Priority pollutants in ArcSolution

Deliverable D3.1

Author: Katrin Vorkamp (AU)

Contributors: Thomas Bucheli (AGRO), Kaj Mantzius Hansen (AU), Gabrielle Haddad-Weiser (NMBU), Gert Mulvad (UGR), Arja Rautio (UOULU), Lars-Otto Reiersen (AKn), Anna Rönkä (UOULU), Christian Sonne (AU), Jakob Strand (AU), Jens Søndergaard (AU)

ArcSolution

Arctic pollution in a One Health perspective
from complex challenges to sustainable solutions

Funded by the European Union

This deliverable is a part of the ArcSolution project.

Deliverable number and info: D3.1 Priority pollutants in ArcSolution
"D3.1 will consist of a list with the ArcSolution priority pollutants with a short explanation of the reasons for inclusion and a short summary of background information on production, use, legal status and physical-chemical properties. The list will include the pre-defined pollutants described in T3.1 (plastics, PFAS, Hg) and the pollutants prioritised in local workshops in T2.2. Relates to T3.1."

Funded by the European Union under the Horizon Europe
Program, Grant No. 101135051 — ArcSolution

www.arcsolution.eu

Title: Priority pollutants in ArcSolution
Author: Katrin Vorkamp (AU)
Contributors (in alphabetical order): Thomas Bucheli (AGRO), Kaj Mantzius Hansen (AU), Gabrielle Haddad-Weiser (NMBU), Gert Mulvad (UGR), Arja Rautio (UOULU), Lars-Otto Reiersen (AKn), Anna Rönkä (UOULU), Christian Sonne (AU), Jakob Strand (AU), Jens Søndergaard (AU)
Internal reviewers: Jan Ludvig Lyche (NMBU), Mario Acquarone (AMAP)
Publication date: 26.05.2025
Page number: 28

Content

Funded by the European Union

Summary

The Arctic is a sink for many types of pollutants causing potential threats to ecosystem and human health. ArcSolution has pre-defined four key pollutant groups including per- and polyfluoroalkyl substances (PFAS), mercury, plastics and plastic additives. These pollutants differ in their physical-chemical properties, sources, use and regulatory status. PFAS and plastics are entirely man-made products that have become global environmental problems due to their persistence, long-range transport and potential adverse effects. PFAS, plastics and plastic additives are complex groups that include thousands of individual PFAS, a broad range of plastic polymers and various chemical classes of additives.

Under the auspices of the United Nations (UN), a global legally binding agreement to end plastic pollution is under negotiation. Three individual PFAS and several plastic additives (including groups of flame retardants and one UV filter) are currently regulated at the global level via the UN Stockholm Convention. In addition to these pre-defined pollutants, polycyclic aromatic hydrocarbons (PAHs) have been identified as a compound group of local concern in the community-based participatory approach in ArcSolution that involves local stakeholders, experts and the public at the ArcSolution study locations.

Mercury and PAHs are highly toxic and occur naturally in the environment, but their environmental emissions are related to human activities and have thus increased substantially since the industrial revolution. They can both be emitted from coal burning. For mercury, another significant source is the artisanal small-scale gold mining. PAHs are emitted from incomplete combustion processes as well as from petrogenic sources. Climate change is expected to increase PAH emissions, for example from wildfires, permafrost thaw and oil exploitation. Mercury is the subject of the UN Minamata Convention, while PAHs are included in the Convention on Long-Range Transboundary Air Pollution of the UN Economic Commission for Europe.

Funded by
the European Union

1 Introduction

For centuries, the Arctic was considered a pristine region, until research and monitoring from the 1970s onwards identified serious pollution, including high levels of harmful chemicals in Arctic human populations and wildlife. In 1998, the Arctic Monitoring and Assessment Programme (AMAP) documented in its first assessment that the Arctic was a sink for certain heavy metals, including mercury, and organic chemicals which were later categorized as persistent organic pollutants (POPs) (AMAP, 1998). This knowledge was instrumental for regulatory frameworks that addressed pollution at the global level, in particular the United Nations Stockholm Convention on POPs and the Minamata Convention on Mercury (UNEP, 2023a; 2024).

The coordinated monitoring under the auspices of AMAP and associated research and screening activities have subsequently identified several other Chemicals of Emerging Arctic Concern (CEACs) (AMAP, 2017). Some of these may have POP characteristics, while others may be of concern for other reasons, for example pharmaceutical residues in wastewater effluents that may affect local aquatic ecosystems (Kallenborn et al., 2018). The compound group of per- and polyfluoroalkyl substances (PFAS) is of particular concern worldwide because of its widespread use and extreme environmental persistence. At present, three PFAS are classified as POPs, while thousands of PFAS remain unregulated (Muir et al., 2019; Glüge et al., 2020).

The globally increasing problem of plastic pollution is also a concern in the Arctic where plastic accumulates in the environment from local and distant as well as land- and sea-based sources (PAME, 2019). Arctic wildlife can be harmed by the ingestion of plastic items or through entanglement (Collard and Ask, 2021). In addition to concerns about plastics themselves, plastic polymers contain a variety of additives for certain functionalities, such as flame retardants, plasticizers or UV filters. These plastic additives can leach from plastic particles into the surrounding environment, including the gut of an animal who swallowed the particle, leading to potential exposure (Kühn et al., 2020).

ArcSolution has pre-defined certain chemicals of priority interest for Arctic research. In addition, the community-based participatory approach in ArcSolution collects information on local concerns and priorities, including pollutants of local concern at the study sites. The objective of this deliverable is to provide a list of the priority pollutants in ArcSolution, both pre-defined and locally identified, the reasons for their inclusion and a short summary of background information on production, use, legal status and physical-chemical properties.

2 Priority pollutants in ArcSolution

Table 1 summarizes the priority pollutants in ArcSolution and the main reasons for their inclusion. The background information on production, use and legal status is given in the following sections, for each of the different compound groups.

Table 1: Summary of priority pollutants in ArcSolution. The presence in the Arctic is not mentioned specifically as a reason for inclusion because it has been documented for all pollutants in the table.

Priority pollutants	**Reason for inclusion**	**References**
Pre-defined priority pollutants		
Per- and polyfluoroalkyl substances (PFAS)	Omnipresence in the environment High levels in high-trophic animals High human exposure Large compound group with thousands of compounds and resulting knowledge gaps High persistence Mobility and toxicity	AMAP (2017; 2021a); Lohmann et al. (2024)
Mercury (Hg)	Continuous high environmental levels despite international regulation High toxicity High levels in high-trophic animals High human exposure	UN Environment (2019); AMAP (2021b)
Plastics	Omnipresence in the environment Effects on Arctic wildlife (e.g. entanglement) Many research questions about sources, transport, fate and impacts	PAME (2019); AMAP (2021c); Bergmann et al. (2022)
Plastic additives	Leaching from plastics in the Arctic environment Large compound group with thousands of compounds and resulting knowledge gaps High volume use and toxicity of some compounds	AMAP (2017); Fauser et al. (2022); Hamilton et al. (2023)
Locally defined priority pollutants		
Polycyclic aromatic hydrocarbons (PAHs)	Local concerns related to Oil and gas exploration and transport and related risks of accidents and spills Fossil fuel use for energy generation Gasoline and diesel for vehicles	Local workshops

3 Per- and polyfluoroalkyl substances (PFAS)

3.1 Introduction

The best known and studied individual PFAS are perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) (Figure 1). They represent the groups of perfluoroalkane sulfonic acids (PFSAs) and perfluorocarboxylic acids (PFCAs). The definition of PFAS was re-visited by an expert group under the Organization of Economic Cooperation and Development (OECD) in 2021 and now considers PFAS as all molecules that include at least one perfluorinated methyl group ($-CF_3$) or methylene group ($-CF_2-$) with no hydrogen or other halogens attached to it (OECD, 2021). As a result, the group of compounds considered PFAS has grown. The CompTox Chemicals Dashboard of the US Environmental Protection Agency contains a list of 14,000 PFAS[1] with and without explicit structures.

Since the first detection of PFOS in wildlife of Greenland and the Faroe Islands about 20 years ago (Bossi et al., 2005), PFAS has gained tremendous scientific and regulatory interest worldwide. Environmental and health concerns in the Arctic and elsewhere have been related to the points summarized in Table 1.

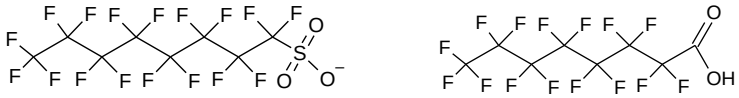


Figure 1: Structures of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), the two best-studied PFAS representing perfluoroakane sulfonic acids (PFSAs) and perfluorocarboxylic acids (PFCAs), respectively.

3.2 Production and use

PFAS have been produced in two different manufacturing processes as summarized in Buck et al. (2011), resulting in different mixtures of PFAS. Electrochemical fluorination was applied starting in the 1940s and has been increasingly replaced by telomerization since the 1970s. The following information is taken from Buck et al. (2011):

- **Electrochemical fluorination:** Starting chemicals were perfluorooctane sulfonyl and perfluorooctanoyl derivatives to produce PFOS and PFOA, respectively. They were electrolyzed in HF, leading to the replacement of hydrogen with fluorine in the molecules. The process produced free radicals that broke chains and led to mixtures of linear and branched PFAS with different chain lengths and functional groups. Varying the raw materials for the reactions directed the main products.
- **Telomerization:** This process starts from a perfluoroalkyl iodide that reacts with tetrafluoroethylene, extending the carbon chain of the molecule. The intermediate perfluoroalkyl iodides and (poly)fluorotelomer iodides formed in the process can be reacted to form a variety of other fluorine-containing molecules, including fluorotelomer alcohols (FTOHs) and PFCAs.

PFAS have some unique properties, including their high stability to e.g. heat, pressure and light, and their hydrophilic and lipophilic nature, which have led to a large number of applications in industrial processes and consumer products. Uses of PFAS were studied in detail by Glüge et al. (2000), who identified more than 200 use categories for over 1400 individual PFAS. They also

[1] https://echo.epa.gov/trends/pfas-tools

studied individual PFAS and reported the number of their uses. The three best-known PFAS applications are their use as Aqueous Film Forming Foam in firefighting, textile impregnation and electroplating.

The European Chemicals Agency (ECHA) lists the following use categories with a PFAS tonnage > 10,000 tonnes/year for the European Union (ECHA, 2023):

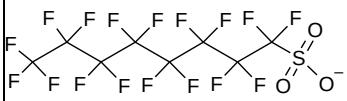
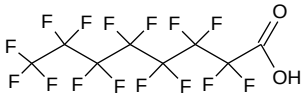
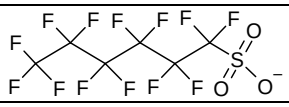
- Applications of fluorinated gases
- Textiles, upholstery, leather, apparel, carpets
- Medical devices
- Manufacture
- Food contact materials and packaging
- Transport

Several other use categories are mentioned in ECHA (2023), with lower tonnages.

3.3 Legal status

Three PFAS are currently included in the United Nations Stockholm Convention on POPs, effectuating a nearly worldwide regulation by all Parties to the Convention (Table 2). In addition, the group of long-chain PFCAs are currently under review for the Stockholm Convention, comprising PFCAs with carbon chain lengths from C_9 to C_{21}. POPs are compounds identified as persistent, bioaccumulative, toxic and subject to transport over long distances.

Table 2: Summary of PFAS regulated under the Stockholm Convention on Persistent Organic Pollutants (POPs)

PFAS acronym	Name	Structure	Year of addition	Regulation status
PFOS	Perfluorooctane sulfonate		2009	Annex B (restriction)
PFOA	Perfluorooctanoic acid		2019	Annex A (elimination)
PFHxS	Perfluorohexane sulfonate		2022	Annex A (elimination)

In the European Union, the Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) has issued several regulations for PFAS, including restrictions of PFOS and some PFCAs, ongoing reviews of proposed restrictions by Member States and listing of various PFAS as Substances of Very High Concern (SVHCs). The European-wide phase-out of PFAS in firefighting foams was proposed by ECHA in 2022. Notably, Denmark, Norway, Sweden, Germany and the Netherlands proposed a comprehensive restriction of PFAS as a group in 2023,

which is now being processed under ECHA. A summary of European regulatory activities was prepared by the OECD as of January 2023[2].

3.4 Physical-chemical properties

Given the wide definition of PFAS, the group includes compounds of solid state (e.g. fluoropolymers), liquids and gases. Considering the best-studied PFAS, i.e. PFSAs and PFCAs, their properties differ from those of other environmental pollutants, especially regarding their environmental partitioning, with consequences for their environmental fate. The long carbon chain in combination with an acid group renders the molecule both lipophilic and hydrophilic, placing it typically at the interface of different environmental media. These properties are the basis for PFAS use as surfactants. However, this partitioning behaviour means that parameters typically used in risk assessments, such as octanol-water partitioning coefficients (K_{OW}) do not apply to PFAS. Furthermore, models that predict physical-chemical properties and resulting environmental fate or toxicity based on chemical structure might not cover PFAS in their domain. Since PFCAs and PFSAs are acids, their physical-chemical properties also depend on pH, i.e. their occurrence as acids or ions.

The extremely stable C-F chemical bond makes PFAS persistent in the environment. However, some precursors can undergo reactions, for example the oxidation of FTOHs to PFCAs. These reactions can take place in the environment and in organisms and are therefore also referred to as biotransformation processes (Butt et al., 2014). This might seem contradictory to the generally described persistence of PFAS, but implies that the C-F bonds remain unchanged and that the reaction products usually have longer half-lives than the precursors.

Some PFAS are POPs because they bioaccumulate (Table 2). Unlike other purely lipophilic POPs, such as polychlorinated biphenyls (PCBs), PFAS bind to proteins and phospholipids in the body (De Silva et al., 2021), with implications for their toxicokinetics. Long-chain PFAS bioaccumulate more strongly than short-chain PFAS, which in turn are more water soluble (Brendel et al., 2018). Their higher water solubility can lead to elevated levels in groundwater and other drinking water sources, and also increase the uptake in plants (Ghisi et al., 2019), causing PFAS exposure through both food (via the food chain) and drinking water.

A summary of physical-chemical properties of PFAS with numerous literature references has been provided by the Interstate Technology and Regulatory Council of the USA[3], including downloadable data. This resource includes data on density, melting point, boiling point, solubility, vapour pressure, Henry's constant, critical micelle concentrations, partitioning coefficients between organic carbon and water (K_{OC}) and acid constants (pK_a values) for many PFAS, with relevant references. However, the high uncertainty of the data is highlighted.

[2] https://www.oecd.org/content/dam/oecd/en/topics/policy-sub-issues/risk-management-risk-reduction-and-sustainable-chemistry2/pfas-country-information/European%20Union.pdf
[3] https://pfas-1.itrcweb.org/4-physical-and-chemical-properties/

4 Mercury

4.1 Introduction

Mercury occurs naturally as mercury(II)sulphide (HgS) or cinnabar in the earth crust and has been anthropogenically used and emitted for centuries. Since the industrial revolution environmental levels of mercury have increased significantly because of coal burning and growing industrial activities. Mercury occurs in several forms, with consequences for its transport, accumulation and toxicity (Driscoll et al., 2013):

- **Elemental mercury Hg(0)** emitted to the atmosphere can be transported over long distances, including to the Arctic before oxidation and deposition.
- **Hg(II)** is the most common oxidation state. Hg(II) can be transported bound to particles, but generally deposits more efficiently. It can be reduced to Hg(0), which can then be re-volatilised, leading to important secondary sources of mercury.
- **Methylmercury ($CH3Hg^{+}$)** can be formed from inorganic mercury by anaerobic bacteria via biomethylation, for example in sediments. It bioaccumulates and biomagnifies in food webs and is highly toxic.

Mercury, more specifically methylmercury, was the main cause of the Minamata disease, which was first discovered in the 1950s. Victims showed various symptoms of neurological effects, which were most severe if exposure had occurred in early developmental stages (foetus, children). The disease was later related to the discharge of methylmercury with the wastewater of a factory producing acetaldehyde. Methylmercury bioaccumulated and biomagnified in the shellfish and fish of the area, resulting in mercury poisoning of the consumers. Since mercury can cross the placenta, mercury exposure also affects the next generation.

Given its long-range transport, bioaccumulation and biomagnification, mercury was already identified as a major concern in the Arctic in the 1990s, which has not been entirely solved today (AMAP, 1998; 2021b). While mercury levels in most Arctic human populations have decreased over time (Adlard et al., 2024), many time series in fish and wildlife from the Arctic still show increasing or no trends (Morris et al., 2022).

4.2 Production and use

Mercury has a long history of use in industry and consumer products, including its former use in thermometers and paints, and its ongoing use in fluorescence lamps and amalgam for tooth fillings. A major industrial use of mercury was in chlor-alkali plants producing chlorine and caustic soda. Mercury cell (Castner-Kellner) processes included reduction reactions of sodium with mercury to form an amalgam (cathode). Sodium atoms then move to an inner cell where mercury acts as an anode and releases oxidised sodium into water. Due to the toxicity of mercury, these processes are increasingly being phased out. According to UN Environment (2019), this process contributes < 1% to the total mercury emissions to air as of 2015. More important industrial processes with contributions to mercury emissions of approximately 10% each included cement production and non-ferrous metal production (UN Environment, 2019).

An updated global budget of mercury releases was presented in the Global Mercury Assessment prepared by the United Nations Environment Programme and AMAP (UN Environment, 2019) (Figure 2). A significant ongoing emission source of mercury is the combustion of coal where

mercury occurs naturally. The burning of coal in industrial processes and for energy consumption accounted for approximately 6 and 13% of total mercury emissions to air, with major sources in China (UN Environment, 2019).

Another significant source of mercury to the environment is from its use in artisanal and small-scale gold mining. Considering the emissions to air assessed by UN Environment (2019), it is the largest single source of mercury, accounting for approximately 38% of total atmospheric emissions. Mercury is used in the extraction of gold by forming an amalgam, which is then heated, releasing evaporated mercury and leaving the gold. Often performed without protective equipment, this procedure leads to local contamination and serious human exposure (Gyamfi et al., 2021), as well as emissions of the heated mercury to the atmosphere where it can be transported over long distances.

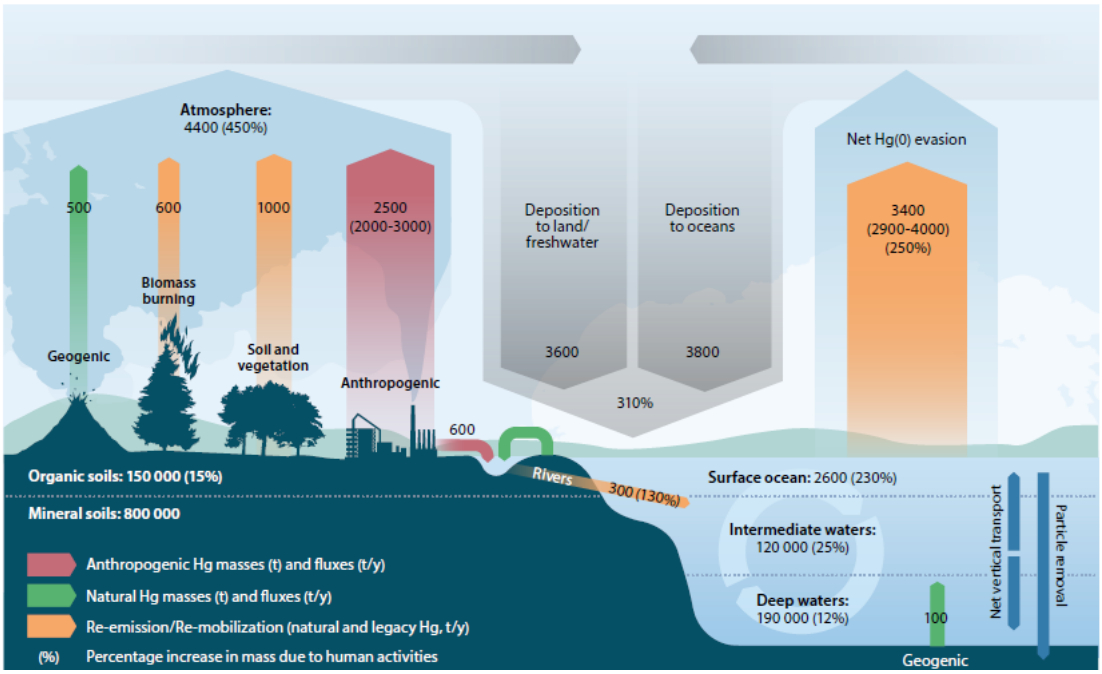


Figure 2: Global mercury budget with anthropogenically caused fluxes relative to a pre-anthropogenic time (1450 BC). The figure is from UN Environment (2019) and AMAP (2021b).

4.3 Legal status

Mercury is regulated under the United Nations Minamata Convention. The Convention aims to protect human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds (UNEP, 2024). The measures to achieve this include the control of the supply and trade of mercury, including limitations on specific sources such as primary mining (UNEP, 2024). Furthermore, its measures include the control of mercury-added products and manufacturing processes in which mercury and its compounds are used. Artisanal and small-scale gold mining is mentioned specifically. It also includes measures regarding mercury wastes and contaminated sites (UNEP, 2024). The Minamata Convention was adopted in 2013 and entered into force in 2017. It has been ratified by 154 countries to date (Figure 3).

In the European Union, the recently revised Regulation (EU) 2024/1849 of 13 June 2024 replaced previous Regulation (EU) 2017/852 and addressed remaining uses of mercury in the EU. These include the use in dental amalgam and certain fluorescence lamps, for which export, import and

manufacturing will be prohibited by 2026. In addition, crematoria were addressed as a source of mercury emissions for which efficient abatement technologies should be developed (EU, 2024).

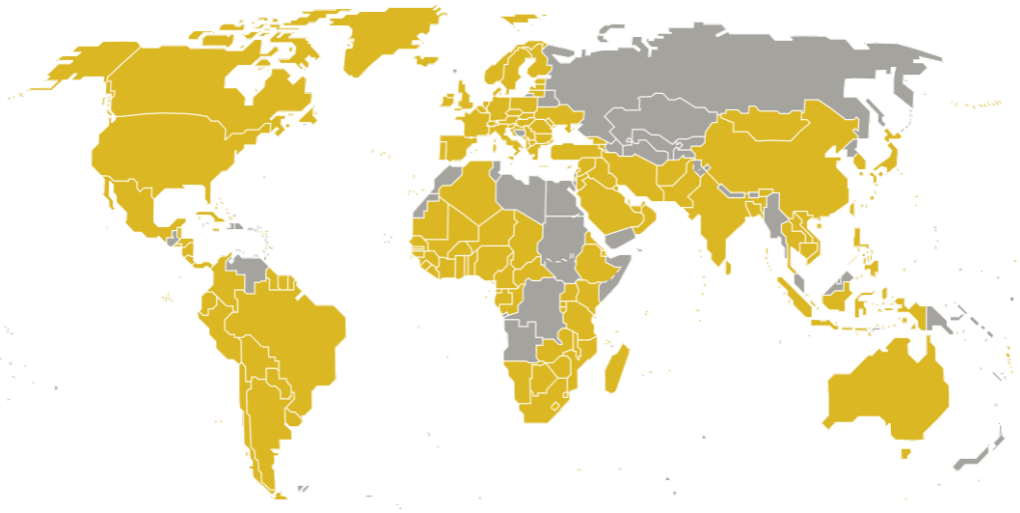


Figure 3: Parties of the Minamata Convention as of March 2025 (indicated with yellow colour). Copied from https://minamataconvention.org

4.4 Physical-chemical properties

As a chemical element, mercury is a silvery, shiny liquid at room temperature with a relatively high vapour pressure (Habashi, 2013). It is not biodegradable, but can occur in different redox states and react with organic molecules to form organometal compounds, as discussed in Section 4.1. As such, mercury is persistent. It bioaccumulates in its methylated form and is highly toxic. A summary of physical chemical-properties is given in Table 3.

Table 3: Physical-chemical properties of mercury, from Habashi (2013)

Property	**Value**
Atomic number	80
Atomic weight	200.59
Melting point	-38.89°C
Boiling point (at 101.3 kPa)	357.3°C
Density (at 0°C)	13.6 g/cm^3
Viscosity (at 0°C)	1.685 mPa·s
Vapour pressure (at 0°C)	0.026 Pa
Vapour pressure (at 20°C)	0.170 Pa
Vapour pressure (at 100°C)	Pa

5 Plastics

5.1 Introduction

Plastics are indispensable in modern everyday life and comprise a large variety of different polymers. Some plastic products are intended for short-term use, causing substantial quantities of plastic waste that require effective collection and disposal systems. If no adequate systems are provided or used, plastic waste turns into litter and becomes a pollution problem. The oceans are typically a sink for plastics, originating from land-based sources, reaching the sea via rivers, wastewater and runoff, as well as from sea-based sources, such as abandoned, lost and otherwise discarded fishing gear (ALDFG). Besides the obvious problem of disrupting experiences of untouched nature, with consequences for e.g. tourism, plastics can also affect fish and wildlife, for example through entanglement (NOAA, 2014). Larger plastic items are eventually broken down to microplastics, which can be taken up by organisms and cause adverse effects.

Microplastics are usually considered plastic particles < 5 mm. While no clear lower limit exists, particles < 0.1 µm have recently been described as nanoplastics. Micro- and nanoplastics can be formed from the physical degradation of larger plastic particles. Plastic particles are further characterized by their shape (e.g. fibres, films, fragments) and their colour. These characteristics can usually be determined with microscopic methods, whereas the determination of polymer identity requires spectroscopic techniques such as Fourier Transform Infrared (FTIR) or Raman spectroscopy. Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) is also used increasingly to determine polymers by mass instead of particle numbers.

Plastics are widely present in the Arctic environment, originating from distant and local sources (PAME, 2019). The Arctic Council Working Group for the Protection of the Arctic Marine Environment (PAME) has developed a Regional Action Plan for Marine Litter consisting of 59 actions in eight categories, ranging from actions to reduce marine litter inputs from fisheries and aquaculture to international cooperation (PAME, 2021). AMAP has developed guidelines for monitoring of (micro-)plastics in the Arctic to ensure harmonized monitoring approaches (AMAP, 2021c).

5.2 Production and use

The production of plastics has increased exponentially since the 1950s, with roughly 400 million tonnes currently produced every year (Figure 4). Most plastics are used in packaging, followed by use in the construction and transportation sector (OECD, 2022). Within packaging, roughly 50% of the plastic used is polyethylene (PE), with polypropylene (PP) and polyethylene terephthalate (PET) as other important polymer materials. In the construction sector, polyvinylchloride (PVC) accounts for about 50% of the materials, besides PE and other polymers for specialized applications (OECD, 2022; Vorkamp et al., 2023).

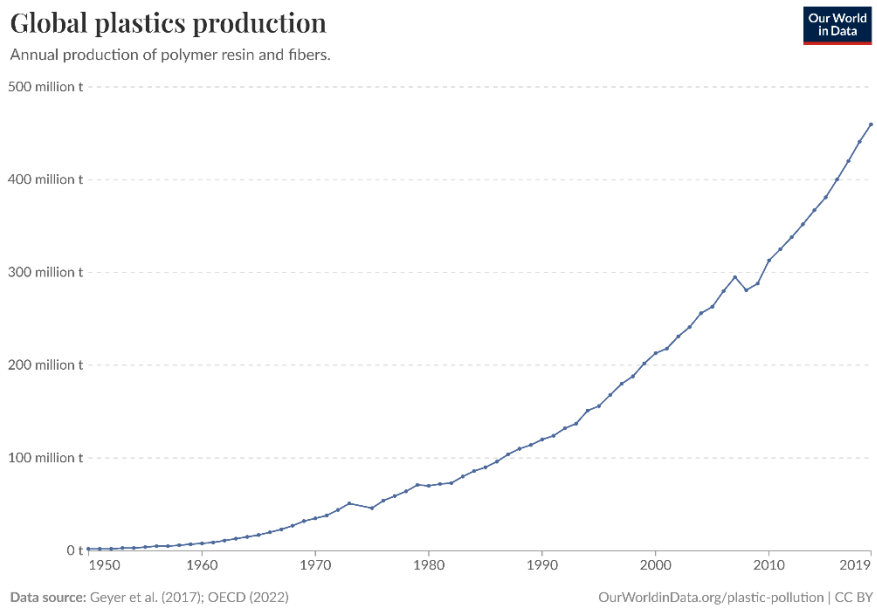
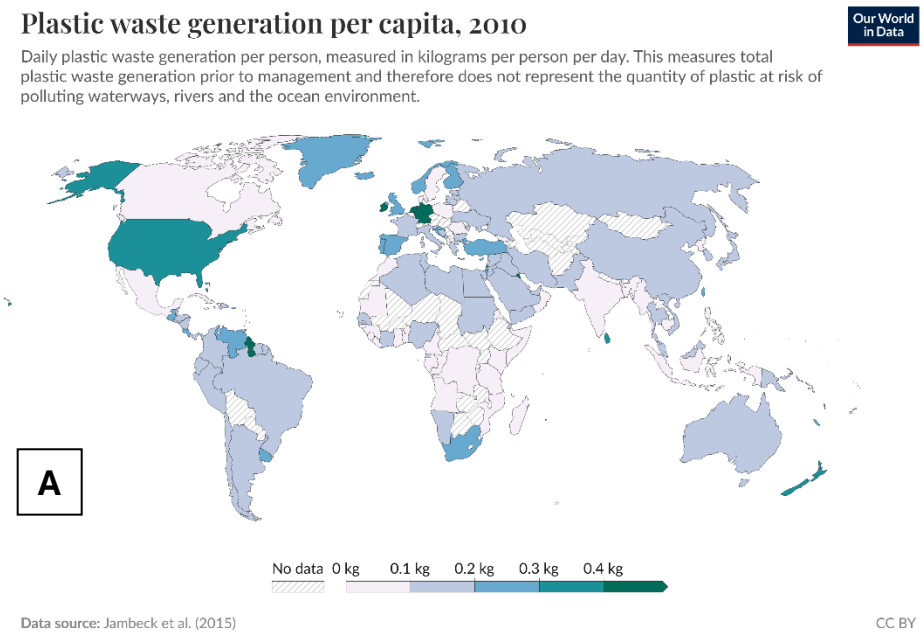


Figure 4: Global plastic production. The graph is taken from Our World in Data (https://ourworld indata.org) and is based on Geyer et al. (2017) and OECD (2022).

The generation of plastic waste follows the patterns of plastic use, with a slightly higher percentage originating from packaging (OECD, 2022; Vorkamp et al., 2023). Consequently, most of the plastic waste consists of PE, PP and PET. Geographically, most of the plastic waste is generated where the plastic is used. However, waste management differs considerably between regions and introduces disproportionality into plastic waste and plastic pollution. Figure 5 shows the amount of plastic waste that is produced per capita and the amount of mismanaged waste, which is more likely to be emitted to the environment and cause plastic pollution of the oceans.



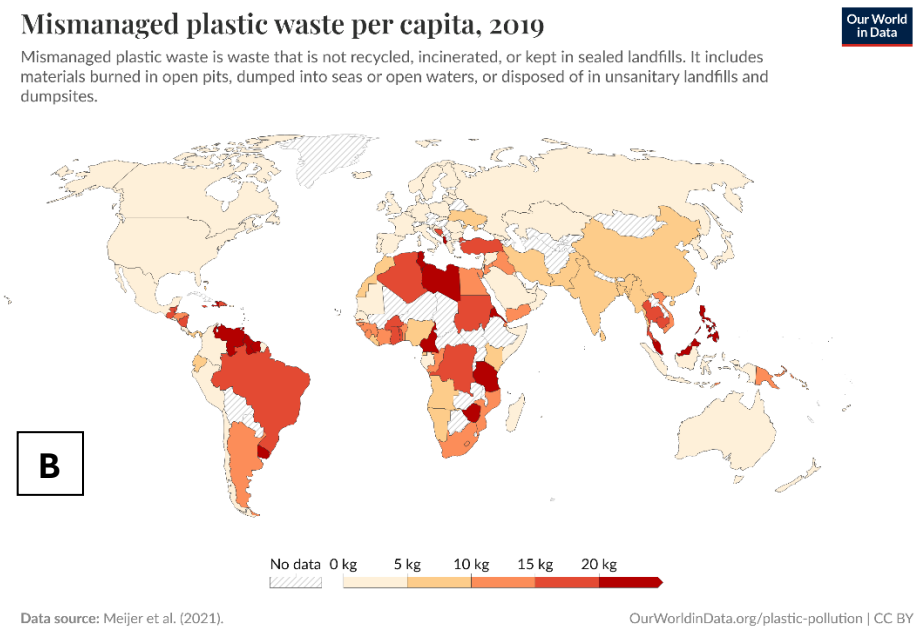


Figure 5: A: Amount of plastic waste produced per capita. B: Amount of mismanaged waste per capita. The graphs are taken from Our World in Data (https://ourworld indata.org) and are based on Jambeck et al. (2015) and Meijer et al. (2021).

Microplastics are characterized as either primary or secondary microplastics, depending on their origin. Primary microplastics were produced in this size for use in e.g. cosmetics, cleaning agents, industrial abrasives etc. (GESAMP, 2016). ECHA proposed a restriction of primary microplastics in the EU in 2019 to reduce emissions into the environment. However, the majority of microplastics in the environment is of secondary origin resulting from the breakdown of larger plastic particles through environmental weathering, including their degradation by mechanical processes, under the influence of UV light, biofilms etc. The development of microplastic quantities in the oceans is shown in Figure 6, including three extrapolation scenarios. Even if the emissions of microplastics were stopped, the amount of microplastics in the oceans will increase as a result of fragmentation of larger particles already present in the environment.

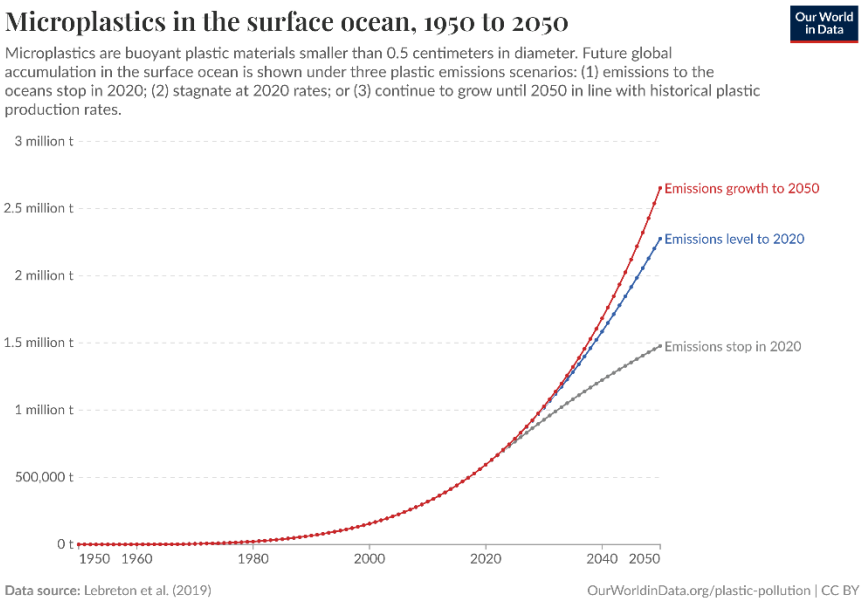


Figure 6: Development of microplastic quantities in the oceans over time, including three scenarios for future development. The graph is taken from Our World in Data (https://ourworld indata.org) and is based on Lebreton et al. (2019).

5.3 Legal status

The United Nations Environment Assembly has passed five resolutions on marine litter since 2014, with the most recent one on the end of plastic pollution via a legally binding global agreement. Since this fifth resolution was adopted, an Intergovernmental Negotiating Committee on Plastic Pollution[4] has worked in four sessions on the development of this agreement which is expected to address the full life cycle of plastics, including production, use and disposal. The first part of the fifth session took place in South Korea in November/December 2024, and the second part of this fifth session is planned for August 2025 in Switzerland. This initiative of a global plastic pollution treaty under the auspices of the United Nations has analogies to the Stockholm Convention on POPs and the Minamata Convention on mercury presented in Sections 3.3 and **Feil! Fant ikke referansekilden.**, respectively.

Table 4: Resolutions of the United Nations Environment Assembly (UNEA) related to plastic pollution.

Number	Topic	Year
UNEA1	Agreeing on the global emerging threat	2014
UNEA2	Identifying knowledge gaps	2016
UNEA3	Recognizing the inefficient global governance	2017
UNEA4	Strengthening cooperation and knowledge	2019
UNEA5	Ending plastic pollution	2022

Plastic pollution is considered in the EU Marine Strategy Framework Directive which aims to achieve Good Environmental Status of Europe's marine waters and to protect the marine resource base. This is defined for eleven descriptors, including *Descriptor 10: Marine Litter does not cause harm*. EU Directive 2019/904 regulates the reduction of the impacts of certain plastic products on the environment (EU, 2019). More recently, the EU has issued new rules to restrict the use of single-use plastic (EU, 2021).

The regional sea conventions, specifically the OSPAR Convention for the Protection of Marine Environment of the Northeast Atlantic and the HELCOM Baltic Marine Environment Protection Commission have developed regional action plans to reduce marine litter, including recent updates (HELCOM, 2015; OSPAR, 2022). As mentioned in Section **Feil! Fant ikke referansekilden.**, PAME has developed a regional action plan for the Arctic (PAME, 2021).

5.4 Physical-chemical properties

Plastic materials are durable, inert and generally resistant to degradation, making them favourable materials for protective containers of food, pharmaceuticals etc. As discussed above, exposure to physical abrasion, UV light and biological processes will lead to weathering in the environment, primarily resulting in generation of micro- and nanoplastics. Bioaccumulation of micro- and nanoplastics in organisms has been suggested, whereas biomagnification has not been finally substantiated (Miller et al., 2020; McMullen et al., 2024).

Given the variety of polymers, physical-chemical properties of plastic particles in the environment vary. Depending on their density, some plastic particles will float, while others will sink. However, their density-related behaviour in the environment can be affected by biofilms grown on the surfaces of the particles. In addition, some polymers are used as in foamed forms,

[4] https://www.unep.org/inc-plastic-pollution

such as foamed polystyrene (“Styrofoam”) and insulation foam made of polyurethane. These foamed polymers are common litter items in the environment (Feld et al., 2024) and have a lower density than non-foamed polymers. Densities of the most common plastics are given in Table 5, not considering foamed polymers.

Table 5: Density of plastic polymers often occurring as pollutants in the environment, taken from Erni-Cassola et al. (2019).

Polymer acronym	**Name**	**Density (g/cm^3)**
PE	Polyethylene	0.89-0.98
PP	Polypropylene	0.85-0.92
PS	Polystyrene	1.04
PET	Polyethylen terephthalate	1.10-1.40
PVC	Polyvinylchloride	1.38-1.41
PA	Polyamide	1.12-1.15
PUR	Polyurethane	1.20-1.26

6 Plastic additives

6.1 Introduction

Plastics contain various chemicals that are added to the polymers to ensure certain properties or functionalities, including, but not limited to, plasticizers (to increase polymer flexibility), flame retardants (to reduce flammability), UV stabilizers (to avoid photodegradation), antioxidants (to avoid oxidative weathering processes) and pigments (to impart colour). Each group of additives includes a multitude of different chemicals (Fauser et al., 2022) whose chemical identities are often unknown and might be proprietary information.

Chemical additives are not chemically bound in the polymer structure and therefore susceptible to gradual leaching from the plastic particle (Hahladakis et al., 2018). As a result, these substances can be released to the surrounding environment in the Arctic and elsewhere and cause exposure of organisms via water and food. Leaching may also take place in the gut of an animals that has swallowed a plastic particle (Kühn et al., 2020). The leaching is a diffusion process along a chemical activity gradient but might be favoured by weathering processes that e.g. enlarge the surface-to-volume area of the particle. However, it has also been argued that the process could go into the opposite direction, essentially cleaning the gut of the organism by absorbing chemicals previously taken up from the environment and prey, which are then excreted with the plastic particle (Koelmans, 2015).

As discussed in Section **Feil! Fant ikke referansekilden.**, plastic can be transported over long distances by oceans and rivers, and microplastics can also be transported in the atmosphere (Bergmann et al., 2019). This leads to an inherent transport of additives that are present in the plastic, including chemicals that might not have the physical-chemical properties to undergo long-range environmental transport by themselves (Jensen et al., 2022).

6.2 Production and use

Plastic additives include a variety of different chemicals and chemical groups with specific production and use patterns. A major group is that of plasticizers, with phthalic acid esters (phthalates) as the main chemical group, although there can also be others. The main use of phthalates is in PVC (see Section **Feil! Fant ikke referansekilden.**). They are produced in reactions of phthalic anhydride with alcohols to form esters and consist of many individual compounds with varying chains (Figure 7). The production of phthalates has increased to about 7.45 million tonnes in 2018 (Nagorka et al., 2022), responding to an increasing demand for PVC. The best-known phthalate is bis(ethylhexyl)phthalate (DEHP), however, it has been phased out from many applications due to health concerns.

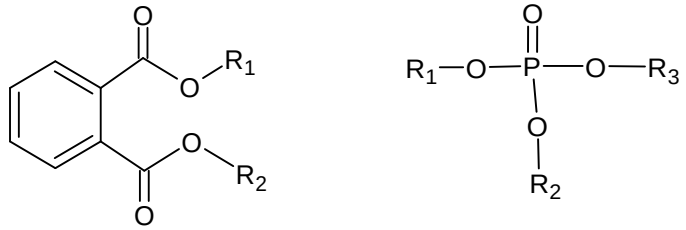


Figure 7: General chemical structure of phthalates (left) and organophosphate esters (right), two examples of chemical groups that are plastic additives, used as plasticizers and flame retardants, respectively. R1-R3 represent aliphatic or aromatic rests, which can be identical or different from each-other.

Another example of chemical additives is that of flame retardants, which include different types of chemicals. Historically, brominated flame retardants were used to prevent and slow down fires. Since the main group of polybrominated diphenyl ethers (PBDEs) was phased out due to their POP characteristics, organophosphate esters (OPEs) have increasingly been used as replacements. Some OPEs are also used as plasticizers. They are also called organophosphorus flame retardants or organophosphates, although this term is also used for organophosphate pesticides. Their general structure is shown in Figure 7. They are produced in reactions of phosphorus oxychloride with alcohols. Their global production volume was 400,000 tonnes in 2020 (Kung et al., 2022).

Phthalates and organophosphate esters are only two examples of plastic additives; however, they represent the two major groups of plasticizers and flame retardants. Each of the chemical groups consists of many individual molecules with different physical-chemical properties, hazard profiles and regulatory status.

6.3 Legal status

The Stockholm Convention on POPs recently classified the UV-filter UV-328 as the first non-halogenated POP at its 11th meeting in 2023 (UNEP, 2023b) (Figure 8). Its long-range transport was discussed in the regulation process and eventually considered transport with plastic particles over long distances, as well as transport with migratory animals who might have swallowed plastics. Some other POPs on the Stockholm Convention, such as PBDEs, hexabromocyclododecane (HBCDD) and short-chain chlorinated paraffins (SCCPs) were also plastic additives, but are now banned from use due to their POP characteristics.

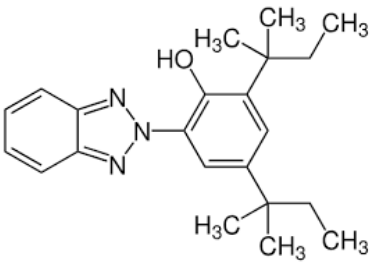


Figure 8: Chemical structure of UV-328, which was included in the Stockholm Convention on POPs in 2023.

The challenges associated with plastic additives leaching from plastics into the environment are included in ongoing negotiations for a global legally binding agreement to end plastic pollution under the United Nations (see Section **Feil! Fant ikke referansekilden.**). In addition, each group of plastic additives is regulated individually, often at the level of the individual compounds, considering their use and potential hazard.

Restrictions of phthalates and organophosphate ester flame retardants used here at the level of the EU were summarized by Vorkamp et al. (2021). Due to their endocrine disruption properties and related toxicity to reproduction, several phthalates are included on the list of SVHCs. DEHP, benzylbutylphthalate (BzBP), dibutylphthalate (DBP) and diisobutylphthalate (DiBP) are subject to EU authorization and cumulatively limited to 0.1% in electric and electronic equipment through the Restriction of Hazardous Substances (RoHS). DEHP, BzBP, DBP and others are also prohibited in cosmetics, toys and childcare articles. Likewise, the chlorinated organophosphate esters tri(2-chloroethyl)phosphate (TCEP), tri(chloroisopropyl)phosphate (TCIPP) and tri(1,3-dichloroisopropyl)phosphate (TDCIPP) are prohibited in toys in the EU. For other plastic additives, the legal status will be different.

6.4 Physical-chemical properties

As plastic additives comprise many different chemical classes, they also differ in their physical-chemical properties and environmental behaviour. Most high-volume plastic additives, including phthalates, organophosphate esters and bisphenols, are not considered persistent and bioaccumulative. However, as shown for the recently regulated UV-328, some plastic additives do fulfil POP criteria. Toxicity is a general concern, as many chemicals associated with plastics have proven or suspected adverse effects.

Most phthalates are liquids at room temperature, generally hydrophobic, lipophilic and with low volatility. Organophosphate esters generally have higher water solubilities than phthalates and are often found in the water phase as well as in the atmosphere, including in Arctic environments (Vorkamp et al., 2019). However, for both compound groups, these properties depend on the type of alcohol that formed the ester (Figure 7), e.g. the length of an alkyl chain in the molecule, and can vary by several orders of magnitude. Water solubilities, vapour pressures and various partition coefficients of a list of phthalates and organophosphate esters were compiled by Cousins and Mackay (2000) and Zhang et al. (2016).

Besides the risk of leaching from plastic particles to the surrounding aquatic environment or in the gut of an animal, the use of plastic additives in consumer products also makes some of them important contaminants in the indoor environment. Emitted from a product, they will partition between air and particles (including settled dust) according to their physical-chemical properties. Phthalates, organophosphate esters and other plastic additives can have relatively high concentrations in dust (Zhu et al., 2023). Thus, the indoor environment can be a significant exposure pathway for humans, especially for children who are more exposed to dust than adults through hand-to-mouth activities and playing on the floor.

7 Polycyclic aromatic hydrocarbons (PAHs)

7.1 Introduction

Polycyclic aromatic hydrocarbons (PAHs) consist of at least two fused aromatic rings (Figure 9). They are emitted to the environment from pyrogenic sources, i.e. from incomplete combustion processes of both natural and anthropogenic nature, for example in wildfires or from fossil fuel burning, and from petrogenic sources, due to their occurrence in coal and oil. To a minor extent, PAHs might also be used commercially (Abdel-Shafy and Mansour, 2016). PAHs only consist of carbon and hydrogen and thus exclude heterocyclic PAHs (with nitrogen, sulphur or oxygen on the ring) or PAHs with substitutions. These are typically summarized with PAHs as polycyclic aromatic compounds (PACs).

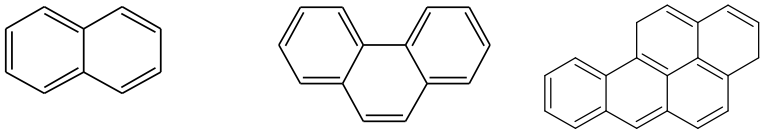


Figure 9: Examples of three polycyclic aromatic hydrocarbons: Naphthalene (left), phenanthrene (middle) and benzo[a]pyrene (right).

PAHs are of concern because of their carcinogenicity, mutagenicity and other adverse effects. The United States Environmental Protection Agency defined 16 priority PAHs in 1976, which are often first choice in measurement campaigns. However, this list likely underestimates PAH toxicity (Andersson and Achten, 2015). PAHs can reach the Arctic with long-range atmospheric transport, as PAHs partition between the gas phase and particles according to their physical-chemical properties. In addition, they can be emitted from local pyrogenic and petrogenic sources in the Arctic. Muir et al. (2025) recently reviewed projections for future development under climate change, including expected increases in

- PAH transport to the Arctic from wildfires,
- PAH releases from thawing permafrost,
- PAH emissions from increasing human activity, for example related to oil exploitation, mining and traffic,
- PAH pollution from accidental oil spills.

7.2 Production and use

As mentioned in Section **Feil! Fant ikke referansekilden.**, PAHs are formed in the incomplete combustion of organic matter, including fossil fuels, such as coal, oil and gasoline, as well as biomass sources such as wood and tobacco. Industrial activities and energy generation significantly contribute to PAH emissions, while natural sources can include forest fires and volcanic activity.

An inventory of the global atmospheric emissions was published by Shen et al. (2013), covering the years 1960-2008 and future predictions. More than half of the pyrogenic PAH emissions originated from residential/commercial biomass burning (60%), followed by open-field natural and anthropogenic biomass burning (wildfires, agriculture, deforestation) (14%) and on-road traffic (13%). Shen et al. (2013) noted significant geographical differences, for example with wildfires/deforestation dominating the profiles from Angola and Brazil, whereas indoor firewood burning was a substantial contribution in most other countries, except Russia, where emissions

from vehicles had the highest percentage of total emissions. Biomass burning emitted a wide spectrum of PAHs, while transport was mainly associated with naphthalene emissions. For human exposure, indoor PAH sources play a role, for example emitted from cooking and heating in combination with insufficient ventilation (Bai et al., 2024).

The study by Shen et al. (2013) also showed that PAH emissions in developed countries peaked in the 1970s, which the authors attributed to emission mitigation technologies in the transport and industrial sector. Although vehicle exhaust has been reduced for individual cars over time, this could not compensate for the increase in vehicle numbers in developing countries, also including China, India and Brazil in this study.

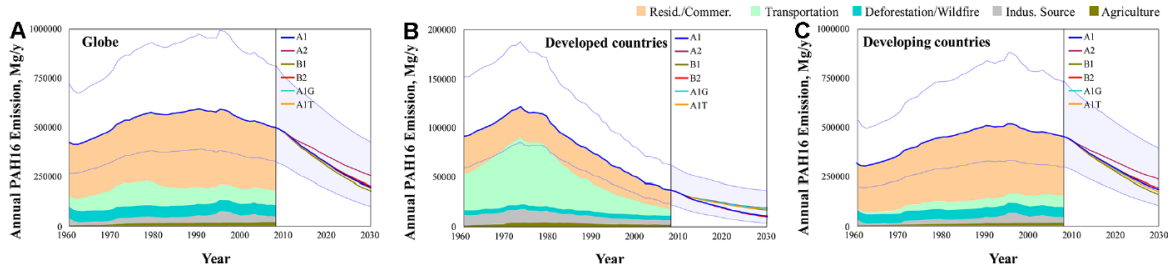


Figure 10: Atmospheric emissions of polycyclic aromatic hydrocarbons (PAHs) since 1960s with future projections, for A: the world; B: developed countries; C: developing countries. Reprinted with permission from Shen et al. (2013) Environ. Sci. Technol. 47, 6415-6424. Copyright 2013, American Chemical Society.

The major oil spill in the Arctic resulting from the Exxon Valdez accident in Prince William Sound, Alaska, in 1989 had many long-term effects on local ecosystems. After the immediate disastrous effects from the oil itself, studies showed that chronic exposures to PAHs at sublethal levels affected fish, seabirds and marine mammals and delayed population recovery (Peterson et al., 2003).

7.3 Legal status

PAHs are not included in the Stockholm Convention on POPs as they do not typically bioaccumulate, except in low trophic animals such as bivalves. However, they are included in the Convention on Long-Range Transboundary Air Pollution of the United Nations Economic Commission for Europe.

The EU has classified eight PAHs as carcinogenic, which are prohibited in consumer products at individual levels above 1 mg/kg, with a level of 0.5 mg/kg for toys and childcare articles (EU, 2013). Questions about potential PAH exposure have been raised in connection with the recycling of rubber from tyres, often re-used on artificial turfs or playground (Diekmann et al., 2019). For granules used as infills, EU regulation 2021/1199 set a limit of 20 mg/kg for the sum of the eight specified PAHs. The EU has also set limit values in food items for benzo[a]pyrene as well as the sum of benzo[a]pyrene, benz[a]anthracene, benzo[b]fluoranthene and chrysene. However, derogations exist for several countries, in order to preserve traditions of preparing and consuming smoked meat and fish (EU, 2023).

7.4 Physical-chemical properties

PAHs are relatively persistent in the environment, but can undergo oxidative and photolytic degradation, potentially leading to transformation products of higher toxicity.

PAHs are generally hydrophobic and lipophilic and consequently have low water solubilities. Their melting and boiling points increase with their molecular weight, while their water solubility and volatility decrease. Low molecular weight PAHs can volatilise and be transported with air. Some physical-chemical properties for the three PAHs in Figure 9 are summarized in Table 6 (Balint et al., 2021).

Table 6: Selection of physical-chemical properties of naphthalene, phenanthrene and benzo[a]pyrene. The data are taken from Balint et al. (2021). Vapour pressures and water solubilities are at 25°C.

	Naphthalene	**Phenanthrene**	**Benzo[a]pyrene**
Molecular weight	128.17 g/mol	178.23 g/mol	252.31 g/mol
Melting point	80°C	99°C	160°C
Boiling point	218°C	338°C	310°C
Density	1.02 g/cm^3	0.98 g/cm^3	1.35 g/cm^3
$\log K_{OW}$	3.40	4.47	6.05
Vapour pressure	11.33 Pa	$1.61 \cdot 10^{-2}$ Pa	$1.33 \cdot 10^{-8}$ Pa
Water solubility	31 mg/L	1.15 mg/L	$2.6 \cdot 10^{-4}$ mg/L

8 References

Abdel-Shafy; Mansour, M.S.M. (2016) A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation. Egypt. J. Pet. 25, 107-123.

Adlard, B.; Bonefeld-Jørgensen, E.C.; Dudarev, A.A.; Olafsdottir, K.; Abass, K.; Ayotte, P.; Caron-Beaudoin, E.; Drysdale, M.; Garcia-Barrios, J.; Gyllenhammar, I.; Laird. B.; Lemire, M.; Lignell, S.; Long, M.; Norström, K.; Packull-McCormick, S.; Petersen, M.S.; Ratelle, M.; Rautio, A.; Timmerman, A.; Weihe, P.; Wennberg, M. (2024) Levels and trends of metals in human populations living in the Arctic. Int. J. Circumpolar Health 83, 2386140.

AMAP (1998) AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, Oslo. xii+859 pp.

AMAP (2017) AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo. Norway. xvi+353pp.

AMAP (2021a). AMAP Assessment 2020: POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii+134pp.

AMAP (2021b). AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 324pp.

AMAP (2021c). AMAP Litter and Microplastics. Monitoring Guidelines Version 1.0. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 257pp.

Andersson, J.T.; Achten, C. (2015) Time to say goodbye to the 16 EPA PAHs? Toward an up-to-date use of PACs for environmental purposes. Polycycl. Aromat. Comp. 35, 330-354.

Bai, L.; Geng, X.; Lui, X. (2024) Review of polycyclic aromatic hydrocarbons pollution characteristics and carcinogenic risk assessment in global cooking environments. Environ. Pollu. 361, 124816.

Balint, A. (2021) Physical, chemical and toxicological properties of polycyclic aromatic hydrocarbons (PAHs) in human exposure assessments to contaminated soil and groundwater. MATEC Web of Conferences 342, 03016. https://doi.org/10.1951/matecconf/202134203016

Bergmann, M.; Mützel, S.; Primpke, S.; Tekman, M.B.; Trachsel, J.; Gerdts, G. (2019) White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 5, eaax1157.

Bergmann, M.; Collard, F.; Fabres, J.; Gabrielsen, G.W.; Provencher, J.; Rochman, C.M.; van Sebille, E.; Tekman, M.B. (2022) Plastic pollution in the Arctic. Nature Reviews Earth & Environment 3, 323-337.

Bossi, R.; Riget, F.; Dietz, R.; Sonne, C.; Fauser, P.; Dam, M.; Vorkamp, K. (2005) Preliminary screening of perfluorinated surfactants in fish, birds and marine mammals from Greenland and the Faroe Islands. Environ. Pollut. 136, 323-329.

Brendel, S.; Fetter, E.; Staude, C.; Vierke, L.; Biegel-Engler, A. (2018) Short-chain perfluoroalkyl acids: environmental concerns and a regulatory strategy under REACH. Environ. Sci. Eur. 30, 9.

Buck, R.C.; Franklin, J.; Berger, U.; Conder, J.M.; Cousins, I.T.; de Voogt, P.; Jensen, A.A.; Kannan, K.; Mabury, S.A.; van Leeuwen, S.P.J. (2011) Perfluoroalkyl and polyfluoroalkyl substances in the

environment: Terminology, classification, and origins. Integr. Environ. Assess. Manag. 7, 513-541.

Butt, C.M.; Muir, D.C.G.; Mabury, S.A. (2014) Biotransformation pathways of fluorotelomer-based polyfluoroalkyl substances: A review. Environ. Toxicol. Chem. 33, 243-267.

Collard, F.; Ask, A. (2021) Plastic ingestion by Arctic fauna: A review. Sci. Total Environ. 786, 147462.

Cousins, I.; Mackay, D. (2000) Correlating the physical-chemical properties of phthalate esters using the “three solubility” approach. Chemosphere 41, 1389-1399.

De Silva, A.O.; Armitage, J.M.; Bruton, T.A.; Dassuncao, C.; Heiger-Bernays, W.; Hu, X.C.; Kärrman, A.; Kelly, B.; Ng, C.; Robuck, A.; Sun, M.; Webster, T.F.; Sunderland, E.M. (2021) PFAS exposure pathways for humans and wildlife: A synthesis of current knowledge and key gaps in understanding. Environ. Toxicol. Chem. 40, 631-657.

Diekmann, A.; Giese, U.; Schaumann, I. (2019) Polycyclic aromatic hydrocarbons in consumer goods made from recycled rubber material: A review. Chemosphere 220, 1163-1178.

Driscoll, C.T.; Mason, R.P.; Chan, H.M.; Jacob, D.J.; Pirrone, N. (2013) Mercury as a global pollutant: Sources, pathways, and effects. Environ. Sci. Technol. 47, 4967-4983.

ECHA (2023) Annex to the ANNEX XV Restriction Report, Proposal for a restriction. Substance name(s): Per- and polyfluoroalkyl substances (PFASs). IUPAC name(s): n.a. EC number(s): n.a. CAS number(s): n.a. European Chemicals Agency.

Erni-Cassola, G.; Zadjelovic, V.; Gibson, M.I.; Christie-Oleza, J.A. (2019) Distribution of plastic polymer types in the marine environment; A meta-analysis. J. Hazard. Mater. 369, 691-698.

plastic infant feeding bottles. Official Journal of the European Union L87, 1-2.

EU (2013) Commission implementing regulation (EU) no. 1272/2013 of 6 December 2013 amending regulation (EU) no. 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards polycyclic aromatic hydrocarbons. Official Journal of the European Union, L328, 7.12.2013.

EU (2019) Directive (EU) 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, L155, 12.6.2019.

EU (2021) European Commission: Directorate-General for Environment, Turning the tide on single-use plastics, Publications Office of the European Union, https://data.europa.eu/doi/10.2779/800074

EU (2023) Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. Official Journal of the European Union, L119, 5.5.2023.

EU (2024) Regulation (EU) 2024/1849 of the European Parliament and of the Council of 13 June 2024 amending Regulation (EU) 2017/1849 on mercury as regards dental amalgam and other mercury-added products subject to expert, import and manufacturing restrictions. Official Journal of the European Union, L Series, 10.7.2024.

Fauser, P.; Vorkamp, K.; Strand, J. (2022) Residual additives in marine microplastics and their risk assessment – a critical review. Mar. Pollut. Bull. 177, 113467.

Feld, L.; da Silva, V.; Strand, J. (2024) Characterization of foamed plastic litter on Danish reference beaches – Pollution assessment and multivariate exploratory analysis, Mar. Pollut. Bull. 180, 113774.

GESAMP (2016) Sources, fate and effects of microplastics in the marine environment: part two of a global assessment. GESAMP no. 93, 220pp.

Geyer, R.; Jambeck, J.R.; Law, K.L. (2017) Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782.

Ghisi, R.; Vamerali, T.; Manzetti, S. (2019) Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: A review. Environ. Res. 169, 326-341.

Gyamfi, O.; Sørensen, P.B.; Darko, G.; Ansah, E.; Vorkamp, K.; Leth, J.B. (2021) Contamination, exposure and risk assessment of mercury in the soils of an artisanal gold mining community in Ghana. Chemosphere 267, 128910.

Glüge, J.; Scheringer, M.; Cousins, I.T.; DeWitt, J.C.; Goldenman, G.; Herzke, D.; Lohmann, R.; Ng, C.A.; Trier, X.; Wang, Z. (2020) An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environ. Sci.: Processes Impacts 22, 2345-2373.

Habashi, F. (2013) Mercury, Physical and Chemical Properties. In: Kretsinger, R.H., Uversky, V.N., Permyakov, E.A. (eds) Encyclopedia of Metalloproteins. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-1533-6_307

Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. (2018) An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard. Mater. 344, 179-199.

Hamilton, B.M.; Baak, J.E.; Vorkamp, K.; Hammer, S.; Granberg, M.; Herzke, D.; Provencher, J.F. (2023) Plastics as a carrier of chemical additives to the Arctic: Possibilities for strategic monitoring across the circumpolar North. Arct. Sci. 9, 284-296.

HELCOM (2015) Regional action plan for marine litter in the Baltic Sea, Baltic Marine Environmental Protection Commission, 20pp.

Jambeck, J.R.; Geyer, R.; Wilcox, C.; Siegler, T.R.; Perryman, M.; Andrady, A.; Narayan, R.; Law, K.L. (2015) Plastic waste inputs from land into the ocean. Science 347, 768-771.

Jensen, S.; Grøsvik, B.E.; Halsband, C.; Halldórsson, H.; Leslie, H.A.; Gunnlaugsdóttir, H.; Guls, H.D.; Vorkamp, K.; Granberg, M.E.; Sigurðsson, V.; Jörundsdóttir, H.Ó. (2022) Understanding microplastic pollution in the Nordic marine environment - knowledge gaps and suggested approaches. Microplastics and Nanoplastics 2, 22.

Kallenborn, R.; Brorström-Lundén, E.; Reiersen, L.-O.; Wilson, S. (2018) Pharmaceuticals and personal care products (PPCPs) in Arctic environments: indicator contaminants for assessing local and remote anthropogenic sources in a pristine ecosystem in change. Environ. Sci. Pollut. Res. 25, 33001-33013.

Koelmans, A.A. (2015) Modeling the role of microplastics in bioaccumulation or organic chemicals to marine aquatic organisms. A critical review. In: Bergmann, M.; Gutow, L.; Klages, M. (eds.) Marine Anthropogenic Litter. Springer, ISBN 978-3-319-16509-7, p. 309-324.

Kühn, S.; Booth, A.M.; Sørensen, L.; van Oyen, A.; van Franeker, J.A. (2020) Transfer of additive chemicals from marine plastic debris to the stomach oil of northern fulmars. Front. Environ. Sci. 8, 138.

Kung, H.C.; Hsieh, Y.-K.; Huang, B.-W.; Cheruiyot, N.K.; Chang-Chien, G.-P. (2022) An overview: Organophosphate flame retardants in the atmosphere. Aerosol Air Qual. Res. 22, 220148.

Lebreton, L.; Egger, M.; Slat, B. (2019) A global mass budget for positively buoyant macroplastic debris in the ocean. Scientific Reports 9, 12922.

Lohmann, R.; Abass, K.; Bonefeld-Jørgensen, E.C.; Bossi, R.; Dietz, R.; Ferguson, S.; Fernie, K.J.; Grandjean, P.; Herzke, D.; Houde, M.; Lemire, M.; Letcher, R.J.; Muir, D.; De Silva, A.O.; Ostertag, S.K.; Rand, A.A.; Søndergaard, J.; Sonne, C.; Sunderland, E.M.; Vorkamp, K.; Wilson, S.; Weihe, P. (2024) Cross-cutting studies of per- and polyfluorinated alkl substances (PFAS) in Arctic wildlife and humans. Sci. Total Environ. 954, 176274.

McMullen, K.; Vargas, F.H.; Calle, P.; Alavarado-Cadena, O.; Pakhomov, E.A.; Alava, J.J. (2024) Modelling microplastic bioaccumulation and biomagnification potential in the Galapagos penguin ecosystem using Ecopath and Ecosim (EwE) with Ecotracer. PLoS ONE 19(1): e0296788.

Meijer, L.J.J.; van Emmerik, T.; van der Ent, R.; Schmidt, C.; Lebreton, L. (2021) More than 1000 rivers account for 80% of global rivering plastic emissions into the ocean. Sci. Adv. 7, eaaz5803.

Miller, M.E.; Hamann, M.; Kroon, F.J. (2020) Bioaccumulation and biomagnification of microplastics in marine organisms: A review and meta-analysis of current data. PLoS ONE 15(10): e0240792.

Morris, A.D.; Wilson, S.J.; Fryer, R.J.; Thomas, P.J.; Hudelson, K.; Andreasen, B.; Blévin, P.; Bustamante, P.; Chastel, O.; Christensen, G.; Dietz, R.; Evans, M.; Evenset, A.; Ferguson, S.H.; Fort, J.; Gamberg, M.; Grémillet, D.; Houde, M.; Letcher, R.J.; Loseto, L.; Muir, D.; Pinzano, M.; Poste, A.; Routti, H.; Sonne, C.; Stern, G.; Rigét, F.F. (2022) Temporal trends of mercury in Arctic biota: 10 more years of progress in Arctic monitoring. Sci. Total Environ. 839, 155803.

Muir, D.; Bossi, R.; Carlsson, P.; Evans, M.; De Silva, A.; Halsall, C.; Rauert, C.; Herzke, D.; Hung, H.; Letcher, R.; Rigét, F.; Roos, A. (2019) Levels and trends of poly- and perfluoroalkyl substances in the Arctic environment – An update. Emerg. Contam. 5, 240-271.

Muir, D.; Gunnarsdóttir, M.J.; Koziol, K.; von Hippel, F.A.; Szumiňska, D.; Ademollo, N.; Corsolini, S.; De Silva, A.; Gabrielsen, G.; Kallenborn, R.; Polkowska, Z.; Krümmel, E.; Vorkamp, K. (2025) Local sources *versus* long-range transport of organic contaminants in the Arctic: future developments related to climate change. Environ. Sci.: Adv. 4, 255-408.

Nagorka, R.; Birmili, W.; Schulze, J.; Koschorreck, J. (2022) Diverging trends of plasticizers (phthalates and non-phthalates) in indoor and freshwater environments – why? Environ. Sci. Eur. 34, 46.

NOAA (2014) Entanglement. National Oceanic and Atmospheric Administration Marine Debris Program. 2014 Report on the Entanglement of Marine Species in Marine Debris with an Emphasis on Species in the United States. Silver Spring, MD. 28 pp.

OECD (2021) Reconciling terminology of the universe of per- and polyfluoroalkyl substances: Recommendations and practical guidance. Series on Risk Management, No. 61.

OECD (2022) Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options. In: Global Plastics Outlook. https://doi.org/10.1787/de747aef-en

OSPAR (2022) The second OSPAR regional action plan on marine litter. RAP ML 2022-2030, OSPAR Agreement 2022-5.

PAME (2019) Desktop study on marine litter including microplastics in the Arctic. Protection of the Arctic Marine Environment, May 2019.

PAME (2021) Regional action plan on marine litter in the Arctic. Protection of the Arctic Marine Environment, May 2021.

Peterson, C.H.; Rice, S.D.; Short, J.W.; Esler, D.; Bodkin, J.L.; Ballachey, B.E.; Irons, D.B. (2003) Long-term ecosystem response to the Exxon Valdez oil spill. Science 302, 2082-2086.

Shen, H.; Huang, Y.; Wang, R.; Zhu, D.; Li, W.; Shen, G.; Wang, B.; Zhang, Y.; Chen, Y.; Lu, Y.; Chen, H.; Li, T.; Sun, K.; Li, B.; Liu, W.; Liu, J.; Tao, S. (2013) Global atmospheric emissions of polycyclic aromatic hydrocarbons from 1960 to 2008 and future predictions. Environ. Sci. Technol. 47, 6415-6424.

UN Environment (2019) Global Mercury Assessment 2018. UN Environment Programme, Chemicals and Health Branch Geneva, Switzerland. ISBN 978-92-807-3744-8.

UNEP (2023a) Stockholm Convention on Persistent Organic Pollutants (POPs). Text and Annexes, revised in 2023. United Nations Environment Programme, Stockholm Convention.

UNEP (2023b) Listing of UV-328. Decision SC-11/11. https://chm.pops.int/Convention/COP/COPDecisions/tabid/208/Default.aspx

UNEP (2024) Minamata Convention on Mercury. Text and Annexes – 2024 Edition. United Nations Environment Programme, UNEP/MC/2024/2.

Vorkamp, K.; Balmer, J.E.; Hung, H.; Letcher, R.J.; Rigét, F.F.; de Wit, C.A. (2019). Current-use halogenated and organophosphorous flame retardants: A review of their presence in Arctic ecosystems. Emerg. Contam. 5, 179-200.

Vorkamp, K.; Castaño, A.; Antignac, J.-P.; Boada, L.D.; Cequier, E.; Covaci, A.; Esteban López, M.; Haug, L.S.; Kasper-Sonnenberg, M.; Koch, H.M.; Luzardo, O.P.; Osīte, A.; Rambaud, L.; Pinorini, M.-T.; Sabbioni, G.; Thomsen, C. (2021) Biomarkers, matrices and analytical methods targeting human exposure to chemicals selected for a European human biomonitoring initiative. Environ. Int. 146, 106082.

Vorkamp, K.; Ryberg, M.; Fauser, P.; Bach, L.; Linnebjerg, J.F.; Strand, J. (2023) Indicators for plastic pollution. TemaNord 2023:526, ISBN 978-92-893-7649-5. https://pub.norden.org/temanord2023-526/index.html

Zhang, X.; Sühring, R.; Serodio, D.; Bonnell, M.; Sundin, N.; Diamond, M.L. (2016) Novel flame retardants: Estimating the physical-chemical properties and environmental fate of 94 halogenated and organophosphate PBDE replacements. Chemosphere 144, 2401-2408.

Zhu, L.; Hajeb, P.; Fauser, P.; Vorkamp, K. (2023) Endocrine disrupting chemicals in indoor dust: A review of temporal and spatial trends, and human exposure. Sci. Total Environ. 874, 162374.