use plastic bags used dropped by more than 85% in the six months.
United Kingdom (Northern Ireland)	2013	Levy - in force	Levy on consumer for plastic bags (£0.05, around €0.06).

Country	Year	Policy	Description
			Impact: first year saw a drop of 71% in the consumption of plastic bags. The second year showed an added 42.6% decrease.
United Kingdom (Scotland)	2014	Levy - in force	Levy on consumer (£0.05, around €0.06) Impact: plastic bag usage declined by 80% in one year.

Globally, nearly 150 countries have implemented some form of legislation aimed at phasing-out the use of single-use plastics. They are indicated in Figure 10, which does not illustrate measures not yet in effect.

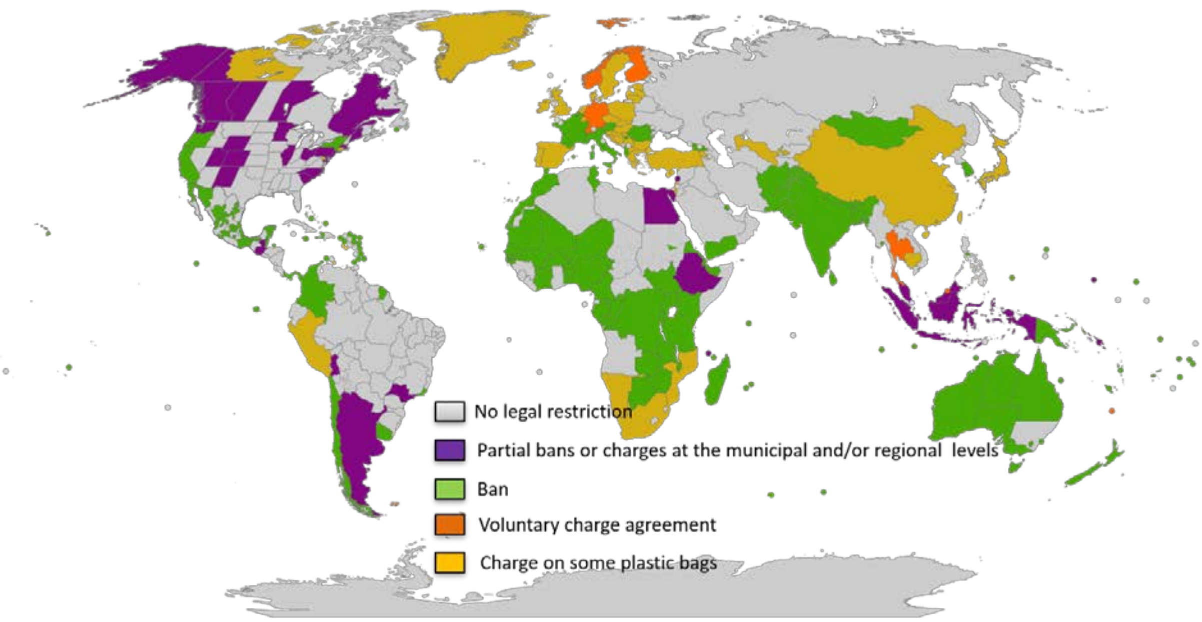


Figure 10: Global current legislative efforts (April 2020) regarding lightweight plastic bag laws. Adapted from Wikipedia and available under Attribution-ShareAlike 3.0 Creative Commons (CC BY-SA 3.0).

Determining the measurable effects of actions such as levies, particularly with regard to behavioural and awareness changes, is challenging. Although strict enforcement may ensure compliance, incremental approaches – such as levies and gradual bans – could yield more effective consumer responsiveness in the long run. This is especially true in emerging economies where fundamental issues such as lack of proper infrastructures or collection systems are still very relevant. Yet, it is a testament to the environmental urgency that plastics and in particular microplastics pose to the environment that these same emerging economies, with little or no plastic production and very limited recycling capabilities, have led the way and proposed ambitious plans at the international stage to reduce the production and use of these materials. In 2019, at the United Nations Environment Assembly (UNEA), India submitted a resolution proposing the phasing out of single-use plastics by 2025.[110] The final March 15th declaration did not contain the "decisive" intention, extended the timeline to 2030, and committed only to a "reduction" by that time.

3. CORRELATION AND EFFCIENCY

KEY FINDINGS

- Regulatory instruments fall within the Preventive, Removal, Mitigation or Educational category.
- Most initiatives, however, are carried out with little to no coordination.
- Intrinsic national and regional challenges are factors that must be considered when devising regulatory instruments.

No matter the level of the regulatory instrument, whether international, regional, national or even local, all of them address pollution in one or more of the following four essential layers of intervention[111], classified as:

1) Preventive – based on the 3R rule: reuse, reduction (at sources) and recycling.
2) Removal – centred on debris monitoring and clean-up initiatives.
3) Mitigation – focussed on litter disposal and on the development of discharge regulations.
4) Educational – concentrated on awareness campaigns, behavioural changes and economic/incentive approaches.

Yet, quite often strategies are devised within precise contexts and at an entrepreneurial level. They are in response to specific consumer concerns and result in incoherently coordinated initiatives between all interested parties.

One such example is the social pressure put on companies aiming at the ban on microbeads in the US. Companies such as Procter & Gamble and Johnson & Johnson lobbied for legislation that would allow for the inclusion of "biodegradable" plastic microbeads[112]. They failed however to consider that there is much debate on what biodegradable plastics are.[113] As a result a "biodegradable loophole" was opened, which - even assuming such biodegradable materials exist - could result in emissions of detrimental materials into the environment. This is because even biodegradable materials may persist within in deep, cold and dark waters, and could very well retain the ability to leach any adsorbed or added chemicals. A more intense collaboration between all stakeholders could have yielded a more effective solution, such as the proposed use of polyhydroxyalkanoate (PHA) microbeads[114], the use of jojoba beads (*Simmondsia chinensis*), salt, ground coffee or even diatomaceous earth[115], now present in some exfoliators.

Another frequent error is the introduction of bans or levies with little or no consultation and, in some cases, without national campaigns and/or limited notification.[116] In such cases, negative outcomes are the result of an apparent lack of interaction and integration of the policies developed at distinct levels of intervention and often because bans or levies are devised and implemented in isolation.

In order to develop more efficient tools, a more desirable approach based on constant dialogue and interaction is needed, whereby the focus of the applied tools percolates from international to regional, national and local levels. Such an approach could actively contribute to closing the existing gaps. Such gaps include regulatory insufficiency affecting the response at different levels of intervention, poor international cooperation, lack of implementation and enforcement of the regulations and actions already in place.

However, it is inherently difficult to legislate, regulate and enforce any measure when the underlying scientific knowledge is still very limited - despite the large volume of data gathered in recent years. The lack of knowledge covers not only the prevalence of all types of plastic in the environment but also their fate and potential effects. On the other hand, the available knowledge is often restricted to scenarios that in most cases are not replicated in the environment, which renders some of the available data of limited value.[24]

There are also intrinsic national and regional challenges. These are due to societal changes, including economic growth, increasing rates of urbanisation, and behavioural changes in both production and consumption. All these are factors that must be considered when devising adequate regulatory instruments.

4. PETITIONS ON MICROPLASTICS – ANALYSIS AND RECCOMMENDATIONS

KEY FINDINGS

- Considering the vast public interest, concern and awareness, the number of petitions pertaining to the issue of plastics, mostly microplastics, seems rather low. This highlights the need for an enhanced outreach to and from European citizens.
- The petitions submitted to PETI focused on plastic pollution at all its key stages: sources, presence in the environment and removal.
- The various petitions, in particular on (food) packaging, should be assessed and adequate legislation, with stricter norms, should be considered by the European Commission.

The Petitions Web Portal of the Committee on Petitions (PETI) contains a rather limited, yet comprehensive, number of appeals focusing on plastic pollution, including microplastics. The selection of petitions used for this study (Annex I) can be categorised as centring on: (i) products containing (micro)plastics, including packaging materials, (ii) preventing pollution, and (iii) remediation procedures/processes.

Before addressing the specific claims in some of the petitions, a brief comment on the reach of the published petitions is warranted. In fact, while researching the petitions returned from a simple search containing the search parameters "microplastics" or "plastics", what immediately emerges is the limited number of supporters. In fact, in light of the seriousness of the issue at hand, it was surprising to note that each studied petition never had more than 24 supporters, averaging 10.3 supporters per petition. Considering that the receptiveness of EU citizens to the issue of plastic pollution and the prevention of its environmental effects is generally positive, and also considering that EU citizens generally provide positive feedback on, for example, the implementation of measures aimed at curtailing the prevalence of plastics in the environment, this low participation/support may stem not from a lack of engagement, but rather from a lack of knowledge of the initiatives developed by PETI.

A higher degree of involvement and disclosure, fostering the active participation of EU citizens, is therefore warranted. This could be achieved by heightening the presence of PETI on social media, not only through the placement of ads, but also through announcements (*posts*) on ongoing activities. In spite of the increasing presence of people on social media, particularly younger citizens, TV continues to be the media of excellence for reaching the general population, and "social TV" is also a perhaps adequate mode to reach such younger audiences.[117] No matter the devised strategy, an increased outreach will benefit the degree of participation of EU citizens and will help to better address their concerns.

Starting at the source, several petitions call for a limitation or full ban on the use of (micro)plastics in numerous items, ranging from hygiene to food products. As noted in the previous sections, especially regarding the use of microplastics, natural alternatives already exist.[73, 114, 115] Therefore, the use of these bio-friendly alternatives should be mandatory and enforced by law.

Cosmetics are not the sole household products that contain (micro)plastics, but economically it may be less feasible to include natural alternatives in products made available in larger volumes, such as cleaning products. Any increase in production costs would almost undoubtedly be passed on to the consumer. However, depending on the added cost, there may be sufficient environmental awareness amongst European citizens to accept and embrace this increased cost, for the benefit of the environment and ultimately of everyone.

The European Chemicals Agency (ECHA) is currently developing an opinion on possible restriction options under REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) to address the potential risks of microplastics. In the proposed scenario, the use of intentionally added microplastics in consumer or professional products of any kind would be severely restricted.[118]

A call for a ban on the use of plastic packaging, in particular on non-recyclable plastic, was also submitted as a petition to PETI. In recent months, as a result of the COVID-19 pandemic, a sharp increase in online shopping and a concomitant surge in plastic consumption for packaging has been observed.[119] This has not only resulted in marked changes in the composition of waste generated during the pandemic, but has also led to concerns that relaxation on the use of plastic during this crisis could impact the behaviour of consumers.

Physically, the sheer volume of unnecessary packaging is staggering. Although the reasoning behind the use of plastic in food is that it may help alleviate food waste by keeping food fresher for longer periods of time, it has been shown that actually the opposite is true. In 2018 a study showed that within the EU28 , food waste per person had doubled between 2004 and 2014 even as the amount of plastic food packaging rose by up to 50%.[120] The cost of food waste in 2015 alone amounted to €143 billion. Hence, in order to combat not only the excessive use of plastics, but also the rising food waste, the EU should set targets for reducing single-use packaging and it should support zero-waste initiatives. Also, it should create the right for consumers to return plastic packaging to the point of sale. This would foster a more effective recycling of these materials.

Among the most wasteful products, coffee pods or capsules rank among the top. Yet, interestingly, the only petition involving coffee pods (0910/2014) dated from 2014 and concerned aluminium capsules, which have a higher recycling rate than similar plastic items. In fact, some patented coffee pods are designed using multiple layers of different polymers in compact format, which prevents their recycling unless performed in specialised locations. Despite the massive marketing strategy aimed at conveying an idea of sustainability and efficiency, such monodose items are anything but. In most cases these items end up in landfills. Thus, they contribute to the ever-increasing prevalence of unrecycled products that are estimated to be enough to circle the globe 10 times.[121]

Associated to coffee pods are other monodose products. These are particularly prevalent in hygiene and cosmetic products. They include razor blades, tooth paste, supplements and, in the food industry, single servings of multiple products. Although the use of monodoses in some products is not only reasonable but recommended, as is the case for individual optical or saline solutions whose packaging eliminates the risk of bacterial contamination, the use of monodoses in other products, such as creams, exfoliators and toothpastes should be regarded as wasteful. These are commonly cheap, highly convenient products that, nonetheless, use far more packaging when compared to their bulk counterparts.

As the use of these convenience products is deeply entrenched in modern Western civilisation, banning them - in particular coffee capsules - or demanding changes in the design of these products, would likely result in some degree of criticism. Even so, unless designs more amenable to recycling replace those currently used in common convenience products, bans should be considered. Alternatively, the EU could consider forcing the manufacturers of these products to allocate financial resources towards the development of adequate, more local infrastructures aimed at recycling. Also, collection, either through the placement of specifically devoted recipients in commercial areas or making use of existing recycling points, could be made mandatory.

Other petitions concerned the presence of (micro)plastics in the environment. A number of them call for the removal of plastics that contaminate the urban and rural landscapes, and for a ban on the presence of microplastics in biosolids used in agricultural fertilisers.

The removal of plastics that contaminate the urban and rural landscapes cannot be addressed through isolated actions or initiatives, but only by a concerted, global and holistic approach. The complete removal of such plastics does not involve actions solely at the end-points, but also at their sources. Such actions include reducing the overall plastic consumption, increasing recycling rates, and gradually substituting plastics by "green" alternatives.

Microplastics found in fertilisers are used with two specific goals: as technical additives, in order to prevent the formation of lumps in moist conditions, and as controlled-release fertilisers, which are coated with a tiny layer of polymer. The polymer allows for the gradual release of nutrients in a timely and targeted way. The EU has already addressed this issue through the Fertilising Products Regulation.[122] According to this Regulation, polymer encapsulation systems for fertilisers and anti-caking/anti-dust additives in fertilisers must reach the established biodegradability criteria by 2026. After entry into force of the Regulation, a transition period of 5 years will apply to the use of microplastics. Additional regulations should be considered on the use of organic fertilisers such as sludge from wastewater treatment facilities and from biowaste fermentation and composting. These have been shown to contain considerable loads of micro-sized plastics[123] and should therefore be regulated. However, specific tools for assessing the prevalence of these materials are lacking and consequently there are inherent difficulties in establishing definitive criteria to control and regulate the use of these bio-fertilisers.

This closely mirrors the concerns raised in another petition, which calls for a procedure establishing purification systems in all European water treatment plants to filter microplastics. Because microplastics are mainly removed during skimming and settling processes[22], typical wastewater treatment processes used in treatment plants are known to successfully remove most of the microplastics found in the influent.[12] Different treatments of the resulting sludge, however, yield different removal rates. For example, in Ireland it has been demonstrated that anaerobic digestion treatments are far more efficient than thermal drying or lime stabilisation processes.[124] Therefore, sewage sludge treatment processes may influence the risk of contamination, in particular in agricultural soils, as this is often the end use of the produced sludge.

Studies should further explore this in order to obtain sufficient data to support science-based policies for the establishment of specific treatment processes that may more adequately remove microplastics during wastewater treatment. Innovative approaches such as advanced treatments should be contemplated as potential solutions for this issue. Technologies such as disc filters and dissolved air floatation are reported to be highly efficient and membrane bioreactors have been shown to remove up to 99.9% of microplastics found in the primary influent.[125]

These advanced final-stage technologies may substantially reduce the microplastics discharged into the aquatic environment, but associated implementation costs are high. As such, public sector investments in the development of suitable infrastructures and monitoring schemes are suggested, because of the potential great benefits, not only to the environment but, ultimately, to human health.

5. RESEARCH TRENDS IN (POTENTIAL) SOLUTIONS, AND POLICY CONSIDERATIONS

KEY FINDINGS

- Current research is focused on numerous potential alternatives to plastics and solutions regarding their fate.
- No single solution, whether pertaining to alternative materials or treatment processes, can be considered sufficient.
- Future legislative and governance efforts should be conducted with the active participation of all stakeholders, from inception and development to implementation and enforcement.
- Regulatory instruments should be stricter and based on effective "stick and carrot" approaches, i.e. by rewarding those conforming with regulations and severely punishing offenders.

Representing a wide and diverse universe with applications across all segments and strata of society, plastic displays a complex and not fully understood life-cycle that is dependent upon a wide range of variables. The biological, ecological and economic consequences of plastic pollution, however, are undeniable and reducing exposure to plastics will require a considerable number of concurrent actions and strategies. These must include a transition to alternative production materials and solutions, management strategies and policy development and implementation, as discussed in the following paragraphs.

5.1. Proffered solutions

As a response to the concerns raised by the scientific community, but also as a result of the pressure by public campaigns highlighting the pervasiveness and ecotoxicological effects of (micro)plastics in the environment, multiple hypotheses to overcome these issues have been put forth. Yet, when subject to scrutiny - both through thorough life-cycle analyses and in the broader context of the climate, plastic waste and the environment - the proposed strategies appear to hold little promise, because of limited time and resources.

5.1.1. Biodegradable plastics

Heralded as the "magic bullet" that would solve the global plastic problems, biodegradable, bio-based or bioplastics have been described as the most innovative solution(s) to achieve the goal of ending plastic pollution. Yet, firstly it is necessary to ascertain what each of the above terms encompasses as they are frequently used interchangeably. However, they refer to different materials. Visually, this distinction is depicted in Figure 11. As noted, bioplastics can be biodegradable, bio-based or both, and may be categorised accordingly[126].

a) Bio-based or partially bio-based materials, such as PE, PP, or PET. This category also includes technical performance polymers, such as PTT (polytrimethylene terephthalate) or TPC-ET (thermoplastic polyester elastomers), which are non-biodegradable plastics.

b) Simultaneously bio-based and biodegradable plastics. These include PLA (polylactic acid), PHA or PBS (polybutylene succinate), starch and starch blends.

c) Biodegradable fossil-based plastics, such as PBAT (polybutylene adipate terephthalate).

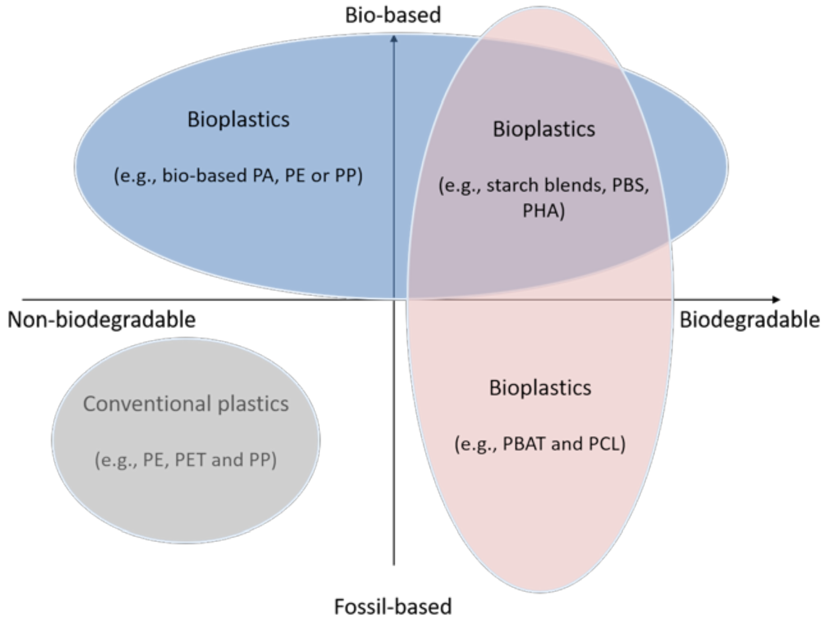


Figure 11: Distribution of polymers according to source materials and degree of biodegradability. Adapted from Paço et al.*, 2019.*[126]

Irrespective of the materials used, these plastics retain some of the issues associated with conventional plastics as many are "biodegradable" only when subjected to specific conditions, namely constant high humidity and high temperatures. Such conditions are rarely attainable in traditional composting facilities and therefore not suitable for home composting. This also means that when littered, these supposedly biodegradable materials do not decompose within reasonable time periods.

Claims of biodegradability should be thoroughly scrutinised. Some materials, previously marketed as "biodegradable", "oxo-degradable" or "oxo-biodegradable", included an oxidising agent that facilitated the disintegration of the material in the presence of oxygen, UV light and heat. However, the end-result was the formation of microscopic plastic fragments. Moreover, by their very design these products start to fragment within a relatively short period of time and thus are not suited for long-term reusable applications. Owing to the presence of the oxidising agent such materials could not be used for composting either, as this could potentially result in a decrease of quality and market value of the compost.[126] In the wake of a report[127], the European Commission has recommended EU-wide measures be taken against these materials.

True bioplastics, such as polyhydroxyalkanoates (PHAs), can actively contribute towards the reduction of pollution caused by the increasing global polymer demand. Multiple bacterial strains - including archaebacteria, Gram positive and Gram negative bacteria and photosynthetic bacteria, such as cyanobacteria - have been described to accumulate PHAs, under aerobic and anaerobic conditions, often with organic waste as material source.[128]

Despite the inherent advantages of using such biodegradable materials, the commercialisation of PHA which has been ongoing since 1980s has met with very limited success. This is because of the high production costs of PHA when compared to its petrochemical-based counterparts. But apart from the cost aspect also other limitations remain.

Bioplastics tend not to generate a net increase in carbon dioxide emissions when breaking down. For example, polylactic acid produces nearly less 70% less greenhouse gases than PET when degrading in landfills. However, despite these benefits, some limitations remain. It is still uncertain whether bioplastics are suitable for food packaging applications and their exact effects once in the environment – if any – are still undetermined. Existing manufacturing chains may require investments, so that they can be adapted to produce bioplastics materials. Also, additional costs may result from the need to invest in modernised equipment for the selection and separation of these new different classes of plastics.

Moreover, there are some ecological benefits resulting from a trade-off that may not be beneficial for the environment.[126] For example, the most widely used bioplastics are starch-based. Starch is easy to obtain, but the production of starch-based plastics requires vast amounts of water and the resulting physical properties, such as tensile strength, are not ideal. This may be overcome by producing co-polymers, frequently by grafting polycaprolactone (PCL). Although PCL is itself a fossil-based polymer (Figure 11), it is susceptible to biodegradation. Although the final starch-PCL blends exhibit improved biodegradability and lower costs, they show reduced crystallinity and thermal stability. Moreover, their malleability greatly increases at temperatures above 40°C, reducing the range of applications.[129]

5.1.2. Biodegrading organisms

From an environmental perspective perhaps the most urgent question is what to do with the vast amounts of plastic already found in the environment. For larger debris, multiple actions exist, including increasing citizen participation in clean-up actions. However, they have proven to be insufficient. Hence, research has focused on the development of biotechnology-based strategies centred on the process of biodegradation.

The development and use of plastic-consuming organisms will however not contribute to a reduction in the significant volume of greenhouse gas emissions that occur throughout the plastic lifecycle.[108] Multiple bacteria and fungi have been reported as potential tools in the biodegradation of plastics, including the bacterial species *Pseudomonas aeruginosa*, *P. stutzeri*, *Streptomyces badius*, *S. setonii*, *Rhodococcus ruber*, *Comamonas acidovorans*, *Clostridium thermocellum* and *Butyrivibrio fibrisolvens*. Fungal strains described as viable biotechnological agents in the bioremediation of plastics include *Aspergillus niger*, *A. flavus*, *Fusarium lini*, *Pycnoporus cinnabarinusand* and *Mucor rouxii*. These organisms have been isolated from diverse environments, including landfills, plastic surfaces buried in soils, marine water or mangrove soil.[130]

Demonstrated within laboratorial settings, it is important to note that the reported efficiency of such biotechnological-based approaches is obtained under optimised conditions for organisms and substrates. This efficiency may be enhanced by, for example, subjecting plastics to different chemical and/or physical pre-treatments. Treatments include photolysis mediated by UV radiation and ozone and thermal treatments, but the effectiveness of the treatments greatly depends on the nature of the polymer.

However, such pre-treatments constitute unlikely steps in potentially large-scale operations, due to associated costs. Not only the costs of the treatments themselves, but also the costs related to the collection and management of the plastic materials to be treated. Consequently, the results achieved should be considered as proof-of-concept. It should also be emphasised that the use of these biodegrading organisms directly into the environment is unlikely or simply unfeasible, given the associated uncertainties and risks, not only for ecosystems, but also for human health.

5.1.3. Energy conversion

Nothing more than a euphemism for incineration, energy recovery, which - extrapolating from the figures shown in Figure 3 accounted for nearly 30 million tons in 2019 - has the potential to significantly increase greenhouse gas emissions, as well as toxic exposures (see Figure 4) for communities near and far from incinerators. As such, these waste-to-energy operations result in a *de facto* transfer of the threats of plastic waste to the atmosphere. This is particularly worrisome from a climate perspective, as emissions of greenhouse gases alone are estimated at approximately 900 kg CO_2 equivalent per metric ton of plastic waste incinerated, roughly 15 times the volume of emissions when this waste is landfilled.[32] Additionally, the process of incineration does not eliminate the presence of microplastics and may very well constitute a source of these materials. In fact, bottom ash from municipal solid waste incinerators have been shown to contain considerable loads of microplastics, reaching up to over 100,000 particles per metric ton of ash.[131] However, it should be noted that multiple parameters and variables may affect the final content of microplastics in ash, including prior source-separation of waste, types of furnace and operation conditions. Nonetheless, the lack of adequacy of incineration as an efficient strategy for addressing the issue of plastic pollution is clear.

5.1.4. Chemical recycling

Chemical recycling of plastics is a process through which the materials are converted into their basic components, leading to the possibility of re-synthesising the same materials. Multiple technologies exist for this purpose, such as thermochemical and catalytic conversion approaches. Generally, these techniques resort to the use of solvents and high temperatures. Broadly speaking, the higher the temperature used, the higher the degree of purity of the recovered monomers.

Chemical recycling is presently considered an attractive technological path towards the reduction of waste and conducive to promoting circular economy. In order to achieve this ambitious goal, it is necessary to explore all available technologies. However, some of these technologies have not yet reached the technological readiness level that allows them to be considered as potential options. This includes technologies such as pyrolysis, catalytic cracking and conventional gasification. Moreover, the economic feasibility of these technologies is difficult to evaluate, given the scarcity of available data and the extremely high energy inputs required. This effectively renders these technologies significantly more costly than traditional methods of producing these materials. Nonetheless, the available technologies should be further assessed as a key part of (a) broader solution(s) for the plastic waste problem. In conjunction with other measures, such as improved plastic design and reducing the use of plastics, effective plastic waste separation will render the feedstocks for these technologies more homogeneous, allowing for a better final product, potentially with reduced costs. In fact, most of the identified problems in chemical recycling closely mirror those of traditional mechanical recycling: accessing quality feedstock, reducing contamination and getting the needed volumes for the process. Hence, the "overall" system challenges of plastic waste treatment remain.

Closely associated, the use of chemically recycled feedstocks from post-consumer plastic manufacturing does not seem feasible. Not only does it fail to address the issues of high energy demands and greenhouse gas emissions[32], it is also unsuited for multiple commonly used plastics, such as PVC. Additionally, the process relies on post-consumer recovery methods, which have already demonstrated to be highly inefficient. Moreover, owing to the low value of the final products, the process is not economically viable, unless subsidised.

5.2. Policy considerations and recommendations

The challenge of plastic waste and its impacts on the environment require urgent attention. As an important element in the EU's Circular Economy Strategy, efforts are needed to identify the key issues where special focus needs to be given. Efforts should be made at different levels and should encompass, where possible, science-based or science-informed solutions. Further research is needed, not only at the level of new materials and technologies to deal with plastic waste but also to expand the already (limited) existing knowledge regarding presence, fate and effects of macro, meso, micro and nanoplastics once in the environment. As such, initiatives should be carried out from a holistic perspective[120], with a view to:

- identifying the underlying drivers of plastic waste;
- fostering stakeholder engagement, which may be ensured by calls for early inputs, policy discussion and awareness campaigns;
- reducing the use of single-use plastics and establishing reduction targets whilst supporting alternatives to retailers;
- devising policies to support the implementation or reusable packaging and to regulate packaging practices throughout the different sectors, with an emphasis on the food supply chain and the cosmetic industry, as well as considering stricter measures to combat single-dose or monodose packaging;
- creating the right for EU customers to return plastic packaging to retailers, thus promoting higher collection efficacies and improved separation for recycling;
- creating clear and concise regulations for the labelling of biodegradable and bio-based plastics, with associated investments in education and dissemination efforts aimed at raising public awareness and education levels;
- fostering activities and actions that stimulate zero-waste or reusable packaging strategies. This may be achieved by harmonising the regulatory framework schemes throughout the EU and promoting the 4R rule: reduction, reuse, repair and recycling. This should be accompanied by severe discouraging penalties for single-use plastics;
- ring-fencing revenues originating from fines and levies for activities associated with zero plastic waste, including awareness programs, financing the recycling industry or supporting specific environmental projects;
- combating the economic preference for the use of virgin polymers by contemplating the application of progressive taxes on these materials, thus reducing the industry's impulses on the unhindered use of plastics in manufacture and packaging;
- concurrently promoting fiscal incentives or tax rebates for manufacturers, suppliers and retailers who develop and implement zero waste transition activities;
- funding and investing in modern infrastructures for the collection, separation and processing of plastic waste, including in rural areas, which are frequently left out of such operations. This should include provisions to disincentivise waste generation or downstream processes (e.g. landfilling as opposite to waste generation);
- establishing local, national, regional and European enforcement and monitoring bodies with clear and defined roles and responsibilities to ensure compliance;
- creating adjustment tools to monitor both progress and effectiveness of the implemented policies and adjusting them where needed.

6. THE PANDEMIC AND PLASTICS – BRIEF COMMENTARY

KEY FINDINGS

- COVID-19 has indelibly changed everyday life, with impacts across all aspects of modern life.
- The pandemic constitutes an unprecedented opportunity to reassess the economy, the climate and the overall quality of life.
- Confinement, as well as the alternating periods of confinement and expansion have led to surges in the generation of plastic waste, with inherent environmental consequences.
- A slowdown in the implementation of policies aimed at regulating plastic waste should not halt them but rather be used to re-evaluate and calibrate them in order to deal with the new (permanent?) reality.

The 2020 COVID-19 pandemic has changed many aspects of daily life and has perhaps forever changed the way we live. The future certainly appears to be less urban and less global.

In 1970, French philosopher Henri Lefebvre predicted that "capitalist" urbanisation processes would become generalised through the establishment of a global web of urbanised spaces.[132] Over the past 40 years, both urbanisation and globalisation have indeed been the most powerful forces driving the world's economy and demographics. World trade increased to over 60% of the global GDP from under 40% in 1980, and, presently, more than half of the world's population (4 billion people) live in cities.

However, it is likely that COVID-19 will reverse these trends, leading to increased distance between people and, consequently, between nations as well. In fact, current efforts developed by numerous nations towards the development of therapies and "hoarding" the largest quantities possible of yet commercially unavailable vaccines, highlight the foreseeable reduced international cooperation as well as the prospects of conflicts.

De-urbanisation and de-globalisation processes will impact economic growth. For instance, cities are considerable scale economies and are incubators of innovation and creativity. Globalisation has resulted in lower production costs, access to new markets, reduction of poverty and increased standards of living.[133] As a consequence, a less global and less urban world will most likely be a less prosperous one. In a post-COVID-19 world, the processes of globalisation and urbanisation will present newer, more complex challenges that should be confronted and managed, not avoided.

The pandemic has also changed the way we think about education. School closures have left over a billion students out of school and - owing to unpreparedness, lack of resources or adequate management - COVID-19 will result in a loss of school time varying between 0.3 and 0.9 years [134] of basic schooling. Inequality and exclusion will also be exacerbated, in particular among ethnic minorities, the disabled, and low-income students. Economically, the world risks losing up to 16% of investments made in education.

It is likely that there will be no return to normality. The global ecosystem upon which modern society has evolved will have to be redesigned. The economy will have to be re-structured and growth will have to be defined as prosperity – not continuous growth. Society as a whole will have to adapt. Until there is a thorough understanding of this reality, governments, propelled by economic and financial pressures may continue to force periods of closure alternated with periods of expansion, while possibly failing to overcome this paralysing disease. Closing and reopening decisions are based on the way the economy is conceived: the constant buying and selling, mostly, of consumer goods. At its core, however, the economy should be based on utilising the needed resources and transforming these into the essential things people need to live. If construed as such, then more opportunities for a different style of living can prosper, where less stuff is used and produced.

However, in the wake of the pandemic and the confinements - voluntary or mandatory - observed all over the globe, the continued need to consume has led to a marked increase in online shopping. As a result, so has packaging plastic waste, especially for healthcare products and in the e-commerce sectors. Comprehensive data on this increase in consumption is as yet unavailable, but initial reports show significant alterations in waste generation dynamics, creating increased uncertainties for policymakers and higher risks to sanitation workers.[119] Multiple types of hazardous medical waste, such as gloves, masks and other personal protective equipment – infected or not – have been generated since the outbreak. This type of waste could potentially contaminate the general municipal solid waste and it carries a risk of transmission. It also caused a steep increase in the generation of waste with the potential of accumulating in the environment in the form of plastics and microplastics, in particular, microfibers stemming from disposable facemasks.[135] Although exact values are not determined, China alone increased its facemask production from January to February to 110 million units, an increase of 450%. Demand for N95 masks grew from about 200,000 to 1.6 M.[136] In Italy alone, the estimated monthly need for PPE for the general public during the deconfinement phase is estimated at 1 billion face masks and 0.5 billion gloves[137]. An extrapolation of these numbers to the entire European population yields an estimated consumption of 7.4 and 3.7 billion units of masks and gloves, respectively, per month.

The fight against COVID-19 has inevitably resulted in significant drawbacks in the development, implementation and enforcement of measures aimed at addressing the widely acknowledged global problem of plastic pollution. The necessary precautionary measures to control transmission of the COVID-19 virus has had an enormous impact on both the plastic industry and waste management, driven by hygiene concerns. For example, Scotland pushed back the implementation date for its deposit return scheme from April 2021 to July 2022 owing to concerns about the possibly insufficient time for businesses to ensure the needed infrastructures would be in place.[138] Similarly, England postponed, for 6 months, the ban on plastic straws and cotton buds.[139]

On the other hand, the European Union has dismissed the industry's calls to lift the ban on single-use plastics and in July a levy on plastic waste to help fund national pandemic recovery efforts was proposed[140]. In France, the increase in improper disposal of personal protective equipment led legislators to consider increased fines for littering[141].

Given the obvious need for disposable protective equipment, it is understandable that some governments have eased the implementation of some bans and regulatory instruments, but these should be considered within the framework in which they were to be implemented. The previously cited case from Scotland, for example, should not be viewed as reasonable within the context in which the return scheme was to be implemented, and the delay has subsequently been fiercely criticised.[138]

Lastly, due to the dramatic decline in land, air and water transportation, the price of petroleum has suffered a marked decrease, which has favoured the manufacture and use of virgin plastics, as opposed to recycled materials. As such, regulations dealing with plastic pollution should focus more intensely on the source of these materials, in particular when they are not intended for the production of necessary materials and equipment to combat COVID-19.

7. CONCLUSIONS

From the previous chapters it is clear that science has yet to establish consistent and reliable baseline data on the presence, fluxes, pathways, fates and effects of plastics in different environmental compartments. Far more attention has been paid to marine pollution, given not only the immediate attention gathered by the directly observable effects the pollution on biota, but also due to the evidenced transboundary and far-reaching presence of plastics. Yet, some estimates suggest that, in particular in the case of microplastics, pollution levels in freshwater systems and soils may exceed those reported in the marine environment. Nonetheless, in spite of these informed conjectures significant speculation and many known unknowns remain. These uncertainties and knowledge gaps greatly undermine a detailed assessment of the health impacts and limit an informed choice by consumers, communities and policy makers. Insufficient and incomplete knowledge also contributes to potentially long-term environmental and health consequences at all stages of the life-cycle of plastic materials. Therefore, it is necessary to draw more intense scientific and policy attention to these environmental compartments, not at the expense of, but in addition to the prevailing marine (micro)plastic pollution research.

The increasing number of regulatory and legislative actions are severely impacted by the lag time between science-gathered data and the translation of the obtained data into meaningful evidence-based strategies and their implementation. Moreover, research and policies are frequently developed within different operating settings characterised by diverse resources, cultures and timeframes. A more proactive interaction and intertwinement of all different stakeholders aiming at the development of such science-based strategies that are not the end-point of linear processes, but rather an important part of a circular approach, is needed.

Whether in the form of taxation, rebates, incentives or bans, policy tools and their implementation are just a part of a wider strategy to combat plastic pollution. In the long term, outreach, awareness and education actions are probably the most effective ways to address the issue of plastic pollution. Including pollution and waste management education in schools could prove to be of great value, as behavioural changes in children are likely to socially influence peers, parents, and, by extension, communities.

Ultimately, however, all the identified (and yet to be identified) problems stemming from the increasing use and presence of plastics in the environment are not only rooted in a single cause, but also have a common solution: the imperative and complete transition from the pervasive disposable plastic habits to a sustainable bio-based economy.

REFERENCES

1. Baztan, J., et al., *Breaking down the plastic age*, in *MICRO 2016*. 2017, Elsevier. p. 177-181.
2. Thompson, R.C., et al., *Our plastic age*. 2009, The Royal Society Publishing.
3. Walker, M., et al., *Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records.* Journal of Quaternary Science: Published for the Quaternary Research Association, 2009. **24**(1): p. 3-17.
4. Zalasiewicz, J., et al., *When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal.* Quaternary International, 2015. **383**: p. 196-203.
5. Grinevald, J., *Anthropocene: conceptual and historical perspectives (The)*. 2011.
6. Vert, M., et al., *Terminology for biorelated polymers and applications (IUPAC Recommendations 2012).* Pure and Applied Chemistry, 2012. **84**(2): p. 377-410.
7. Kricheldorf, H.R., *Handbook of polymer synthesis*. Vol. 24. 1991: CRC Press.
8. PlasticsEurope, *Plastics – the Facts 2019*. 2020, Plastics Europe: Belgium.
9. da Costa, J.P., et al., *(Nano) plastics in the environment–sources, fates and effects.* Science of the Total Environment, 2016. **566**: p. 15-26.
10. Barnes, D.K., et al., *Accumulation and fragmentation of plastic debris in global environments.* Philosophical Transactions of the Royal Society B: Biological Sciences, 2009. **364**(1526): p. 1985-1998.
11. Jambeck, J.R., et al., *Plastic waste inputs from land into the ocean.* Science, 2015. **347**(6223): p. 768-771.
12. da Costa, J., *Microplastics–occurrence, fate and behaviour in the environment. In 'Comprehensive analytical chemistry'.(Eds APT Rocha-Santos, AC Duarte) pp. 1–24*. 2017, Elsevier: Amsterdam.
13. Zhang, Y., et al. *Reduce the plastic debris: a model research on the great Pacific ocean garbage patch*. in *Advanced Materials Research*. 2010. Trans Tech Publ.
14. Zettler, E.R., T.J. Mincer, and L.A. Amaral-Zettler, *Life in the "plastisphere": microbial communities on plastic marine debris.* Environmental science & technology, 2013. **47**(13): p. 7137-7146.
15. Lebreton, L., et al., *Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic.* Scientific reports, 2018. **8**(1): p. 1-15.
16. Ayre, M., *Plastics' poisoning world's seas'.* ed. BBC. London: BBC, 2006.
17. Gouin, T., et al., *Use of micro-plastic beads in cosmetic products in Europe and their estimated emissions to the North Sea environment.* SOFW J, 2015. **141**(4): p. 40-46.
18. Andrady, A.L., *Microplastics in the marine environment.* Marine pollution bulletin, 2011. **62**(8): p. 1596-1605.
19. Da Costa, J.P., et al., *Degradation of polyethylene microplastics in seawater: Insights into the environmental degradation of polymers.* Journal of Environmental Science and Health, Part A, 2018. **53**(9): p. 866-875.
20. Hernandez, E., B. Nowack, and D.M. Mitrano, *Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing.* Environmental science & technology, 2017. **51**(12): p. 7036-7046.
21. Sommer, F., et al., *Tire abrasion as a major source of microplastics in the environment.* Aerosol Air Qual. Res, 2018. **18**(8): p. 2014-2028.
22. Carr, S.A., J. Liu, and A.G. Tesoro, *Transport and fate of microplastic particles in wastewater treatment plants.* Water research, 2016. **91**: p. 174-182.

23. Duis, K. and A. Coors, *Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects.* Environmental Sciences Europe, 2016. **28**(1): p. 2.
24. da Costa, J.P., *Nanoplastics in the Environment*, in *Plastics and the Environment*. 2019, The Royal Society of Chemistry. p. 82-105.
25. Gigault, J., et al., *Current opinion: What is a nanoplastic?* Environmental pollution, 2018. **235**: p. 1030-1034.
26. Commission, E., *Commission recommendation of 18 October 2011 on the definition of nanomaterial.* Off. J. Eur. Union, 2011. **275**: p. 38.
27. Wagner, S., et al., *First steps towards a generic sample preparation scheme for inorganic engineered nanoparticles in a complex matrix for detection, characterization, and quantification by asymmetric flow-field flow fractionation coupled to multi-angle light scattering and ICP-MS.* Journal of Analytical Atomic Spectrometry, 2015. **30**(6): p. 1286-1296.
28. Zhang, H., et al., *Co-release of hexabromocyclododecane (HBCD) and nano-and microparticles from thermal cutting of polystyrene foams.* Environmental science & technology, 2012. **46**(20): p. 10990-10996.
29. Zhan, F., et al., *Release and gas-particle partitioning behaviors of short-chain chlorinated paraffins (SCCPs) during the thermal treatment of polyvinyl chloride flooring.* Environmental Science & Technology, 2017. **51**(16): p. 9005-9012.
30. Stephens, B., et al., *Ultrafine particle emissions from desktop 3D printers.* Atmospheric Environment, 2013. **79**: p. 334-339.
31. Lambert, S. and M. Wagner, *Characterisation of nanoplastics during the degradation of polystyrene.* Chemosphere, 2016. **145**: p. 265-268.
32. Hamilton, L.A., et al., *Plastic & Climate: The Hidden Costs of a Plastic Planet.* Center for International Environmental Law (CIEL), 2019.
33. Silva, B., *Quase metade dos europeus não sabe reciclar. Custam dois mil milhões por ano à economia*, in *ECO*. 2020, Sapo: Lisbon.
34. Geyer, R., J.R. Jambeck, and K.L. Law, *Production, use, and fate of all plastics ever made.* Science advances, 2017. **3**(7): p. e1700782.
35. Blankenship, A., et al., *Toxic combustion by-products from the incineration of chlorinated hydrocarbons and plastics.* Chemosphere, 1994. **28**(1): p. 183-196.
36. Azoulay, D., et al., *Plastic & Health: the hidden costs of a plastic planet*. 2019: CIEL.
37. Bergmann, M., et al., *Vast quantities of microplastics in Arctic Sea Ice—a prime temporary sink for plastic litter and a medium of transport.* MICRO 2016: Fate and Impact of Microplastics in Marine Ecosystems: From the Coastline to the Open Sea, 2016: p. 75.
38. Cincinelli, A., et al., *Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR.* Chemosphere, 2017. **175**: p. 391-400.
39. Cincinelli, A., et al., *A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea.* TrAC Trends in Analytical Chemistry, 2019. **110**: p. 321-326.
40. Woodall, L.C., et al., *The deep sea is a major sink for microplastic debris.* Royal Society open science, 2014. **1**(4): p. 140317.
41. Hurley, R., J. Woodward, and J.J. Rothwell, *Microplastic contamination of river beds significantly reduced by catchment-wide flooding.* Nature Geoscience, 2018. **11**(4): p. 251-257.
42. Zhang, K., et al., *Microplastic pollution of lakeshore sediments from remote lakes in Tibet plateau, China.* Environmental Pollution, 2016. **219**: p. 450-455.
43. Boots, B., C.W. Russell, and D.S. Green, *Effects of microplastics in soil ecosystems: above and below ground.* Environmental science & technology, 2019. **53**(19): p. 11496-11506.

44. Chouchene, K., et al., *Microplastic pollution in the sediments of Sidi Mansour Harbor in Southeast Tunisia.* Marine pollution bulletin, 2019. **146**: p. 92-99.

45. Vianello, A., et al., *Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin.* Scientific reports, 2019. **9**(1): p. 1-11.

46. Liu, K., et al., *Consistent transport of terrestrial microplastics to the ocean through atmosphere.* Environmental science & technology, 2019. **53**(18): p. 10612-10619.

47. Alshehrei, F., *Biodegradation of synthetic and natural plastic by microorganisms.* Journal of Applied & Environmental Microbiology, 2017. **5**(1): p. 8-19.

48. Gewert, B., M.M. Plassmann, and M. MacLeod, *Pathways for degradation of plastic polymers floating in the marine environment.* Environmental Science: Processes & Impacts, 2015. **17**(9): p. 1513-1521.

49. Paluselli, A., et al., *Phthalate release from plastic fragments and degradation in seawater.* Environmental science & technology, 2018. **53**(1): p. 166-175.

50. Lambert, S., C. Sinclair, and A. Boxall, *Occurrence, degradation, and effect of polymer-based materials in the environment*, in *Reviews of Environmental Contamination and Toxicology, Volume 227*. 2014, Springer. p. 1-53.

51. Orhan, Y. and H. Büyükgüngör, *Enhancement of biodegradability of disposable polyethylene in controlled biological soil.* International biodeterioration & biodegradation, 2000. **45**(1-2): p. 49-55.

52. Sadi, R.K., G.J. Fechine, and N.R. Demarquette, *Photodegradation of poly (3-hydroxybutyrate).* Polymer Degradation and Stability, 2010. **95**(12): p. 2318-2327.

53. Gall, S.C. and R.C. Thompson, *The impact of debris on marine life.* Marine pollution bulletin, 2015. **92**(1-2): p. 170-179.

54. Good, T.P., et al., *Derelict fishing nets in Puget Sound and the Northwest Straits: patterns and threats to marine fauna.* Marine Pollution Bulletin, 2010. **60**(1): p. 39-50.

55. Goldstein, M.C., H.S. Carson, and M. Eriksen, *Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities.* Marine Biology, 2014. **161**(6): p. 1441-1453.

56. Winton, D.J., et al., *Macroplastic pollution in freshwater environments: Focusing public and policy action.* Science of the Total Environment, 2020. **704**: p. 135242.

57. Lwanga, E.H., et al., *Field evidence for transfer of plastic debris along a terrestrial food chain.* Scientific Reports, 2017. **7**(1): p. 1-7.

58. Hurley, R., et al., *Plastic waste in the terrestrial environment*, in *Plastic Waste and Recycling*. 2020, Elsevier. p. 163-193.

59. Piehl, S., et al., *Identification and quantification of macro-and microplastics on an agricultural farmland.* Scientific reports, 2018. **8**(1): p. 1-9.

60. He, G., et al., *Plastic mulch: Tradeoffs between productivity and greenhouse gas emissions.* Journal of Cleaner Production, 2018. **172**: p. 1311-1318.

61. Omidi, A., H. Naeemipoor, and M. Hosseini, *Plastic debris in the digestive tract of sheep and goats: An increasing environmental contamination in Birjand, Iran.* Bulletin of environmental contamination and toxicology, 2012. **88**(5): p. 691-694.

62. Koelmans, B., et al., *A scientific perspective on microplastics in nature and society*. 2019: SAPEA.

63. Browne, M.A., et al., *Ingested microscopic plastic translocates to the circulatory system of the mussel, Mytilus edulis (L.).* Environmental science & technology, 2008. **42**(13): p. 5026-5031.

64. Crawford, C. and B. Quinn, *7-The biological impacts and effects of contaminated microplastics.* Microplastic Pollutants; Elsevier: Kidlington, UK, 2017: p. 159-178.

65. Huerta Lwanga, E., et al., *Microplastics in the terrestrial ecosystem: implications for Lumbricus terrestris (Oligochaeta, Lumbricidae)*. Environmental science & technology, 2016. **50**(5): p. 2685-2691.
66. Lwanga, E.H., et al., *Incorporation of microplastics from litter into burrows of Lumbricus terrestris.* Environmental Pollution, 2017. **220**: p. 523-531.
67. da Costa, J.P., A.C. Duarte, and T.A. Rocha-Santos, *Microplastics–occurrence, fate and behaviour in the environment*, in *Comprehensive Analytical Chemistry*. 2017, Elsevier. p. 1-24.
68. Nerland, I.L., et al., *Microplastics in marine environments: Occurrence, distribution and effects.* 2014.
69. Liu, X., et al., *Microplastics as Both a Sink and a Source of Bisphenol A in the Marine Environment.* Environmental Science & Technology, 2019. **53**(17): p. 10188-10196.
70. Rochman, C.M., et al., *Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment.* Science of the Total Environment, 2014. **493**: p. 656-661.
71. Paul-Pont, I., et al., *Exposure of marine mussels Mytilus spp. to polystyrene microplastics: toxicity and influence on fluoranthene bioaccumulation.* Environmental pollution, 2016. **216**: p. 724-737.
72. Wang, J., et al., *Negligible effects of microplastics on animal fitness and HOC bioaccumulation in earthworm Eisenia fetida in soil.* Environmental Pollution, 2019. **249**: p. 776-784.
73. da Costa, J.P., et al., *The Role of Legislation, Regulatory Initiatives and Guidelines on the Control of Plastic Pollution.* Frontiers in Environmental Science, 2020.
74. Pabortsava, K. and R.S. Lampitt, *High concentrations of plastic hidden beneath the surface of the Atlantic Ocean.* Nature Communications, 2020. **11**(1): p. 1-11.
75. Lithner, D., Å. Larsson, and G. Dave, *Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition.* Science of the Total Environment, 2011. **409**(18): p. 3309-3324.
76. Groh, K.J., et al., *Overview of known plastic packaging-associated chemicals and their hazards.* Science of the total environment, 2019. **651**: p. 3253-3268.
77. UN, *United Nations Convention on the Law of the Sea (UNCLOS), Montego Bay, 10 December 1982, in force 16 November 1994.* International Legal Materials, 1982. **21**: p. 1261.
78. Bateman, S., *UNCLOS and its limitations as the foundation for a regional maritime security regime.* The Korean Journal of Defense Analysis, 2007. **19**(3): p. 27-56.
79. Shevealy, S., K. Courtney, and J.E. Parks, *The Honolulu Strategy: a global framework for prevention and management of marine debris.* 2012.
80. IMO, *MARPOL, Annex V - Prevention of Pollution by Garbage from Ships*. 1988, International Maritime Organization.
81. Čampara, L., N. Hasanspahić, and S. Vujičić. *Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines*. in *SHS Web of Conferences*. 2018. EDP Sciences.
82. Crawford, C. and B. Quinn, *Plastic production, waste and legislation.* Microplastic pollutants, 2017. **30**: p. 39-56.
83. Dewey, J.T., *Rethinking MARPOL Enforcement.* Coast Guard Journal of Safety & Security at Sea, Proceedings of the Marine Safety & Security Council, 2018. **75**(1).
84. Jie, H. and H. Jiaxiang, *Can Free Trade Agreements Enhance MARPOL 73/78 Compliance.* Tul. Mar. LJ, 2018. **43**: p. 59.
85. UNEP, *Draft resolution on marine litter and microplastics* 2017: Nairobi.
86. AISE, et al., *Cross Industry Agreement for the prevention of microplastic release into the aquatic environment during the washing of synthetic textiles*. 2017: Belgium.

87. Butler, S., *Ikea commits to phase out single-use plastic products by 2020.* The Guardian, 2018.

88. Cotter, B., *Ethical Problems with Plastic in the Ocean.* 2019.

89. Beament, E., *McDonalds to ban plastic straws in all of its restaurants in UK and Ireland*, in *The Independent*. 2018: London.

90. UN. *United Nations Decade of Ocean Science for Sustainable Development*. 2020 [cited 2020 August 15th]; Available from: https://www.oceandecade.org/.

91. G20, *Annex to G20 Leaders Declaration: G20 Action Plan on Marine Litter*. 2017, Federal Ministry for the Environment, Nature Conservation, Building and …. p. 7.

92. G7. *Statement on the issue of Marine Litter for the G7 Environment Ministers Meeting* 2018 [cited 2020 August 15th]; Available from: https://fslci.org/g7-marine-litter-statement.

93. EU, *Directive 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.* Official Journal of the European Union, 2019. **155**.

94. EU, *Directive 2008/56/EC of the European Parliament and of the Council.* Official Journal of the European Union, 2008.

95. EU, *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy*. 2000: Brussels.

96. EU, *Directive 2000/59/EC of the European Parliament and of the Council of 27 November 2000 on port reception facilities for ship-generated waste and cargo residues*, EU, Editor. 2000: Brussels.

97. ESPO, *Position of the European Sea Ports Organisation on the Commission's proposal on Port Reception Facilities*, ESPO, Editor. 2018: Brussels.

98. EU, *Directive on Port Reception Facilities For The Delivery Of Waste From Ships, Amending Directive 2010/65/EU and repealing Directive 2000/59/EC in PE/85/2018/REV/1*, E. Parliament, Editor. 2019: Strasbourg.

99. Commission, O., *Guideline for monitoring marine litter on the beaches in the OSPAR maritime area.* OSPAR Commission: London, UK, 2010. **84**.

100. Neretin, L., *UNEP Efforts to Combat Marine Litter.* 2018.

101. Ehlers, P., *The Helsinki Convention, 1992 Improving the Baltic Sea Environment.* The International Journal of Marine and Coastal Law, 1993. **8**(2): p. 191-243.

102. HELCOM. *Publications*. 2020 [cited 2020 August 15th]; Available from: https://helcom.fi/helcom-at-work/publications/.

103. Vince, J. and B.D. Hardesty, *Governance solutions to the tragedy of the commons that marine plastics have become.* Frontiers in Marine Science, 2018. **5**: p. 214.

104. Lam, C.-S., et al., *A Comprehensive Analysis of Plastics and Microplastic Legislation Worldwide.* Water, Air, & Soil Pollution, 2018. **229**(11): p. 345.

105. Martinho, G., N. Balaia, and A. Pires, *The Portuguese plastic carrier bag tax: The effects on consumers' behavior.* Waste management, 2017. **61**: p. 3-12.

106. Kandalgaonkar, S. and J. Harchekar, *Ban on Plastic! A Blessing or A Curse.* International Journal of Engineering and Management Research (IJEMR), 2018. **8**(5): p. 77-79.

107. Froidbise, A., *Behind the scenes of the plastic bag ban in rwanda: Connections to culture, power and sustainability.* 2015.

108. Giacovelli, C., *Single-Use Plastics: A Roadmap for Sustainability.* 2018.

109. EU, *Directive (EU) 2015/720 of the European Parliament and of the Council of 29 April 2015 amending Directive 94/62/EC as regards reducing the consumption of lightweight plastic carrier bags.* 2015.

110. Vasilevskaia, D. *Marine Plastic Pollution: Can Law Help?* 2018 [cited 2020 May 15th]; Available from: https://legal-dialogue.org/marine-plastic-pollution-can-law-help.

111. Bergmann, M., L. Gutow, and M. Klages, *Marine anthropogenic litter*. 2015: Springer Nature.

112. Dauvergne, P., *The power of environmental norms: marine plastic pollution and the politics of microbeads.* Environmental Politics, 2018. **27**(4): p. 579-597.

113. Van den Oever, M., et al., *Bio-based and biodegradable plastics: facts and figures: focus on food packaging in the Netherlands*. 2017: Wageningen Food & Biobased Research.

114. Bhattacharya, P., *A review on the impacts of microplastic beads used in cosmetics.* Acta Biomedica Scientia, 2016. **3**(1): p. 47-52.

115. Mastrup, N.S., et al., *Non-Respirable Powdered Diatomaceous Earth Products*. 2018, Google Patents.

116. Adam, I., et al., *Policies to reduce single-use plastic marine pollution in West Africa.* Marine Policy, 2020. **116**: p. 103928.

117. Proulx, M. and S. Shepatin, *Social TV: How Marketers Can Reach and Engage Audiences by Connecting Television to the Web, Social Media, and Mobile*. 2012: Wiley.

118. Kentin, E., *Restricting microplastics in the European Union: Process and criteria under REACH.* The European Physical Journal Plus, 2018. **133**(10): p. 425.

119. Sharma, H.B., et al., *Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic.* Resources, Conservation and Recycling, 2020. **162**: p. 105052.

120. Schweitzer, J., et al., *Unwrapped: How throwaway plastic is failing to solve Europe's food waste problem (and what we need to do instead).* Institute for European Environmental Policy, 2018.

121. KGM. *The amount of K-Cups that have been trashed in landfills could wrap around the planet 10 times.* 2020 [cited 2020 August 10th]; Available from: http://action.storyofstuff.org/sign/amount-k-cups-have-been-thrown-landfills-could-wrap-around-planet-over-11-times.

122. Huygens, D., et al., *Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009).* FeHPO CaHPO, 2019. **4**.

123. Weithmann, N., et al., *Organic fertilizer as a vehicle for the entry of microplastic into the environment.* Science Advances, 2018. **4**(4): p. eaap8060.

124. Mahon, A.M., et al., *Microplastics in Sewage Sludge: Effects of Treatment.* Environmental Science & Technology, 2017. **51**(2): p. 810-818.

125. Talvitie, J., et al., *Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies.* Water Research, 2017. **123**: p. 401-407.

126. Paço, A., et al., *Biotechnological tools for the effective management of plastics in the environment.* Critical Reviews in Environmental Science and Technology, 2019. **49**(5): p. 410-441.

127. EU, *Report from the Commission to the European Parliament and the Council on the impact of the use of oxo-degradable plastic, including oxo-degradable plastic carrier bags, on the environment*. 2018, Geraadpleegd van [https://ec. europa. eu/environment/circular-economy/pdf.](https://ec.europa.eu/environment/circular-economy/pdf)

128. Pratt, S., et al., *Polyhydroxyalkanoate (PHA) bioplastics from organic waste*, in *Biorefinery*. 2019, Springer. p. 615-638.

129. Niranjana Prabhu, T. and K. Prashantha, *A review on present status and future challenges of starch based polymer films and their composites in food packaging applications.* Polymer Composites, 2018. **39**(7): p. 2499-2522.

130. Pathak, V.M., *Review on the current status of polymer degradation: a microbial approach.* Bioresources and Bioprocessing, 2017. **4**(1): p. 15.

131. Yang, Z., et al., *Is incineration the terminator of plastics and microplastics?* Journal of Hazardous Materials, 2021. **401**: p. 123429.

132. Lefebvre, H., *The Urban Revolution*. 2003: University of Minnesota Press.

133. Garret, G. *The post-COVID-19 world could be less global and less urban*. 2020 [cited 2020 August 25]; Available from: https://www.weforum.org/agenda/2020/05/coronavirus-covid19-urbanization-globalization-change/.

134. Azevedo, J.P.A.H., Amer%A Goldemberg, Diana%A Iqbal, Syedah Aroob%A Geven, Koen, *Simulating the Potential Impacts of COVID-19 School Closures on Schooling and Learning Outcomes: A Set of Global Estimates*. Simulating the Potential Impacts of COVID-19 School Closures on Schooling and Learning Outcomes: A Set of Global Estimates.

135. Fadare, O.O. and E.D. Okoffo, *Covid-19 face masks: A potential source of microplastic fibers in the environment.* The Science of the total environment, 2020. **737**: p. 140279-140279.

136. Bown, C.P., *COVID-19: China's exports of medical supplies provide a ray of hope.* PIIE Trade and Investment Policy Watch, March, 2020. **26**.

137. WWF. *Nello smaltimento di mascherine e guanti serve responsabilità*. 2020 [cited 2020 August 25th]; Available from: https://www.wwf.it/scuole/?53500%2FNello-smaltimento-di-mascherine-e-guanti-serve-294.

138. BBC. *Coronavirus: Deposit return scheme delayed until July 2022*. BBC 2020; Available from: https://www.bbc.com/news/uk-scotland-scotland-politics-51920357.

139. O'Connor, K., *Covid-19 pandemic delays plastic straw and cotton bud ban by six months*, in *Evening Standard*. 2020: London.

140. Simon, F., *EU dismisses industry calls to lift ban on single-use plastics*, in *EURACTIV*. 2020, EURACTIV: Brussels.

141. Tidman, Z., *France 'looks to increase fines for littering' amid coronavirus waste*, in *The Independent*. 2020: UK.

ANNEX I - PETITIONS ANALYSED WITHIN THE SCOPE OF THIS STUDY

Petition Number

2350/2013

Petition Status

Closed

Petition Summary Title

Petition 2350/2013, by Oliver Steiner (German), on microplastics in cosmetics, body-care products and clothing

Petitioner

European Parliament

Creation date

28-09-2013

Number of supporters

1

Petition summary

According to the petitioner, cosmetics, body-care products and clothing (fleece) contain microplastics in the form of fibres or plastic beads. After a single use, these enter waste water and eventually seawater. Waste water purification plants are unable to filter the microplastics out of the water. Microplastic is harmful and pollutes seas and oceans throughout the world. The plastic particles are ingested by marine animals with their food. Harmful substances, such as bisphenol A, carcinogens and chemicals such as DDT or PCBs, are released from these plastics in the digestive system of these animals. These substances eventually also enter the human body via the food chain. The petitioner calls for a ban on microplastics in cosmetics, body-care products and clothing and measures to encourage the development of water purification plants that are able to filter microplastics out of the water.

EN

Petition Number

0910/2014

Petition Status

Closed

Petition Summary Title

Petition No 0910/2014 by Thomas Gommel (German) on a ban on aluminium capsules for coffee

Petitioner

European Parliament

Creation date

14-04-2014

Number of supporters

Petition summary

The petitioner is asking for a ban on the use of aluminium in coffee capsules. He is requesting this ban, on the basis of an article in 'Die Welt' newspaper, due to the amount of waste involved in using this material and the environmental alternatives that exist.

EN

Petition Number	Petition Status
2553/2014	Available to supporters

Petition Summary Title

Petition No 2553/2014 by Ludwig Bühlmeier (German) on microplastics and nanoparticles

Petitioner

European Parliament

Creation date	Number of supporters
03-12-2014	9

Petition summary

The petitioner calls for an EU-wide ban on microplastics and nanoparticles. Microplastics can be found in the environment and in water and are even absorbed by plants. The petitioner says they are carcinogenic. Nanoparticles are so small that they penetrate cells effortlessly and can damage them, causing cancer. Because the precautionary principle applies in the EU, the petitioner urges a ban on these small particles as soon as possible.

EN

Petition Number

0663/2015

Petition Status

Available to supporters

Petition Summary Title

Petition No 0663/2015 by Oliver Steiner (German) on a procedure for establishing a purification system in all European water treatment plants to filter microplastics

Petitioner

Oliver Steiner

Creation date

26-06-2015

Number of supporters

8

Petition summary

The petitioner stresses the harmful nature of microplastics. Microplastics can be found in cosmetic products and care products, as well as in fibres in clothing. They escape into water and thus find their way into the food chain, affecting both animals and humans. The petitioner states that washing machine filters and the filters of most treatment plants are unable to filter microplastics out of the water. He calls on the European Parliament to issue a regulation to equip all common European treatment plants with filters which can ensure that the fourth water treatment stage of water purification is attained. He asks that a financial support system be established to support this initiative.

EN

Petition Number	Petition Status
0793/2015	Available to supporters

Petition Summary Title

Petition No 0793/2015 by Oliver Steiner (German) on the prohibition of microplastics in cosmetics, toiletries and clothing products

Petitioner

European Parliament

Creation date	Number of supporters
27-07-2015	18

Petition summary

The petitioner calls for a ban on microplastics in cosmetics, personal hygiene products and clothing and State funding of special filters for these microplastics in sewage treatment plants. These microplastics contribute to marine pollution and harm animals and humans through the chemicals absorbed from food, because after washing fleece-type clothes, these small pieces of plastic pass with domestic waste water to sewage processing plants where they are not filtered and pollute the seas and oceans. There they are ingested by fish and birds and end up in the human body.

EN

Petition Number

0741/2017

Petition Status

Closed

Petition Summary Title

Petition No 0741/2017 by E.D. (German) on waste management and imposing a ban on the use plastic packaging for organic fruit and vegetable produce

Petitioner

E P

Creation date

31-07-2017

Number of supporters

Petition summary

The petitioner notes that plastic packaging of organic fruit and vegetables is not always necessary and in fact is used to further increased sales. The petitioner believes that minimising the use of plastics is an important factor in tackling climate change and better water quality conditions.

EN

Petition Number

1120/2017

Petition Status

Closed

Petition Summary Title

Petition No 1120/2017 by Belarimino Teixeira (Portuguese) on forbidding non-biodegradable plastics in the food industry

Petitioner

Belarmino Teixeira

Creation date

27-11-2017

Number of supporters

Petition summary

The petitioner calls for the creation of the European legislation forbidding the use of non-biodegradable plastics in the food industry like plastic cups, plates, straws and cutlery for single use that don't follow the stream of recycling.

EN

Petition Number

0874/2018

Petition Status

Available to supporters

Petition Summary Title

Petition No 0874/2018 by Patricio Oschlies Serrano (Spanish) on marine pollution

Petitioner

Patricio Oschlies Serrano

Creation date

24-09-2018

Number of supporters

8

Petition summary

The petitioner denounces marine pollution, particularly by plastics. He asks that Member States join a campaign to clean-up coastal areas, run public awareness campaigns and that EU funding is provided to tackle the accumulation of plastics in the oceans.

EN

Petition Number	Petition Status
0587/2018	Available to supporters

Petition Summary Title

Petition No 0587/2018 by Maria del Pilar Barriendos Clavero (Spanish) on the contaminating effects of plastic

Petitioner

Maria Pilar Barriendos Clavero

Creation date	Number of supporters
24-06-2018	24

Petition summary

The petitioner complains of the indiscriminate use of plastics that pollute the environment. She complains that they harm the ecosystem, marine biology, tourism and health. She requests the withdrawal of plastics that contaminate the urban and rural landscape.

EN

Petition Number	Petition Status
0874/2018	Available to supporters

Petition Summary Title

Petition No 0874/2018 by Patricio Oschlies Serrano (Spanish) on marine pollution

Petitioner

Patricio Oschlies Serrano

Creation date	Number of supporters
24-09-2018	8

Petition summary

The petitioner denounces marine pollution, particularly by plastics. He asks that Member States join a campaign to clean-up coastal areas, run public awareness campaigns and that EU funding is provided to tackle the accumulation of plastics in the oceans.

EN

Petition Number

1013/2019

Petition Status

Available to supporters

Petition Summary Title

Petition No 1013/2019 by W.T. (German), on behalf of the association Bewegung Bewusster Friseure international e.V., on healthy and environmentally sound cosmetics

Petitioner

B W

Creation date

24-10-2019

Number of supporters

11

Petition summary

The petitioner believes that thousands of cosmetic and care products with chemical/synthetic ingredients, which can be harmful to health and/or the environment, are partly responsible for the degradation of the world's habitats and for destroying water, air and soil, which are vital to life. He calls for a legislative and fiscal framework at EU level which favours a more environmentally friendly approach and which so far as possible restricts or prohibits the use of substances that have been proven to be harmful to the environment. The ban on animal testing for cosmetics must be respected without exception and become effective worldwide. The petitioner calls, inter alia, for the introduction of a uniform EU-wide label for natural cosmetics. Environmental pollution should be made more expensive, and respect for the environment should be promoted. The petitioner welcomes the European Parliament resolution of May 2018 on a global ban on animal testing for cosmetics. However, legal loopholes should be closed. The petitioner refers to various harmful ingredients, including aluminium salts, oil, microplastics and nanoparticles.

EN

This study, commissioned by the European Parliament's Policy Department for Citizens' Rights and Constitutional Affairs at the request of the Committee on Petitions (PETI), focuses on the pervasive use of plastics and reviews the rising consensus on the potential eco-toxicological impacts of these materials, in particular of smaller plastic particles, dubbed microplastics. It discusses possible mitigation strategies aimed at curtailing the prevalence of (micro)plastics, as well as emerging alternatives and their environmental adequacy.

Propelled by increasing awareness of the impacts of plastics and by public opinion, in recent years a multitude of norms, regulations, laws and recommendations have been proposed and/or implemented. These vary greatly across local, national, regional and international levels, and it is not clear what the beneficial impacts of these tools are. This study assesses these existing instruments, analyses whether they are based on sound scientific data, and discusses foreseeable challenges that could restrain the relevance and suitability of existing and future legislative proposals.

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