Plastics :
Poison most handy

March 2024 (English version)

ALLIANCE
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INTRODUCTION

by Christophe Prazuck

We are dependent on plastics.

Because they are light, strong, inexpensive, versatile and highly competitive, their industrial and commercial success over the last 60 years has been phenomenal. This success has been accompanied by an inordinate amount of production, which is itself often instantly transformed into waste, accumulated, sometimes recycled, sometimes incinerated, but above all buried underground, drained, beached, immersed in all the world's oceans and abysses, then fragmented to sizes so small that these particles find their way to the heart of living organisms, from the most microscopic plankton to those who feed on them, molluscs, fish, humans, disrupting their development and functioning.

The United Nations Environment Program (UNEP) estimates that the mass of plastic waste dumped into aquatic ecosystems each year could rise from 9-14 million tons in 2016 to 27-37 million tons in 2040.

All this already has a considerable cost in terms of human health, ecosystem health, water and soil quality. An ethical cost, of course, and more prosaically, a financial cost that runs into hundreds of billions of euros every year.

In March 2022, the United Nations opened international negotiations on plastic pollution. These negotiations must be informed by science, or rather by the sciences, and the multiple disciplines that contribute to understanding this unprecedented crisis, its impacts and the means to resolve it.

The Sorbonne University Alliance – i.e. Sorbonne University, the National Museum for Natural History and Compiègne University of Technology - is contributing to this vital international effort, thanks to the talents of its researchers and the immense variety of their skills. It is the first French university accredited by UNEP to take part in international negotiations.

Its Ocean Institut leads the Alliance's Plastics Group, within which some forty researchers share their questions and research findings. They are chemists, agronomists, microbiologists, virologists, ecotoxicologists, neuroendocrinologists, ecologists, oceanographers, marine biologists, etc. Only such a wide range of skills makes it possible to approach a crisis of universal scope such as plastic pollution.

They have written the twenty factsheets in this collection, driven by a concern for pedagogy and the imperative of rigor. Pedagogy, with a succinct form, free of technical vocabulary. Scientific rigor, with references at the bottom of each page to the best and most recent publications on each of the subjects covered.

Let every reader, armed with the facts and arguments he or she has found in this compendium, contribute to the development of remedies that will save us from the dangers of that handy poison, plastic.

A FEW FACTS ABOUT PLASTICS

Since 1950, we have produced **8.3 billion tons of plastic**, with 460 millions produced in 2023.

The plastics industry employs over **1.5 million people** directly in 52,000 companies.

16,000 chemical compounds are used in the manufacture of plastics.

5,300 polymer formulations are commercially available, and over 4,000 known substances are associated with plastic packaging alone.

60 to 80% of plastics production has become waste, 50% of this production was used only once before being thrown away (single-use plastic), 9% was recycled, 12% was incinerated.

In 1950, every human being produced 800 grams of plastic waste per year, compared with 52 kg today. 70 kg for each French person.

80% of plastic pollution comes from land-based sources (uncontrolled dumping, agricultural activities, etc.), 20% from sea-based sources (fishing, transport, pleasure boating, extractive industry).

Nearly **11 million tons of plastic are dumped into the oceans every year** - that's one dump truck every minute.

It is estimated that there are between **75 and 199 million tons of plastic in the oceans**.

Biodegradable or bio-sourced plastics account for **1% of plastics production**.

Microplastics are smaller than **5 millimeters.** Nanoplastics are smaller than 1 micrometer (one thousandth of a millimeter).

Machine-washing one kilogram of synthetic clothing can release between **640,000 and 1,500,000 plastic microfibers.**

In the most polluted areas of the Mediterranean sea, there are as many microplastic particles as zooplankton.

The most polluted soils contain several hundred kilograms of microplastics per hectare.

CHAPTER 1:

FROM EVERYDAY USE TO DISSEMINATION

Sheet 1: Plastics and microplastics in everyday life items

by Jean-Baptiste Fini, Valentin Dettling, Claire Laguionie, Sarah Samadi

Plastics are everywhere in many forms

© Pour la science

Since the 1950s, plastic compounds have infiltrated both our professional and private spheres, becoming an integral part of our daily lives. In this era, dubbed the 'Plasticene' by some, the plastic revolution, driven by its inherent hygiene properties, has transformed our consumption habits. However, this convenience comes at a cost: more than half of the plastic compounds we use have a lifespan of less than three years.

More than 5,300 polymer formulations are available commercially, and over 4,000 known substances are associated with plastic packaging alone. The major polymers underlying bottles, clothing, furniture, electronic components, household appliances, materials in contact with food, cosmetics packaging, toys, tires, masks, etc., are polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), polypropylene (PP), polycarbonates (PC), polyurethanes (PU), and new plastics based on lactic acid (PLA, PCL, PHA, PLGA, etc.) (see Diversity of Plastic Chemistry). Plastic compounds are theoretically classified according to the type of polymer used in their manufacture. There are seven families identified by a number (the last category No. 7, encompasses a wide variety of polymers) indicating recycling processes.

Synthetic fibers

During the single year of 2015, between 5 and 14 million tons of plastic waste were estimated to have reached the sea. Indeed, whether on land or at sea, these wastes do not decompose on a human life scale. Whether ingested or not, they gradually fragment into microplastics, or even nanoplastics. Depending on the properties of synthetic textiles, machine washing one kilogram of synthetic clothing can release between 640,000 and 1,500,000 plastic microfibers[1]. The majority of these microfibers are small enough to pass through wastewater treatment plant filters. This implies that water used for agriculture contains microplastics that can end up in food, such as sunflower seeds used for oil, which is partly packaged in plastic bottles. Thus, we ingest both these particles and the substances associated with the plastic of the bottle that have diffused into the oil. The health and environmental consequences are the subject of growing investigations.

Food

For food containers, over 1,200 scientific studies clearly demonstrate the migration of several molecules from plastic materials in contact with food. This migration is increased by temperature, storage duration, and depends on the chemical composition of the contacting article. For food, the thickness of the layer in contact with food and the size of the packaging are also aggravating parameters, with migration proportionally higher in small packages due to increased surface-to-volume ratio. In a 2022 study, Jane Muncke's team showed that a majority of products migrating into foods came from plastic containers[2]. Plastic bottles, plastic-coated cardboard cups, or reusable bottles are also sources of contamination, with over 400 plastic compounds found in water after washing

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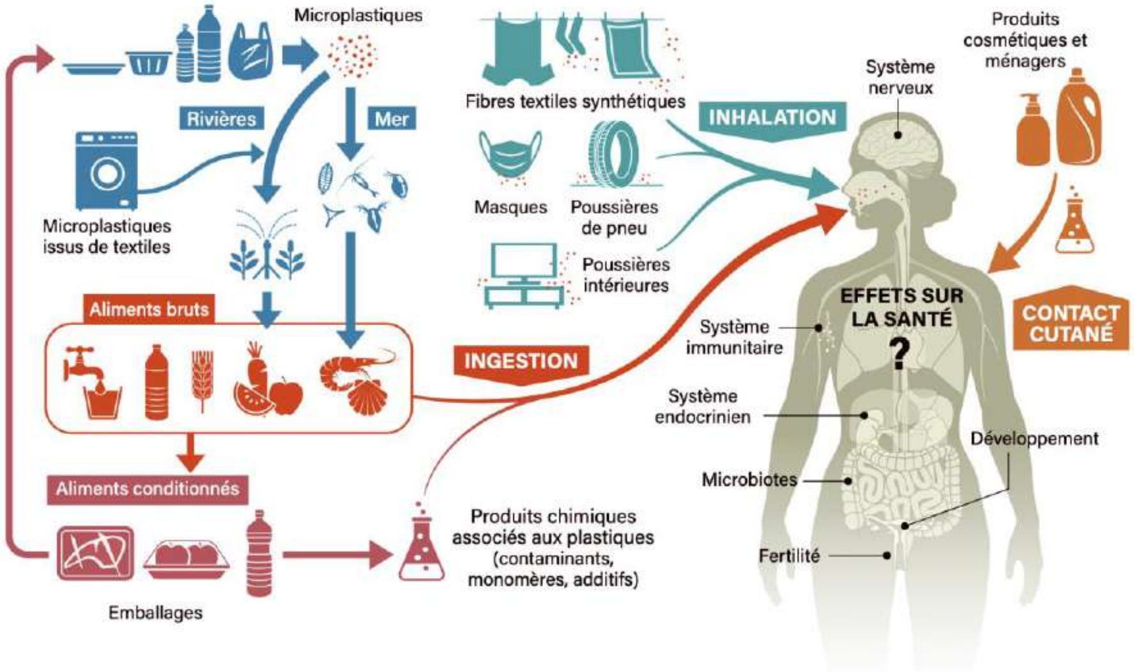
[1] De Falco et al. 2019. First Investigation of Microfibre Release from the Washing of Laminated Fabrics for Outdoor Apparel. In: *International Conference on Microplastic Pollution in the Mediterranean Sea*(pp. 277-281). Cham: Springer International Publishing.

[2] Geueke et al 2022. Systematic evidence on migrating and extractable food contact chemicals: most chemicals detected in food contact materials are not listed for use. *Crit. Rev. Food Sci. Nutr.* 2022, 63 (28), 9425–9435. https://doi.org/10.108 0/10408398.2022.2067828.

reusable bottles[3], and up to several thousand microplastics detected in plastic-coated or plastic cups[4]. Finally, items like tea bags, which appear to be paper, can be a source of several thousand microplastics[5].



©Bruno Bourgeois published in "La pollution invisible des plastiques", JB-Fini, *Pour la Science* n° 524, june 2021

There is ample documentation on the presence of microplastics in what we ingest. Ranges varying from a few milligrams per day to 5 grams per week (the latter figure widely publicized but largely overestimated) are explained by a variety of methods to isolate, quantify, and analyze these particles in various types of food or water[6]. Although the exact estimate is complex, the ingestion of plastic particles or additives through our everyday objects is undeniable. To limit our exposure, a reduction in production (see Normative, Ethical, and Economic Challenges of Our Societies Facing Plastic Production) as well as the use of new methodologies to assess the health impact on organisms should be implemented. Plastics containing numerous molecules potentially disruptive to hormonal systems (see Impacts of Plasticizers on the Environment and Health) necessitate an approach to evaluating health and environmental risks based on danger (as is the case with endocrine disruptors) rather than risk (which is a general approach taking into account exposure).

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[3] Tisler & Christensen 2022. Non-target screening for the identification of migrating compounds from reusable plastic bottles into drinking water. *Journal of Hazardous Materials*, *429*, p.128331

[4] Chen H, Xu L, Yu K, Wei F, Zhang M. Release of microplastics from disposable cups in daily use. *Sci Total Environ.* 2023 Jan 1;854:158606. doi: 10.1016/j.scitotenv.2022.158606. Epub 2022 Sep 9. PMID: 36089043.

[5] Mei T, Wang J, Xiao X, Lv J, Li Q, Dai H, Liu X, Pi F. Identification and Evaluation of Microplastics from Tea Filter Bags Based on Raman Imaging. *Foods*. 2022 Sep 16;11(18):2871. doi: 10.3390/foods11182871. PMID: 36140997; PMCID: PMC9497986.

[6] Barceló D, Picó Y, Alfarhan AH. Microplastics: Detection in human samples, cell line studies, and health impacts. *Environ Toxicol Pharmacol.* 2023 Aug;101:104204. doi: 10.1016/j.etap.2023.104204. Epub 2023 Jun 28. PMID: 37391049

Sheet 2: Dynamics of contamination sources

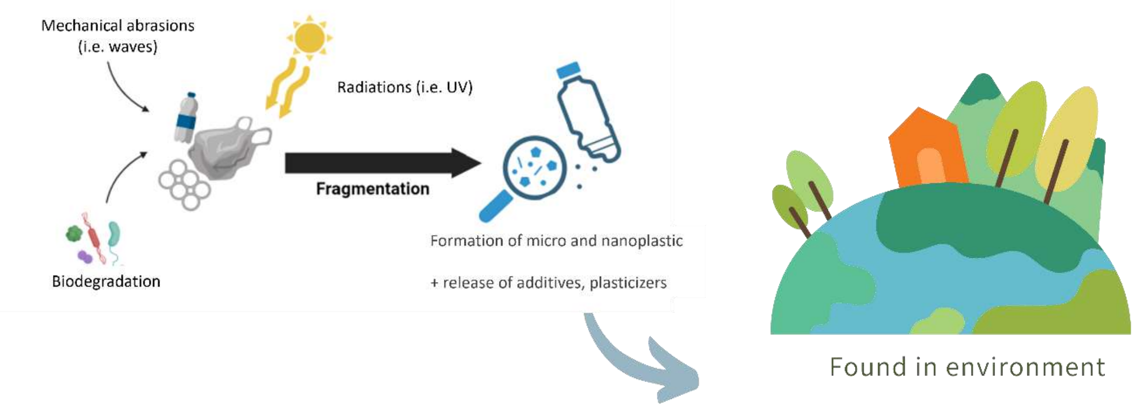
by David Siaussat

Originally designed as resistant and long-lasting materials, plastics were quickly and widely used for single uses of very short duration leading to the annual production of a very large quantity of plastic waste. They contain numerous chemical compounds (16,000 are used in their manufacture), many of which are toxic to humans or the environment (see Is plastic toxic? and Impacts of plasticizers on the environment and health) and few are regulated (see The normative, ethical and economic challenges of our societies facing plastic production).

Alarming figures on household plastic waste

All countries in the world produce or consume large quantities of plastics, which leads to the production of as much waste (between 60 and 80% of the quantity produced). The figures fluctuate between millions and billions of tonnes of waste per year, including 353 million tonnes of plastic waste in 2019. A study[7] showed the progression between 1950 and 2015 of this quantity: 0.8 kg of plastic waste per inhabitant in 1950 compared to 52 kg in 2015.

Waste that undergoes transformation



© David Siaussat

One of the major problems is that a lot of this plastic waste, in particular single-use plastics and those used for food packaging, is poorly managed (see Waste treatment) and ends up in nature (see Plastic pollution, from rivers to the sea) producing macro-waste which will undergo degradation. This degradation of plastics in nature is dependent on:

- environmental conditions : physical parameters such as frost or mechanical movements (wind, waves) inducing fragmentation or wear of material, chemical parameters such as the action of ultraviolet rays, oxygen and water
- biological factors: microorganisms which can deteriorate plastics by forming a biofilm on the surface of the plastic or fragment them by releasing enzymes, which will transform the plastic polymers into smaller molecules (see The plastisphere).

The degradation of plastics results in their fragmentation into particles of increasingly smaller dimensions: plastic waste => plastic macro-waste => microplastics (< 5 mm) => nanoplastics (< 1 µm). At each stage, there may also be a release of additives and various chemical substances added to the plastic polymer to give it particular properties (hardness, elasticity, etc.) (see Diversity of plastic chemistry).

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[7] Geyer et al., 2017. Production, use, and fate of all plastics ever made. Science Advances, 3(7).

Note: Some of these microplastics, so-called primary microplastics, are intentionally manufactured for different uses (cosmetic scrub particles or detergents for example) while secondary microplastics come from accidental fragmentation in the environment (wear of tires, textiles, synthetic lawns, paints, etc.).

The lifespan of plastics in the environment

The degradation kinetics depends on the chemical nature of the polymer and external factors linked to the environment in which it is found. Thus, the same polyethylene will degrade differently depending on the conditions of its environment and the microorganisms that surround it. Data on the aging of plastics is quite difficult to obtain and estimates vary depending on the study, from a few years to several tens of thousands. However, there is scientific consensus on the persistence of polymers in the environment.

Different sources around the globe

Due to the massive use of plastics in everyday life (see Plastics and microplastics in everyday objects), leaks can appear throughout their existence. These leaks are the cause of the presence of plastics, in different forms, throughout the environment. Human activities on land play a major role in the origin of this pollution. Daily, in our various professional or personal activities, as part of our leisure and consumption, we use plastics that are likely to contribute to plastic pollution. It is estimated that around 80% of this pollution is of land origin (see Plastic in soil).

20% of plastic pollution is due to maritime sources. Four sectors are particularly impactful: fishing and aquaculture activities (nets and plastic equipment for example); maritime transport (antifouling paint, loss at sea of containers containing industrial plastic granules, etc.); recreational activities (waste, discharge, etc.); mining and petroleum exploration and exploitation.

Transfer dynamics between compartments and accumulation zones

Plastic pollution is a dynamic process which is due to:

- losses or leaks of plastics over their entire existence, from their production to their use and treatment as waste;
- the transfer of plastics into the environment through wastewater or rainwater networks, air and wind, rain and snow, rivers and sea currents;
- the arrival and accumulation of plastics in one of the four environmental compartments: fresh water, soil, air and seas/oceans.

Plastic pollution can therefore be indirect and come from a transfer pathway or direct due to a local event.

Sheet 3: Plastic pollution along the river-to-sea continuum

by Jean-François Ghiglione

Rivers of plastics flowing into the sea

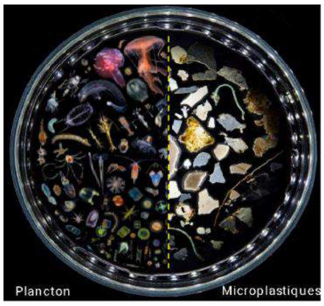

© Esmeralda Labye, RTB

More than 11 million tons of plastic enter the oceans each year, the estimated equivalent of one dump truck per minute. 80% of plastics come from the continent, carried by rivers. The most polluted rivers are located in Asia. **There are between 75 and 199 million tons of plastic currently in the oceans**[8].

Microplastics, a time bomb

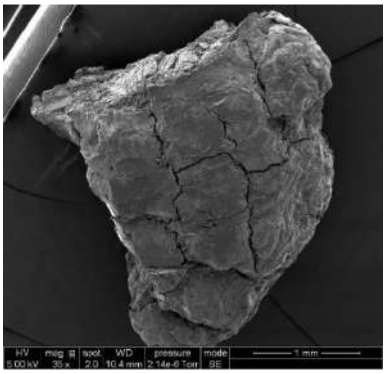
Plastics found in the environment are mainly (in number) **in the form of microplastics**, which are impossible to clean. They are either in the form of granules from plastic producers (primary microplastics), or they come from the waste fragmentation under the effect of abrasion and ultraviolet (secondary microplastics).

More than 90% of the pieces of plastic found in rivers are already in the form of microplastics. **In the Mediterranean Sea, we sometimes find as many microplastics as zooplankton, which the fish we eat feed on**[9].



© Christian Sardet et Jean-François Ghiglione

Fragmentation down to nanoplastics



© Alexandra ter Halle

Most studies focused their attention on microplastics visible to the naked eye (5 to 0.5 mm), which mainly float on the surface. But the smallest microplastics (0.5 mm to 1 µm) are distributed throughout the water column; they are 100 times more numerous and they represent the same mass. In the environment, they will continue to fragment into **nanoplastics (<1 µm), which are capable of passing through the barriers of organs and cells.** Quantifying nanoplastics in the environment is a new challenge for scientists[10] (see Methods for quantifying micro- and nanoplastics).

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[8] UNEP 2021. From pollution to solution: a global assessment of marine litter and plastic pollution. https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution

[9] Pedrotti et al., 2022. An integrative assessment of the plastic debris load in the Mediterranean Sea. Science of the Total Environment, 838, 155958. https://doi.org/10.1016/j.scitotenv.2022.155958

[10] Poulain et al., 2018. Small microplastics as a main contributor to plastic mass balance in the North Atlantic subtropical gyre. Environmental science & technology. https://doi.org/10.1021/acs.est.8b05458

CHAPTER 2:

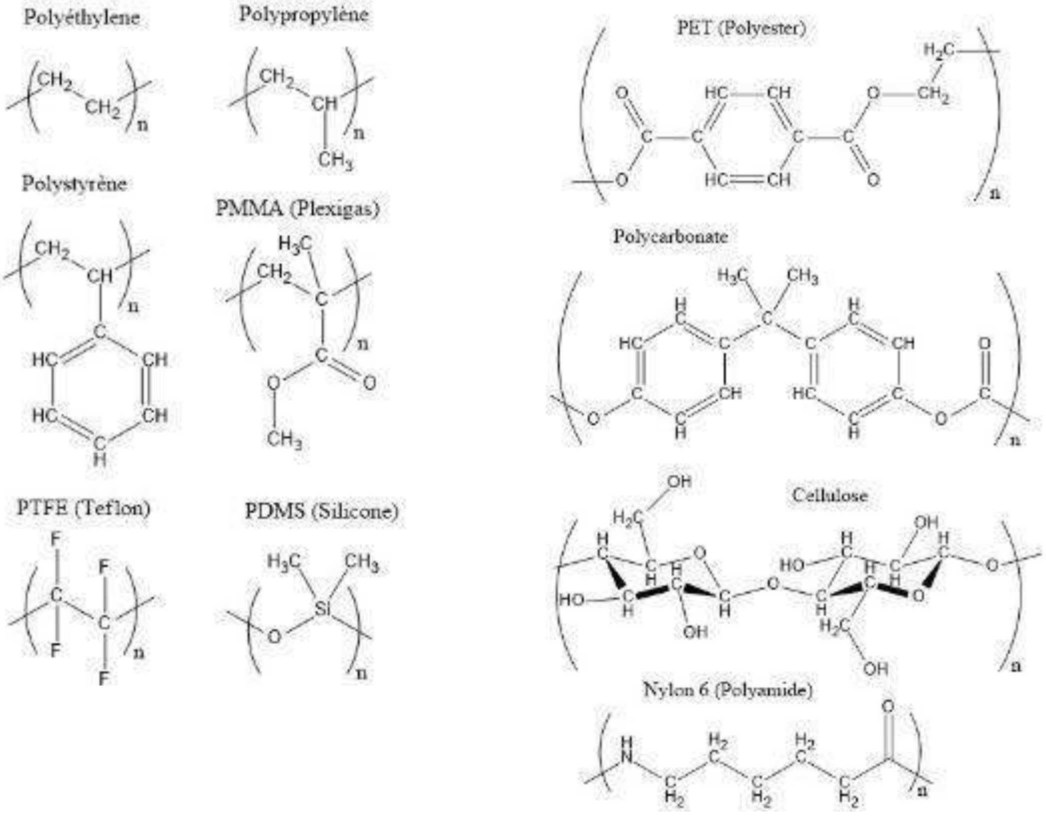
PLASTICS: CHEMISTRY AND LIFE CYCLE

Sheet 4: The diversity of plastics’ chemistry and Non Intentionally Added Substances (NIAS)

by Patrice Castignolles, Philippe Guégan

The diversity of plastics’ chemistry : polymers

Plastic materials are made up of polymers, fillers and different additives. Polymers correspond to an assembly of very large molecules: macromolecules. The polymer in a plastic is typically formed by thousands or even millions of different macromolecules[11]. The macromolecules in a polymer tend to contain the same atoms but in variable numbers, arranged differently (isomers, branches).
Some polymers contain only carbon and hydrogen atoms (polyethylene, polystyrene, polypropylene), which are the basis of organic matter. Other polymers also contain atoms of oxygen (plexiglass, polycarbonate, polyester, cellulose), nitrogen (nylon), chlorine (PVC), fluorine (Teflon), or even silicon instead of carbon (silicones).



The diversity of plastics’ chemistry: additives and fillers

Plastics are not made up only of polymers (PE, PS, PP, etc.), they also contain other chemical compounds called additives and fillers, which are added during their manufacture for different reasons:

- aesthetic: color
- durability: antioxidant, anti-UV
- safety: anti-static, flame retardant
- improvement of processing: lubricants, anti-shrinkage agents, plasticizers
- improvement of mechanical properties (flexibility, hardness, etc.): plasticizers

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[11] Fontanille et al. 2021. Chimie et physico-chimie des polymères. 594 pages. ISBN : 9782100819478. URL : https://www.cairn-sciences.info/chimie-et-physico-chimie-des-polymeres--9782100819478.htm

The purpose of the fillers is to strengthen the material, or reduce its cost. The fillers or additives can be minerals containing a wide variety of atoms such as calcium, potassium, silicon, aluminum. They can represent from 0% to the majority (90%) of the plastic material. They are not chemically covalently bonded to polymer chains. The additives can also be small molecules that are more or less miscible with the polymer. An additive typically contains only a few different molecules. On the other hand, the different additives (more than 16,000 different ones are used, see Plastics and microplastics in everyday life items) have greater chemical diversity than polymers, with atoms of fluorine, bromine, phosphorus, metals. A quarter of additives used in plastics are of concern for human health and the environment (see Impacts of plasticizers on environment and health).

Polymer synthesis and NIAS

Polymers are natural, artificial or synthetic. Natural polymers come from the plant or animal world, for example cellulose used to produce the plastic cellophane. Artificial polymers are obtained after chemical modification of natural polymers such as cellulose acetate (viscose). Synthetic polymers come from human engineering, such as polyethylene and polystyrene. They are obtained by a cascade of chemical reactions: the polymerization of molecules, called monomers. Monomers currently come mainly from petroleum but can be biobased. Synthetic polymers represent an annual tonnage of more than 400 million worldwide[12]. Among the notable advantages of polymers, we can highlight their low cost price, the creation of previously inaccessible object shapes and a very favorable weight/volume ratio, which makes them a material of choice for many industrial sectors. But they present environmental and health risks (see Impact of plasticizers on environment and health et Microplastics and ocean biogeochemical cycles).

Non-intentionally added substances (NIAS) are typically present in small but variable amounts in plastics. The sources vary greatly throughout the production of plastics and their recycling: impurities in the monomers, unwanted chemical reactions during polymerization, pollution during the polymerization or shaping of the plastic. The NIAS deriving from monomers will differ between oil-based and biobased ones. Different NIAS can be formed during different types of polymerization and depending on the type of reactor used and its previous use.

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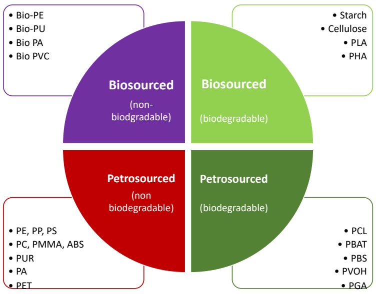
[12] https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/

Sheet 5: Biodegradable plastics: distinguishing the real from the fake

by Jean-François Ghiglione & Marie-France Dignac

Biosourced, biodegradable, compostable, bioplastic, what are we talking about?



© Jean-François Ghiglione

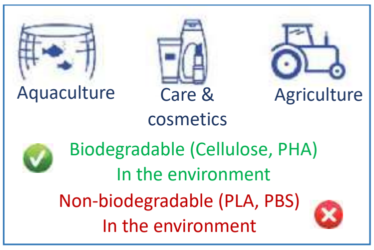
- **Biodegradable:** Ultimate transformation of the polymer by microorganisms into biomass and CO_2, CH_4 or mineral salts.
- **Biosourced:** Polymer produced from biomass, as opposed to petrosourced made of fossil origin. Biosourced is not necessarily associated with biodegradability.
- **Bioplastic:** Biosourced and/or biodegradable.
- **Compostable:** Complete biodegradation under industrial and/or domestic composting conditions.[13]

Note: These definitions only consider the polymer, which constitutes part of the plastic, without taking into account additives[14]. The term bioplastic is rarely used, because it is misleading and suggests that a biosourced polymer is ecological.

Biodegradable plastics do not replace conventional plastics

If the market has been increasing slightly over the past ten years, **biosourced and biodegradable plastics** (see Sustainable alternatives to plastics) **represent less than 1% of plastic production**.

Biodegradable plastics are only of interest for products whose end of life is mainly in the environment (cosmetics, agricultural mulch films, fishing nets, etc.). **They are not intended to replace all conventional plastics**[14].



© Jean-François Ghiglione

Let us remember that the history of biosourced materials in the 19th century (latex, resins, cotton, etc.) is punctuated by serious attacks on the environment and human rights[15].

Current standards do not represent the reality of the environment

© Richard Thompson

Several scientific studies have shown that **current standards (ISO, AFNOR) do not reflect the reality of the environment**, with so-called “biodegradable” plastics which do not show signs of biodegradation after several years in the natural environment. The question of the biodegradability of additives is not addressed. **The collection system for compostable plastics is difficult to set up and they are generally not biodegradable in the environment**[16].

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[13] Gontard et al. (2019) Les bioplastiques biodégradables et compostables. Sphere.

[14] Paul-Pont et al. (2023) Discussion about suitable applications for biodegradable plastics regarding their sources, uses and end of life. Waste Management Journal. https://doi.org/10.1016/j.wasman.2022.12.022.

[15] Altman 2021. The myth of historical bio-based plastics. Science, 373(6550), pp.47-49.

[16] Napper & Thompson (2019). Environmental deterioration of biodegradable, oxo-biodegradable, compostable, and conventional plastic carrier bags in the sea, soil, and open-air over a 3-year period. Environmental science & technology. https://doi.org/10.1021/acs.est.8b06984.

Sheet 6: Quantitative life cycle assessment and its limits

by Alba Marcellan & Nadège Pantoustier

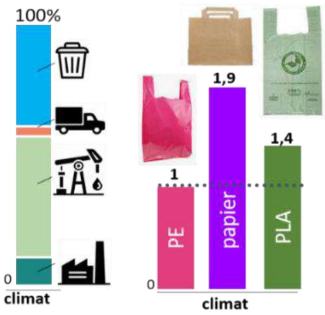
What is Life Cycle Assessment (LCA)?

©Alba Marcellan & Nadège Pantoustier

Life Cycle Assessment (LCA) has become an indispensable decision-making tool for eco-design. Since the emergence, in the late 1960s, of the concept of limited growth in a finite world[17], the evaluation of the environmental impact of products and services has been a subject of reflection. This impact assessment (for example, of "buying a polyethylene (PE) bag to carry my shopping") is based on a multi-stage, multi-criteria "cradle-to-grave" life-cycle assessment, including impacts on the climate, but also water consumption, human toxicity and so on. This approach has been standardized since 2006: ISO 14040 provides guidelines for the practice of LCA.

From intuition to quantification

Once the objectives and the system have been strictly defined, it is necessary to draw up an inventory of the physico-chemical flows involved in each stage of the life cycle, from the extraction of raw materials to final disposal.
Once the data has been collected, the physico-chemical flows identified need to be translated into environmental impacts. In the case of a single-use PE shopping bag, we can clearly see that the resource extraction and end-of-life stages have the greatest impact. Thinking in terms of comparative environmental benefits[18] enables us to make better decisions: conventional plastic bag (PE), paper bag or compostable biosourced polymer bag (PLA)?



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Plastics: towards a redefinition of needs

The limitations of LCA today concern two aspects: 1/ the availability and quality of data, and 2/ methodological discrepancies between actual and potential impact calculations. For example, the "human toxicity" impact is assessed using a standardized method (ISO standard), but its quantification is clearly complex. Greater scientific robustness of impact indicators remains a challenge in this field.
Rigorous interpretation of results involves assessing the uncertainties of available data and calculation methods, in order to set a significance threshold. By comparing a paper or biobased polymer bag with a standard polyethylene bag, the impact indicators are operational and relevant, provided that the uncertainty of the results is appreciated. However, the method does not take socio-economic impacts into account.
Knowing that the best waste is the waste we don't produce, it seems essential to redefine the need for and use of plastics: How often can I use my PE shopping bag rather than my paper bag? How does this affect my impact? Why is plastic single-use?

Public policy must therefore take into account the entire life cycle of plastics, in particular by considering the problem of managing the waste generated, but above all by giving ourselves the means to redefine our needs in plastics, by integrating the socio-economic impacts.

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[17] Donella et al. 1972. The Limits to Growth; a Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books.
[18] Civancik-Uslu et al. 2019. Life cycle assessment of carrier bags and development of a littering indicator. STOTEN 685: 621-630.

Sheet 7: Waste management

by Marie-France Dignac, Gabin Colombini & Jean-François Ghiglione

In our trash bins


©Jules Vagner-Objectif Zero Plastique

- The proportion of plastics in municipal waste in the United States surged from less than 1% in 1960 to over 12% by 2018[19], imposing a substantial financial burden on local authorities for its management (see Normative, ethical and economic challenges of our societies regarding plastic production).
- Approximately **half of the plastics manufactured are designated for single use[20], with nearly two-thirds intended for short-term use[21]**.
- A staggering 80% of the 8.3 billion tons of plastics produced since 1950 have ultimately found their way into the environment[20].
- Urban waste also comprises 34% of organic matter[19], which holds potential for valorization to enrich soil fertility with organic content.

The paradox of plastics found in organic waste

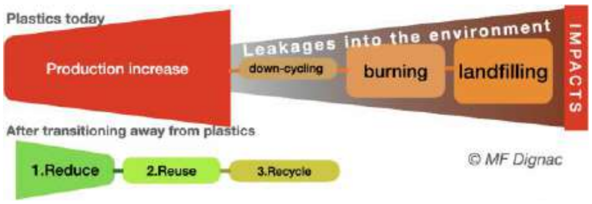
Plastics and microplastics contaminate the organic fraction of biologically treated waste (through composting, methanization, etc.), which is returned to the soil, thus becoming a source of soil pollution (see Plastic in soils). They end up in organic waste due to sorting inaccuracies or the absence of separation of biowaste at the source, or during the unpacking of biowaste preceding anaerobic digestion (for biogas production), where digestates are applied onto soils. **Reducing the plastic content in waste would facilitate the enhanced valorization of its organic fraction, which serves as a vital source of nutrients and carbon for soils.**


©CEFAS/FAO

Transitioning away from plastics

The waste hierarchy or 3R concept establishes priorities based on waste's environmental impact:

1. **Reduce[22]** plastic and waste production by fostering more durable consumption, minimizing packaging, and phasing out non-essential plastics.
2. **Reuse** essential plastics instead of discarding them after initial use. This necessitates designing items for repairability and ensuring plastics are reusable and refillable, while also guaranteeing they do not become toxic over time.
3. **Recycle** after waste collection and sorting, as a final recourse. Today, recycling merely delays ultimate disposal as plastics undergo limited cycles of recycling, resulting in plastics of lower quality[23] ("downcycling"). Transitioning away from plastics entails reimagining and simplifying plastic compositions[24] to increase the recycling rate, which presently accounts for a mere 12% of plastics waste in Europe.



© MF Dignac

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[19] Environmental Protection Agency, 2018. Advancing Sustainable Materials Management: Facts and Figures Report.
[20] Geyer et al., 2017. Production, use, and fate of all plastics ever made. Science advances, 3. 10.1126/sciadv.1700782
[21] Geyer et al., 2017. Production, use, and fate of all plastics ever made. Science advances, 3. 10.1126/sciadv.1700782
[22] Lau et al., 2020. Evaluating scenarios toward zero plastic pollution. *Science*, *369*(6510), pp.1455-1461.
[23] Carmona et al., 2023. A dataset of organic pollutants identified and quantified in recycled polyethylene pellets. *Data in Brief*, *51*.
[24] Dey et al., 2022. Global plastic treaty should address chemicals. Science, 378, pp.841-842. 10.1126/science.adf5410

Sheet 8: Recycling processes

by Nicolas Illy, Patrice Castignolles

In order to minimize the environmental impact of plastic materials, the reduction of waste or plastics' direct reuse are to be favored as a priority. The development of recycling channels complements the 3R (reduction, reuse, recycling) for plastics that cannot be removed or reused, to avoid incineration and landfill.

Recycling plastics represents a technological challenge that does not have a single or established solution. Several complementary solutions are being developed to consider the treatment of waste of different types and tonnages. The production of plastic follows several stages: synthesis of the polymer from small molecules, called monomers (mainly from petroleum and anecdotally from biomass), processing of the plastic (extrusion, injection-molding, injection blowing, etc.) typically in melting the polymer and adding mostly additives and fillers. Recycling involves using plastic waste as a supply at one stage of plastic production. Depending on the stage of plastic production at which recycled plastic is used, there are 2 main categories of recycling processes[25] :

- Physical recycling processes aim to recover the polymer chains without significantly degrading their structures at the scale of (macro)molecules and then to put them back into shape.
- Chemical recycling processes aim to cut polymer chains into small molecules, which can be either monomers usable to synthesize new polymers, or fuels or raw materials usable as additives or for chemical processes other than for the production of plastics.

Physical recycling

There are currently two types of physical recycling processes: mechanical recycling and dissolution processes. Mechanical recycling involves isolating a type of plastic by sorting waste, crushing it then melting it and putting it back into shape. This method has the advantage of being able to remanufacture plastic with low energy costs. On the other hand, not all plastics can be isolated and, moreover, there is a reduction in the performance (in terms of usage properties) of recycled materials due to the degradation of the polymer chains during melting and contamination by the disposal of waste and by the accumulation of previous additives or NIAS. This loss of quality forces manufacturers either to add a variable percentage of virgin resins in order to enhance the properties or to recycle the plastic for a different application less demanding in terms of usage properties (such as the recycling of PET from plastic bottles in the textile industry). This method of recycling is particularly suitable for PET, because it is easy to separate from other plastics.

Recycling by dissolution consists of dissolving the plastic material in a good solvent for the polymer chains then reprecipitating the latter using a bad solvent. This technique, applicable to almost all polymers derived from thermoplastics in theory, is suitable for more complex mixtures, and is less energy consuming[25] than mechanical recycling and allows the production of a relatively pure recycled material but it requires the use of significant quantities of organic solvents and is therefore not very suitable for high tonnages.

Chemical recycling

Chemical recycling involves isolating a specific plastic, washing it and then cutting it into small molecules. This cutting step is called depolymerization and can be carried out in a number of ways: heating the polymer (thermolysis), cutting the polymer in pieces with an organic reagent in the presence of catalysts (solvolysis), or use of enzymes (enzymatic recycling). Depolymerization is not possible with all polymers: for example, it is much simpler with polyesters than with polyolefins (polyethylene, polypropylene). It needs to be adapted to each family of polymers. Chemical recycling

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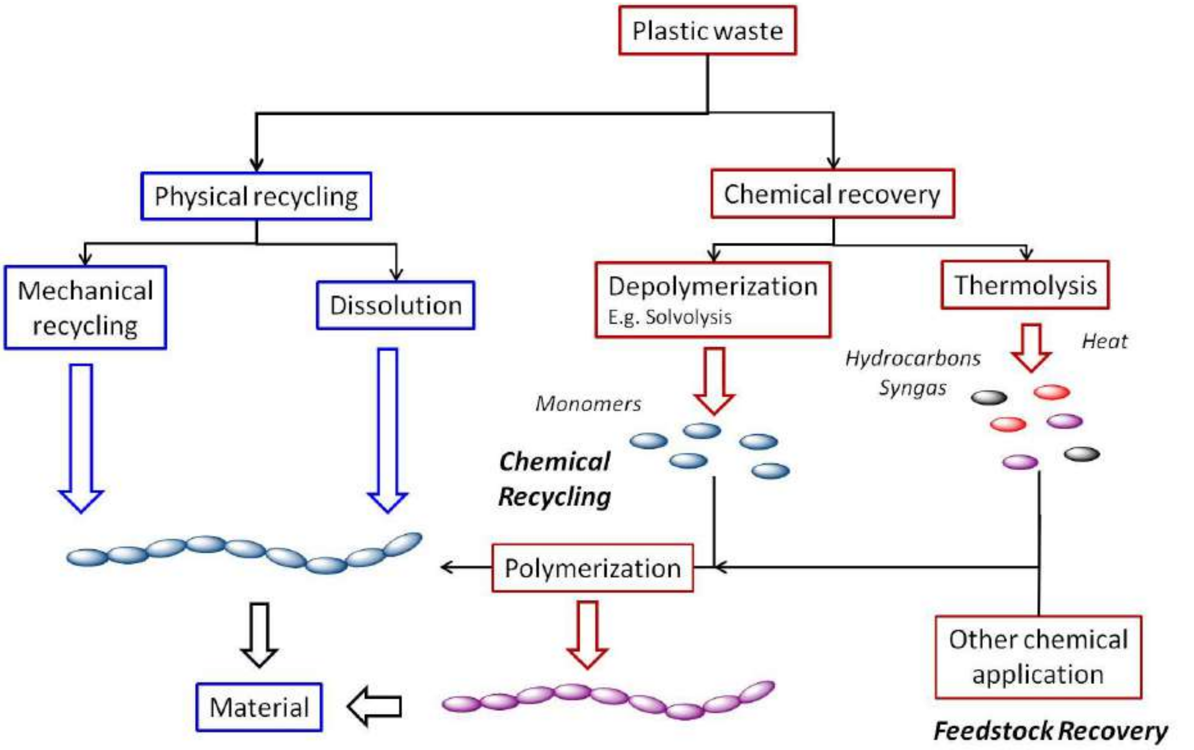
[25] Goring, P. D.; Priestley, R. D. Polymer Recycling and Upcycling: Recent Developments toward a Circular Economy. *Journal of the American Chemical Society Au* **2023,** 3 (10), 2609-2611.

therefore covers a greater diversity of processes than physical recycling with even more fundamental and applied research necessary to understand how these processes work, their performance and ultimately their usefulness. The advantage of chemical recycling is to be able to obtain a new polymer then a new plastic without loss of performance, or depending on the process with a lower loss of performance than with mechanical recycling. On the other hand, the different stages allowing depolymerization have variable financial, energy and ecological costs, but higher than mechanical recycling. Understanding depolymerization at a fundamental and applied level is a current priority for research on plastics with the particular objective of achieving recycling without leading to lower quality products ("downcycling") to contribute to the establishment of circular economies.[26]

The great diversity of plastics leads to a great diversity of recycling processes. Mechanical, dissolution or chemical recycling are different, with weak points in terms of end of life of the material, pollution by solvents, etc., which differ depending on the process. This great diversity makes recycling complex to understand and implement but at the same time offers many avenues to explore for the future.[27] [28]



©Illy N

The different processes of chemical recycling.

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[27] Liu &. Lu 2023. Emerging Trends in Closed-Loop Recycling Polymers: Monomer Design and Catalytic Bulk Depolymerization. Chemistry–A European Journal *29*(23), p.e202203635.

[28] Lummwer et al. 2023 Ring-opening polymerization for the goal of chemically recyclable polymers. Macromolecules 2023, 56, 3, 731–750

CHAPTER 3:

ENVIRONMENTAL AND HEALTH IMPACTS

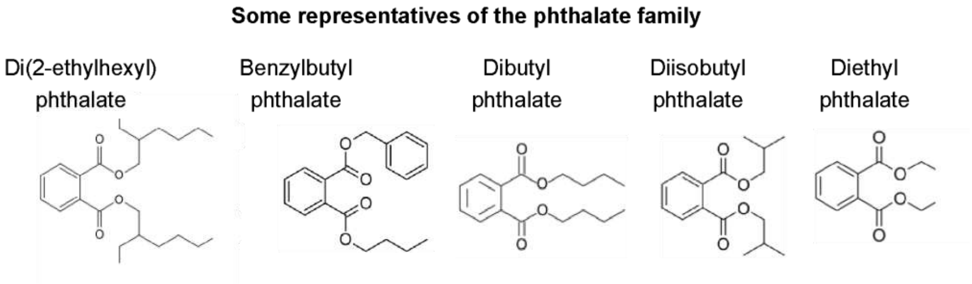
Sheet 9: Impact of plasticizers on environment and health

by Jean-Baptiste Fini & Sakina Mhaouty-Kodja

© Transparency Market Research Analysis, 2017

Humanity produced 8.3 billion tons of plastics between 1950 and 2015, and this production continues at an annual growth rate of 8.4%[29]. Because of their abundance, plastics are a major source of human and biodiversity exposure to plastic micro/nanoparticles, as well as to the plasticizers (additives) and (unpolymerized) monomers used in their formulation. A recent study indicates that 4,000 of the 16,000 substances used in plastics are problematic for health or the environment[30].

What are plasticizers?



© Mhaouty-Kodja S.

Phthalates are among the most commonly used and abundant plasticizers. These additives soften plastic compounds and make them flexible. They find application in the manufacturing of various plastics, such as polyvinyl chloride (PVC) and low-density polyethylene (PE). However, their use extends beyond plastics, as they are also incorporated into cosmetic formulations and herbicide adjuvants.

Which human and environmental contamination by phthalates?

Due to their non-covalent bond to plastic, phthalates can gradually leak and diffuse into the environment. The French Esteban study showed that at least one phthalate metabolite was found in 80-99% of adult and child urine samples[31]. This contamination is not restricted to industrial regions, but concerns also wildlife in remote areas, such as ants in the Amazon rainforest[32] or marine mammals in the Arctic[33]. Fauvelle *et al.*[34] have estimated that cumulative discharges of plastic additives into surface and deep waters vary from 2.3 to 132 tons per year for PVC and 0.4 to 3.4 tons per year for PE, during the first week of their introduction into the ocean. As these compounds have a short half-life in organisms, such levels of impregnation suggest that exposure is almost permanent.

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[29] Geyer et al., 2017. Production, use, and fate of all plastics ever made. Science advances, 3. 10.1126/sciadv.1700782

[30] Wagner et al. 2024 State of the science on plastic chemicals - Identifying and addressing chemicals and polymers of concern. http://dx.doi.org/10.5281/zenodo.10701706.

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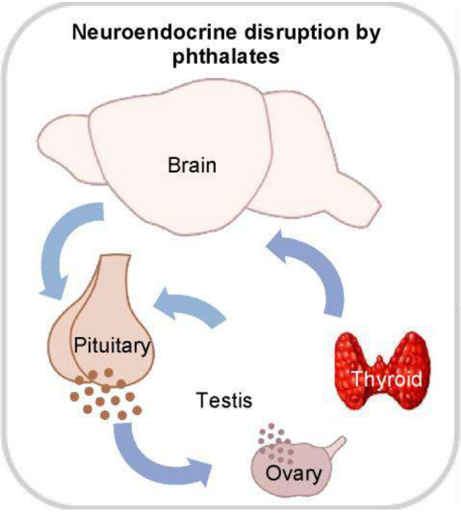
Impacts of plasticizers on health



Initially described as interfering with androgen action and male reproduction, phthalates also impact female reproduction at environmental doses, as shown in mice[35]. Under similar conditions of chronic exposure to environmental doses, phthalates disrupt the blood-brain barrier and reproductive and cognitive behaviors through neuroendocrine modes of action[36,37;38].

In addition, recent epidemiological studies show that cognitive disorders in children are associated with prenatal exposure to a mixture containing phthalates and bisphenol. Complementary studies on this mixture have shown disruptive effects on the thyroid axis, whose proper balance is crucial for harmonious brain development[39].

To protect the health of future generations, it is therefore mandatory to create a blacklist of plasticizers whose effects are increasingly well known, and to consider the old studies. The famous bisphenol A, initially developed in 1936 for its ability to mimic female hormones, was re-used, like other bisphenols, in the 1970s for its polymerization properties. This polycarbonate monomer was widely used before being banned in childcare articles in Europe and in food containers in France in 2015. Bisphenols S and F, which have replaced bisphenol A for these uses, exhibit similar harmful effects and are considered as regrettable substitutions.

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[35] Adam et al. 2021. Exposure of adult female mice to low doses of di (2-ethylhexyl) phthalate alone or in an environmental phthalate mixture: evaluation of reproductive behavior and underlying neural mechanisms. Environ Health Perspect. 129(1):17008

[36] Ahmadpour et al. 2021. Disruption of the blood-brain barrier and its close environment following adult exposure to low doses of di (2-ethylhexyl) phthalate alone or in an environmental phthalate mixture in male mice. Chemosphere. 282:131013

[37] Ducroq et al. 2023. Behavior, Neural Structure, and Metabolism in Adult Male Mice Exposed to Environmentally Relevant Doses of Di (2-ethylhexyl) Phthalate Alone or in a Phthalate Mixture. Environ Health Perspect. 131(7):77008

[38] Ducroq et al. 2023. Cognitive and hippocampal effects of adult male mice exposure to environmentally relevant doses of phthalates. Environ Pollut.;323:121341

[39] Caporale et al. 2022. From cohorts to molecules: Adverse impacts of endocrine disrupting mixtures. Science, Vol 375, Issue 6582. doi: 10.1126/science.abe8244

Sheet 10: Is plastic debris toxic ?

by Jean-François Ghiglione, Marie-France Dignac

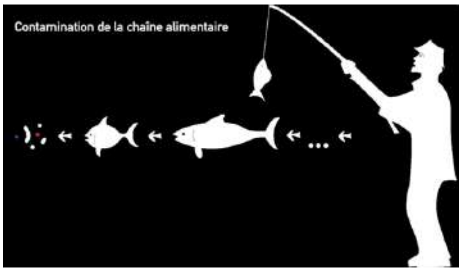
The effects of plastics on organisms


© Paulo Oliveira/Alamy Stock Photo

When ingested by organisms, plastics can cause **obstruction of the airways and digestive tract** which leads to malnutrition and death. More pernicious effects come from chemicals added to plastics (additives) to give them their resistance properties, their color, flame retardant properties, etc. There are now **more than 16,000 additives in commercial plastics, of which 4,000 have proven toxic effects on organisms** and only 4% are banned on the market. Many plastics placed on the market are toxic to the environment[40].

All links in the food chain are impacted, including humans

From plankton to large predators, plastics accumulate in the food chain. No organism is spared from this global pollution which affects all ecosystems, from the highest peaks to the deepest oceans. Plastics also contaminate human organs and blood, which are not spared. Liver failure, slowed growth, reduced motor skills, disturbance of sexuality, neurological damage, illness and death are all symptoms which indicate a **strong toxic impact of plastics on health**[41].



© Pascaline Bourgain
see Microplastics and marine biogeochemical cycles

The resulting health costs, borne by communities, are very high[42] (see The normative, ethical and economic challenges of our societies facing plastic production).

Ban toxic components in plastics and require product transparency


© Antoine2k / Dreamstime
see Diversity of plastics chemistry

Current standards (ISO, AFNOR) are not sufficiently representative of the original characteristics of plastics and their fate in the environment. The toxicity of products must be assessed by independent researchers and lead to an immediate ban in the event of proven toxicity.

The traceability of plastic additives placed on the market is not ensured under the cover of industrial secrecy, whereas more transparency is essential. A list of non-toxic additives for humans and the environment is essential to ban toxic plastics before they become waste[43].

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[40] United Nations Environment Programme & Secretariat of the Basel, Rotterdam and Stockholm Conventions Chemicals in Plastics. 2023. A Technical Report

[41] Meeker et al. 2009. Phthalates and other additives in plastics: human exposure and associated health outcomes. https://doi.org/10.1098/rstb.2008.0268.

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Sheet 11: Quantifying micro- & nanoplastics

by Gabin Colombini, Marie-France Dignac & Jean-François Ghiglione

Why quantifying micro- & nanoplastics?


©Jean-François Ghiglione

Macroplastics are the most visible and mass-wise significant part of plastic pollution. Derived largely from the breakdown of macroplastics, microplastics (1µm-5mm) and nanoplastics (< 1 µm) are more abundant and present greater risks to the health of humans and the environment[44] (see Microplastics and ocean biogeochemical cycles and Is plastic toxic?). **Micro- and nanoplastics are released throughout the entire lifecycle of plastics, not solely when they become waste[45].**

Quantification approaches

Scientists are studying plastics by assessing their size, morphology, quantity, mass, as well as the chemical composition of their polymers and additives. The collection of micro- and nanoplastics necessitates distinct methodologies for water (using Manta nets or sampling of water), air (passive or active collection), and soil (plastic particle separation in sampled soils based on density). Particle sorting is partially conducted manually for larger microplastics (>500 µm to 5 mm), while modern chemical techniques (such as analytical pyrolysis and infrared spectroscopy) are employed for direct analysis of smaller microplastics (ranging from 1 to 25 µm) and nanoplastics (< 1 µm).


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Current limitations


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- The distribution of plastics in the environment is highly heterogeneous. **Research often focuses on accumulation sites rather than on diffuse pollution, even though the latter has considerable impacts.**
- While analytical techniques are available to characterize polymers in environmental samples, **the identification of additives—comprising thousands of potentially hazardous molecules** (see Diversity of chemicals in plastics)—remains challenging within complex matrices.
- The development of **analysis of micro- and nanoplastics in biological tissues**, crucial for understanding their impacts on organisms, is still in progress[46].

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[44] Rai et al., 2021. Environmental fate, ecotoxicity biomarkers, and potential health effects of micro- and nano-scale plastic contamination. J. Hazard. Mater. 403, 123910

[45] Gontard et al., 2022. Recognizing the long-term impacts of plastic particles for preventing distortion in decision-making. Nature Sustainability, 5(6), pp.472-478.

[46] Albignac et al., 2022 Determination of microplastic content in Mediterranean benthic organisms by pyrolysis-gas chromatography- tandem mass spectrometry. Marine Pollution Bulletin 181, 113882.

Sheet 12: Plastics in soils: impacts on agriculture and food

by Marie-France Dignac & Gabin Colombini

Sources and extent of plastics pollution in soils

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The presence of microplastics in soils, revealed about a decade ago, remains relatively unknown. However, the masses of plastics accumulated in soils could potentially exceed those in oceans, particularly for the tiniest particles—microplastics[47]. These tiny particles in soils originate from various sources such as **illegal dumping, compost application, plastic mulching, wastewater irrigation, atmospheric deposition, runoff**, etc. In just over twenty years, certain agricultural soils have accumulated **several hundred kilograms of microplastics per hectare**[48].

Impacts of plastics in soils

©INRAE

Plastics and the chemicals they release into soils are harmful to biodiversity. Toxic effects have been notably evidenced on earthworms, which are essential for soil functioning. **Microplastics can migrate from soil to edible parts of plants, such as fruits and vegetables** (carrots, lettuce)[49].

Pollution of soil with plastics can affect crop yields and food security [50]. Plastics can also be transferred from soils to water through various processes (erosion, infiltration, animal transport), contributing to aquatic pollution (see Plastic pollution, from rivers to oceans).

The fate of plastics in soils

© Gabin Colombini

Once in soils, plastics degrade very slowly and are not degradable within a human lifetime. So-called biodegradable plastics do not necessarily biodegrade in soils and can also release toxic particles and chemicals (see Biodegradable and biosourced plastics). **Soils are therefore an accumulation medium where microplastics remain stable**[51].

There is currently **no remediation method for soil clean-up**. Hence, it is necessary to prioritize upstream measures to prevent this pollution (see Waste management).

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[47] Plastic Atlas 2019. Facts and figures about the world of synthetic polymers. Heinrich-Böll-Stiftung. https://www.boell.de/en/2019/11/05/plasticatlas

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[50] Zhang et al.., 2020. Plastic pollution in croplands threatens long-term food security. *Global Change Biology*, *26*(6), pp.3356-3367.

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Sheet 13: Microplastics and ocean biogeochemical cycles

by Camille Richon

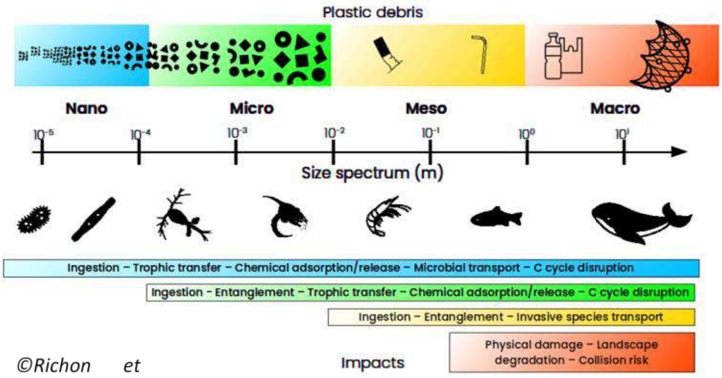
From macro- to microplastics

Microscopic picture of a copepod with microplastic in its digestive tract. ©Cole et al., 2013[52]

Plastic waste breaks down into an infinite number of small elements, known as microplastics (<5 mm) or nanoplastics (<1 µm). **These particles are now found in all regions of the ocean and can be ingested by the smallest marine organisms**, notably zooplankton, which are at the basis of the marine food chain (see Plastic-biota interaction at sea) and are keystone species for marine ecosystems.

Small size, large impacts

Ingestion of microplastics by zooplankton leads to contamination of the trophic chain, which can spread to top predators (biomagnification). **Moreover, their high surface-to-volume ratio makes microplastics particularly sensitive to the transport and release of contaminants and nutrients**[53], as well as to the formation of biofilms (see The plastisphere). The growth of phytoplankton on the surface of microplastics has been widely demonstrated in the laboratory and also observed in the natural environment[54], with possible consequences for species transport (raft effect)[55] as well as for primary production and surface nutrient cycles.



©Richon et al., 2023

A threat for ocean biogeochemical cycles?

Laboratory and *in situ* experiments have demonstrated multiple interactions between microplastics and marine biogeochemical processes (primary production, predation, zooplankton metabolism, particle and carbon export, dissolved nutrient cycling, etc.)[56]. The use of global models demonstrates that microplastics pose a serious threat to marine ecosystems, as their spatial and seasonal dynamics coincide with those of plankton in many regions. Initial estimates show that **the toxic effects of microplastics on zooplankton could lead to a reduction in surface carbon fluxes (primary production and carbon export) of the same order as climate change (a few percent over a century)**[57].

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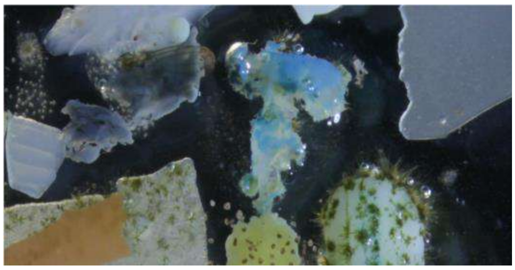
Sheet 14: The plastisphere: the vibrant life of the organisms that live on our waste

by Jean-François Ghiglione

Plastic waste is a new ecosystem for organisms

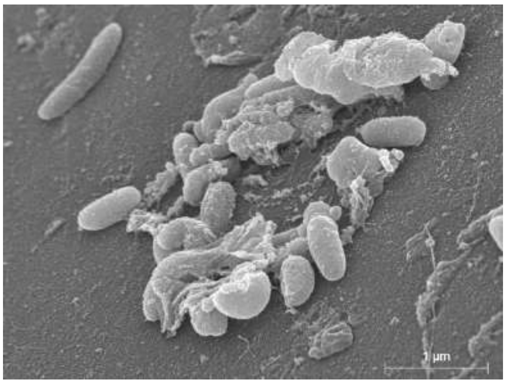


© Christian Sardet

The organisms living on plastic waste are unique compared to those that live in their immediate environment. They are different from those that live on glass surfaces or natural organic matter. Their affinity for plastic is linked to their ability to form biofilms on surfaces where a very large number of species coexist. Plastic is a **new ecological niche for organisms**[58].

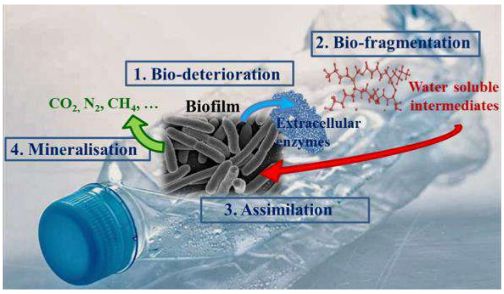
Pathogenic bacteria and viruses on plastics

Many viruses and bacteria settle on plastics, which act as rafts to disseminate them in the environment. These microorganisms can spread diseases (i.e. pathogens). They are transported via wastewater treatment plants, the fibers of our clothing or surgical masks. They participate in the resistance to antibiotics produced by microorganisms in the plastisphere. Virulent human or animal pathogens (*Shewanella putrefaciens*, *Vibrio parahaemolyticus,* etc.) are sometimes very abundant and raise the question of **the impact of plastics on human health and the health of the environment ("One Earth" concept)**[59].



© Yonko Gorand

Biodegradation possible, but very slow…



© Jean-François Ghiglione

Bacteria and fungi that live on our waste can break down plastics, **but it is a very slow process**. In the marine environment, once the plastic has been oxidized by ultraviolet light, microorganisms can feed on it and transform the carbon in the polymer into CO_2 (mineralization). In the oceans, it will take several decades for microorganisms to overcome a piece of plastic. **Nature will not be able to cope with the enormous amount of plastic that enters the environment every year**[60].

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[58] Jacquin et al. (2019) Microbial ecotoxicology of marine plastic debris: a review on colonization and biodegradation by the 'plastisphere'. Frontiers in microbiology https://doi.org/10.3389/fmicb.2019.00865.

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Sheet 15: Plastic-biota interaction in the sea

by Maria Luiza Pedrotti & Rocío Rodríguez Torres

Impact of microplastics on marine organisms


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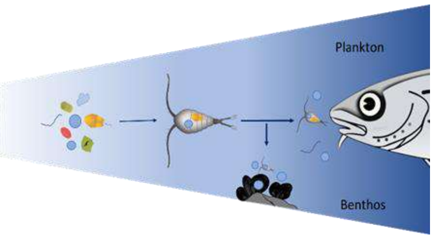
Various filter-feeding organisms, from zooplankton to large vertebrates, interact with plastic debris through entanglement, colonization or ingestion (see From entanglement to ingestion, marine mammals and plastics). Because of their small size, microplastics (MP < 5 mm) are ingested by filter-feeding organisms such as zooplankton (see Microplastics and marine biogeochemical cycles), molluscs, crustaceans, fish and whales.

Many species of fish ingest microplastics by mistaking them for food, attracted by their smell[61]. **The ubiquity of plastic in the oceans poses a threat to 90% of marine organisms.**

Microplastics in the food chain

The ingested plastics cause physical damage, obstructions in the digestive system, malnutrition, and even mortality among marine organisms. These plastics contain toxic additives added during manufacturing and adsorb contaminants from seawater. Organisms that ingest them can concentrate these substances in their tissues (bioaccumulation), leading to adverse physiological effects. **Plastics and associated toxic chemicals can be transferred through the food chain[62] and reach humans, with potential health risks that remain to be elucidated.**



Transfer of microplastics via zooplankton ©Rodriguez-Torres, R.

Nanoplastics penetrate biological membranes


Larve sea urchin with algae and plastic microbeads in its stomach @Pedrotti M.L.
@Pedrotti M.L.

Small-sized microplastics, particularly nanoplastics (<1 µm), due to their size and ubiquity, pose an even greater threat. Nanoplastics can penetrate cell membranes and enter tissues. Despite methodological constraints in detecting them in the environment (see Quantifying micro- & nanoplastics), some laboratory studies have assessed nanoplastic interactions with biota. Nanoplastics have been detected in fish brain tissue, affecting their behavior. They decrease fertility and increase embryonic malformations in crustaceans[63]. Therefore, nanoplastics pose a risk to marine organisms and human health.

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[61] Savoca et al., 2017. Odours from marine plastic debris induce food search behaviours in a forage fish. Proceedings of the Royal Society B: Biological Sciences, 284(1860), 20171000. https://doi.org/10.1098/rspb.2017.1000

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Sheet 16: Marine mammals and plastics: from entanglement to ingestion

by Jean-Luc Jung

Marine mammals are mammals that have adapted secondarily to marine life. They are therefore dependent on the marine environment and, like all disturbances to it, plastic pollution affects them. Images of large pieces of plastic found in the stomachs of dead cetaceans, or whales entangled in the remains of plastic nets, have become emblematic of the direct impact of plastic pollution. However, the less visible ingestion of microplastics has become just as worrying.

Like humans, cetaceans and pinnipeds are mammals. Mainly long-lived top predators, they are the sentinels of our oceans' quality. Their proven contamination by plastics must be particularly alarming.

Plastic macro-waste, entanglement and ingestion

Large piece of plastic found in the stomach of a Cuvier's beaked whale in the Iroise Sea (summer 2023). Photo ©Laurent Hervé, transmitted by Cécile Gicquel, Parc naturel Marin d'Iroise (OFB) and Réseau National Echouage, Pelagis.

Plastic macro-waste is the most common form of marine macro-waste. Mistaken for prey, they can be ingested by marine macrofauna, including marine mammals, causing injury and internal dysfunction that can lead to death[64]. They can also act as traps, causing injuries and harmful entanglements. Waste from fishing nets, lost or abandoned at sea, can even lead to what is known as "ghost fishing".

Microplastics as internal contaminants

Microplastics (< 5 mm) contained in seawater (see Plastic pollution, from rivers to the sea) can be ingested directly by marine mammals, or contained in ingested prey. The latter route of contamination, by trophic transfer, appears to be the most important. Mysticetes, or baleen whales, feed by filtering large volumes of seawater in search of zooplankton or small schooling fish. Hundreds of thousands of microplastic particles can be ingested daily by the largest whale species[65]. Toothed whales and pinnipeds, feeding during targeted hunts, are also concerned: microplastics have been found in the digestive systems and faeces of around twenty different species[66]. Exposure to and ingestion of microplastics by marine mammals is therefore, unsurprisingly, well established. Exposure levels and impacts, depending on species and ecosystem, remain to be better understood (see Plastic-biota interaction at sea).

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CHAPTER 4:

PLASTICS AND SOCIETY

Sheet 17: Natural history collections: a tool to date and track the evolution of plastic pollution

by Valentin Dettling, Sarah Samadi, Claudia Ratti,
Jean-Baptiste Fini & Claire Laguionie

Natural history collections and their use

Natural history collections (or biobanks) are composed of biological, geological, and anthropological material, collected as part of scientific research aiming to document natural objects. Most collections consist of non-living specimens, preserved in natural history museums, universities, or research centers. These institutions manage their storage, conservation, inventory, and archiving. Natural history collections constitute archives of naturalistic research that can be used to answer contemporary scientific questions. Notably, they can be used to establish time-series to investigate the impacts of anthropogenic pressures on biodiversity. By helping to understand recent changes linked to human activities, collections can help to better anticipate the future. For example, collections have already been successfully used to understand organisms' response to climate change[67], the emergence of zoonoses[68], and to track the spread of pollutants through food chains[69].

Plastic pollution studies using natural history collections

Collections are beginning to be used to study plastic pollution. Studies have mainly used organisms living in aquatic environments since it is one of the main reservoirs of microplastics (11 studies as of January 1st, 2024[70]). Collections of plankton, fish, sea stars, sponges, and mussels have been studied, covering periods from 1900 to the present. The results of these studies show that fibers are the most common type of microplastic found in these animals. Some studies using long time-series (starting before the use of plastic in our daily lives) show an increase in the quantity of plastic found in the studied organisms, while others show a stagnation in plastic quantity. These differences raise scientific questions that cannot be resolved using only 11 studies performed over varying periods of time. Nonetheless, it is clear that collections are a relevant tool for monitoring the evolution of plastic in ecosystems, and that studies using these types of samples should be pursued and expanded upon.

The value of collections for assessing public policies

Despite technical challenges in using collections to study the evolution of plastic pollution, collections represent a readily available resource that does not require additional spending on further field sampling. Collections should continue to be expanded to continue to serve their role for future generations[71]. They are a precious source of samples to better understand the past and future evolution of plastic pollution, enabling the evaluation of current public policies regarding plastic pollution management and the implementation of appropriate plastic management policies (see The normative, ethical and economic challenges our societies face regarding plastic production).

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Sheet 18: Sustainable alternatives to plastics

by Maria Luiza Pedrotti

Homo Plasticus

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Since 1950, 9 billion tons of plastics have been produced, of which only 9% have been recycled and 12% incinerated[72]. Half of these plastics become waste in less than a year, with most of them ending up in landfills or in the environment, where they take centuries to decompose. **It is urgent to adopt sustainable practices and rethink our use of plastic to preserve our planet and limit adverse effects on the climate.**

Innovative and natural solutions for plastics

Over the past 15 years, biosourced and biodegradable plastics have been proposed as an alternative to non-biodegradable petroplastics (see Biodegradable plastics), giving rise to a diversity of more environmentally-friendly materials, especially in the packaging industry. Examples include mycelium, starch-based bioplastics, edible packaging such as those made from algae, as well as materials based on cellulose, wood, bamboo or agricultural residues[73].

Mushrooms to stop plastic pollution. Cultivating mycelium mixed with agricultural waste enables the creation of a sturdy and completely biodegradable packaging material.
© Fungus Sapiens.

To promote sustainable alternatives, it is essential to evaluate the life cycle and environmental impact of these materials (see Quantitative life cycle analysis and its limitations). **The United Nations Environment Programme (UNEP) also recommends that they do not compete with food production, favoring renewable and abundant resources while preserving water and soil.**

Technological and policy challenges: socio-economic impacts

Sustainable alternatives to plastic go beyond the development of new materials. It is not only about producing differently but also about rethinking the entire production system, prioritizing a "from cradle to grave" approach. The real challenge is to reduce waste, ban single-use plastics, thus contributing to reducing the total demand for disposable plastics (see Waste treatment). Solutions mainly focus on prevention, reduction, and reuse of plastics, aligned with the zero-waste strategy[74]. Furthermore, it is crucial to establish a circular management system that takes into account the end of life of plastics and waste utilization. This requires an assessment of socio-economic and environmental consequences, as well as an understanding of consumer behavior (see The normative, ethical and economic challenges our societies face regarding plastic production), which should play a major role in the adoption of relevant alternative solutions.

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Sheet 19: Gathering knowledge to take action: the « Zéro Déchet Sauvage” collaborative web platform

By Isabelle Poitou, Florian Cornu, Quentin Courtier,
Maxime Thorel, Benoit Fauvet-Messat, Romain Julliard

The Zéro Déchet Sauvage platform (i.e “Zero Wild Waste”) is a complete participatory science tool which aims to tackle the challenge of marine litter. Designed to steer public action, it allows to:

- optimise cleanups carried out by associations and professionals by acquiring quantitative and qualitative knowledge about the waste collected in order to set-up reduction plans;
- standardise the methods used to acquire this knowledge and enables data to be compared with each other;
- centralise data in a tool used as a dashboard for national policies ;
- identify, promote and coordinate the stakeholders involved;
- map litter accumulation zones and hotspots and identify transfer routes;
- identify and target the economic sectors and brands involved, guide and evaluate national, European and international public policies;
- help to set-up tailored intervention plans and prevention actions with identified target actors.

Mobilise local stakeholders to identify and reduce litter

The number of waste collection operations has increased steadily in recent years. Rarely coordinated, they are mainly carried out by associations or technical services of local authorities. Most of them try to solve this problem without any standardised method nor centralised database.

Convinced that quantitative and qualitative knowledge is essential for steering plans to reduce this pollution at local, national and European levels, associations such as MerTerre, have devoted themselves to defining standardised data acquisition methods adapted to the different contexts of public and professional waste collection. Since 2006, MerTerre has trained many associations and stakeholders to characterize methods on the field.

The need to create a participatory science platform to build-on and centralise the information coming from those cleanups, whether by associations or professionals, was quickly identified.

The "Zéro Déchet Sauvage" platform keys to success

⇨ Listen and meet the needs of both associations and public authorities, and obtain the financial resources to create a tool that wins everyone's support.

In 2017, with the support of the Provence-Alpes-Côte d'Azur Region, the MerTerre association joined forces with the National Museum of Natural History (MNHN) to develop its first collaborative web tool: ReMed Zéro Plastique. The decision to work with an institutional partner specializing in data banking systems for participatory sciences was key to guarantee the long-term viability of the tool and its acceptance by users.

The success of this participatory science programme depends on the quality of the data collected. To support it in this mission, MerTerre has brought together a scientific committee made up of researchers and engineers specializing in the field of litter and participatory science. They guarantee the scientific use of the data and their contribution to research in this field.

The ReMed platform has been designed by gathering and understanding concrete needs identified by regional and national NGOs and public partners, in line with European scientific measurement methods[75]. Launched in 2019, this first pilot platform helped develop the national *Zéro Déchet Sauvage* (ZDS) platform. It was officially launched in 2021, with the support of the French Ministry for Ecological Transition (MTE). The maintenance and development are now handled by the Mosaic service unit (MNHN - Sorbonne University) and steered by MerTerre and its partners.
MerTerre coordinates and leads a shared governance between a Steering Committee and a Technical Committee including co-pilot organizations, recognised for their experience in the field and their ability to federate communities and various stakeholders. These organizations run *Zéro Déchet Sauvage* in their local areas, promote and support local actors and data collection to feed the global database.

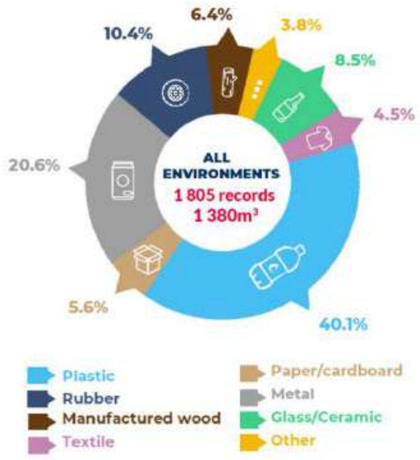
⇨ create a framework to help gather high-quality collaborative data thanks to a scientific committee.

The success of this participatory science program depends on the quality of the data collected. To succeed in this mission, MerTerre has created a scientific committee made up of researchers and engineers specializing in litter and participatory science. They guarantee the scientific use of the data and their contribution to research in this field.

Training in characterisation methods and supporting the local stakeholders involved, who are experts in their area, is key to get quality data. Those data enhance the value of their operations by providing the knowledge managers need to reduce macro-waste with concrete and tailored actions.

⇨ offer datavisualizations that help better understanding to foster better management

The information obtained using standardized characterisation methods can thus be compared and used by all the actors involved. This tool also helps to coordinate actors and actions, to structure a network of committed partners to combating abandoned waste that can end up at sea and in the oceans, and to guide corrective actions.
The "Zéro Déchet Sauvage'' platform offers automated data retrieval with datavisualizations, enabling trends to be monitored in a specific area or territory. A genuine dashboard for steering preventive and curative action plans, the "Zéro Déchet Sauvage'' platform enables a link to be built between citizens and decision-makers for the implementation of public policies to concretely reduce abandoned waste.



Share of materials (in volume), all environments combined

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Sheet 20: The normative, ethical and economic challenges our societies face regarding plastic production

By Juan Baztan, Bethany Jorgensen, Mateo Cordier, Christian Gorini, Denis Bailly, Aanchal Jain & Baptiste Monsaingeon

December 2024 marks the conclusion of the first five negotiation meetings of the Intergovernmental Negotiating Committee for the United Nations Environmental Programme, tasked with developing an internationally legally binding instrument on plastic pollution, including in the marine environment, driving international dialogue and Member States' commitments for the years to come.

Among the 193 Member States, only a small minority oppose reducing plastic production; in other words, the vast majority of Member States support upstream reduction at the source of this pollution: production.

Twenty years ago, in 2004, a journal article inaugurated contemporary studies on microplastics.[76] Scientific communities have organized themselves internationally, for example, around the MICRO conference on plastic pollution from macro to nano and its biennial meeting, which has brought together a large part of the community since 2014. Starting in 2022, the "Scientists' Coalition for an Effective Plastics Treaty" has strengthened the links between science and policy regarding the Plastics Treaty. At the French level, the Coalition relies on the Plastics Group of the Sorbonne University Alliance; the GDR Plastics, Environment, Health; the Waste, Values, and Societies Thematic Network; as well as the coordination of the "Zero Plastic in Biosphere Reserves" working group through UNESCO, among others. These reflect an intense level of activity through collective efforts reflecting on the question: “What are the challenges to addressing plastic pollution?”

What are the challenges to addressing plastic pollution?

The production of plastics and its consequent use continue to grow, increasing impacts on ecosystems as a whole (see Microplastics and marine biogeochemical cycles and Plastic in soils), and living organisms (see Plastic-biota interaction at sea and From entanglement to ingestion), including humans (see Is plastic toxic? and Impact of plasticizers on the environment and health). Do we want to reduce plastic pollution? If the answer is YES, our societies will have to overcome three challenges:

A normative challenge to strengthen the role of science in our societies

Three distinct elements constitute the basis of the normative challenge and the question of plastic pollution: (i) defining research priorities; (ii) identifying and understanding cause-and-effect relationships; and (iii) explicating the values and norms upon which the choices of each active element in research are based. If we analyze scientific work from the perspective of these three elements, we observe that 100% of scientific articles articulate priorities (point (i) above), a large majority highlight causalities (point (ii)), but only a small percentage make explicit their normative framework (point (iii)).

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An ethical challenge to address highly imbalanced power dynamics

Citizen-consumers and public agents are in highly imbalanced power dynamics with producers and recyclers of plastics. The keys to ethical balance lie in improving transparency and eliminating conflicts of interest; replacing the dominant ethic of disconnection, where efforts are made to disconnect profits from the environmental and societal consequences of activities that generate those profits. Several studies have demonstrated the link between lack of transparency and plastic pollution, through corruption and the influence of industrial lobbies.[77]

An economic challenge to balance social injustices

In the various value chains of plastic products, the costs are frequently externalized and the benefits are internalized, meaning: our societies dedicate considerable resources to mitigate pollution that is highly profitable for the producers emitting the pollutants, as well as for recyclers.

An example is the glaring imbalance between, on one hand, the very high cost to our communities for collecting and treating plastic waste and, on the other hand, the significant financial profitability enjoyed by producers and recyclers at the end of the treatment chain. The three most cited teams of scientists modeling material and economic flows[78,79,80] propose an explanation for this imbalance: the opacity of information from plastic producers and recyclers. Reducing production constitutes the most robust solution-hypothesis to significantly reduce pollution.

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LABPLAS project H2020 EU (16 partners 8 countries), 2021-2025 : *Understanding the sources, transport, distribution and impacts of plastic pollution*. The aim is to build capacity (sampling, analysis and quantification, models) to assess the interactions of plastics with environmental compartments (air, water, sediment) and natural cycles.– (*cood. R. Beiras, M.L. Pedrotti PI for France*).

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In March 2022, the United Nations opened international negotiations to end plastic pollution.

Since 2023, the Sorbonne University Alliance has been mobilized to contribute to this scientific and political effort.

It has brought together researchers from Sorbonne University and the Muséum National d'Histoire Naturelle. It is the first French university accredited by UNEP to take part in international negotiations.

In this collection, some forty researchers have written twenty factsheets, driven by a concern for pedagogy and the imperative of rigor. Pedagogy, with a succinct form, free of technical vocabulary. Scientific rigor, with references at the bottom of each page to the best and most recent publications on each of the subjects covered.

The authors are chemists, agronomists, microbiologists, virologists, ecotoxicologists, neuroendocrinologists, ecologists, oceanographers, marine biologists, etc. Only such a wide range of skills makes it possible to approach a crisis of universal scope such as plastic pollution.

Sorbonne University is a multidisciplinary research university in the heart of Paris. It comprises three faculties: humanities, science and engineering, and health. It carries out its missions of teaching, research, innovation, mediation and technology transfer in an innovative and creative way, for the benefit of the common good.

The National Natural History Museum is a scientific center of excellence that studies the Earth and all living organisms, from the most remote periods of the past to the present day, and questions our future. The Museum shares its knowledge and works to conserve biodiversity and natural and cultural heritage.

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