2.1: Introduction

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Leaning objectives:

You should be able to:

- mention the main groups of environmental pollutants
- comprehend the molecular structures of the most important organic pollutants
- mention the most important functional groups determining the environmental properties of organic pollutants

Keywords: natural toxicants, molecular structures, pollutant classes, anthropogenic pollutants

Introduction

Environmental toxicology deals with the negative effects of the exposure to chemicals we regard as pollutants (or contaminants/toxicants). Environmental toxicants receive a lot of media attention, but many critical details are getting lost or are easily forgotten. The clip "You, Me, DDT" shows the discovery of the grandson of the works of his grandfather, the Swiss inventor of the insecticide DDT, Paul Hermann Müller, who received the Nobel Prize for Medicine for that in 1948 (see also Section 1.3). The clip "Stop the POPs" interviews (seemingly) common people about one of the most heavily regulated group of pollutants.

Organisms, including humans, have always been exposed to chemicals in the environment and rely on many of these chemicals as nutrients. Volcanoes, flooding of acid sulfur lakes, and forest fires have caused widespread contamination episodes. Organisms are also in many cases directly or indirectly involved in the fate and distribution of undesirable chemicals in the environment. Many naturally occurring chemicals are toxicants already (see also Section 1.3), think for example about:

- local arsenic or mercury hotspots in the Earth's crust, contaminating water pumps or rice irrigation fields;
- plant-based defence chemicals such as alkaloids, morphine in poppy seeds, juglone from black walnut trees);
- fungal toxins, such as mycotoxins threatening grain storage depots after harvests;
- bacterial toxins, such as the botulinum toxin, a neurotoxic protein produced by the bacterium *Clostridium botulinum* which is the most acutely lethal toxin known at ~10 ng/kg body weight when inhaled;
- phycotoxins, produced by algae, in mass algal blooms or those that may end up at dangerous levels in shell food;
- zootoxins in animals, such as venom of snakes and defensive toxins on the skin of amphibians.

Human activities have had an enormous impact on the increased exposure to natural chemicals as a result of, for example, the mining and use of metals, salts and fossil fuels from geological resources. This is for example the case for many metals, nutrients such as nitrate, and organic chemicals present in fossil fuels. Additionally, the industrial synthesis and use of organic chemicals, and the disposal of wastes, have resulted in a wide variety of hazardous chemicals that had either never existed before, or at least not in the levels or chemical form that occur nowadays in our heavily polluted global system. These are typically organic chemicals that are referred to as *anthropogenic* (`due to humans in nature´) or *xenobiotic* (`foreign to organisms´) chemicals. In this chapter we aim to clarify the key properties and functionalities of the most common groups of pollutants as a result from human activities, and provide some background on how we can group them and understand their behaviour in the environment.

In the field of environmental toxicology, we are most often concerned about the effects of two distinct types of contaminants: metals and organic chemicals. In some cases other chemicals, such as radioactive elements, may also be important while we could also consider the ecological effects of highly elevated nutrient concentrations (eutrophication) as a form of environmental toxicology.

Metals

Metals and metalloids (elements intermediate between metals and non-metals) comprise the majority of the known elements. They are mined from minerals and used in an enormous variety of applications either in their elemental form or as chemicals with inorganic or organic elements or ions. Many metals occur as cations, but many processes influence the dissolved form of metals. Aluminium for example for example is only present under very acidic conditions as dissolved cation (Al^{3+}), while at neutral pH the metal speciates into for example certain hydroxides ($Al(OH_3)^0$). Mercury as free ion is present at (Hg^{2+}) but due to microbial transformation the highly toxic product methylmercury (CH_3Hg^+, or $MeHg^+$) is formed. Mining and processing of metals together with disposal of metal-containing wastes are the main contributors to metal pollution although sometimes metals are introduced deliberately into the environment as biocides. The widely used pesticide copper sulfate in e.g. grape districts is an example (LINK on comparison to glyphosate here). More information on metals considered to be environmental pollutants is given in Section 2.2.1.

Organic chemicals

Organic chemicals are manufactured to be used in a wide variety of applications. These range from chemicals used as pesticides to industrial intermediates, fossil fuel related hydrocarbons, additives used to treat textiles and polymers, such as flame retardants and plasticisers, and household chemicals such as detergents, pharmaceuticals and cosmetics.

Organic chemicals that we regard as environmental pollutants include a huge variety of different structures and have a wide variety of properties that influence environmental distribution and toxicity. With such a wide variety of chemicals to deal with, it is useful to classify them into groups. Depending on our interest, we can base this classification on different aspects, for example on their chemical structure, their physical and chemical properties, the applications the chemicals are used in, or their effects on biological systems. These aspects are of course closely related to their chemical structure as this is the basis of the properties and effects of chemicals. An overview of different ways of classifying environmental contaminant (sometimes referred to as ecotoxicants) is shown in Tables 1A, 1B, and 1C.

Table 1A. *Grouping options of organic contaminants with specific chemical structures*

Term	Characteristics	Examples
Hydrocarbons	More CH_x units: higher hydrophobicity/lipophilicity, and lower aqueous solubility	hexane
Polycyclic aromatic hydrocarbons	Combustion products. Flat structure	naphthalene, B[a]P
Halogenated hydrocarbons	H substituted by fluor, chlorine, bromide, iodine. Often relatively persistent	PCB, DDT, PBDE
Dioxins and furans	Combustion/industrial products, one or two oxygen atoms between two aromatic rings. Highly toxic.	TCDD, TCDF
Organometallics	Organic chemicals containing metals, used e.g. in anti-fouling paints	tributyltin
Organophosphate pesticides	Phosphate esters, often connecting two lipophilic groups. Act on nervous system	chlorpyrifos
Pyrethroids	Usually synthetic pesticides based on natural pyrethrum extracts	fenvalerate
Neonicotinoids	Synthetic insecticides with aromatic nitrogen, related to the alkaloid nicotine	imidacloprid
… Endless varieties / combinations and ...	...too many characteristics to list	...

Table 1B. *Grouping options of organic contaminants with specific properties*

Term	Characteristics	Examples
Persistent organic pollutants (POPs)	Bioaccumulative, end up even in remote Arctic systems	PCBs, PFOS

Persistent mobile organic chemicals (PMOCs)	Difficult to remove during drinking water production	PFBA, metformin
Ionogenic organic chemicals (IOCs)	Acids or bases, predominantly ionized under environmental pH	Prozac, MDMA, LAS
Substances of unknown or variable composition, complex reaction products or of biological materials (UVCB)	Multicomponent compositions of often analogue structures with wide ranging properties.	Oil based lubricants
Plastics	Chains of repetitive monomer structures. Wide ranging size/dimensions.	Polyethylene, silicone, teflon
Nanoparticles (NP)	Mostly manufactured particles with >50% having dimensions ranging 1 - 100 nm.	Titanium dioxide (TiO_2), fullerene

Table 1C. *Grouping options of organic contaminants with specific usage*

Term	**Characteristics**	**Examples**
Pesticides **Herbicides** **Insecticides** **Fungicides** **Rodenticides** **Biocides**	Toxic to pests Toxic to plants Toxic to insects Toxic to fungi Toxic to rodents Toxic to many species	DDT atrazine, glyphosate Chlorpyrifos, parathion Phenyl mercury acetate Hydrogen cyanide Benzalkonium
Pharmaceuticals	Specifically bioactive chemicals with often (un)known side effects. Many bases.	diclofenac (pain killer), iodixanol (radio-contrast), carbemazepine, prozac
Drugs of abuse	Often opioid based but also synthetic designer drugs with similar activity. Many are are ionogenic bases.	cannabinoids, opioids, amphetamine, LSD
Veterinary Pharmaceuticals	Can include relatively complex (ionogenic) structures	antibiotics, antifungals, steroids, non-steroidal anti-inflammatories
Industrial Chemicals	Produced in large volumes by chemical industry for a wide array of products and processes	phenol
Fuel products	Flammable chemicals	kerosene
Refrigerants and propellants	Small chemicals with specific boiling points	freon-22
Cosmetics/personal care products	Wide varieties of specific ingredients of formulations that render specific properties of a product	sunscreen, parabenes
Detergents and surfactants	Long hydrophobic hydrocarbon tails and polar/ionic headgroups	Sodium lauryl sulfate (SLS), benzalkonium
Food and Feed Additives	To preserve flavor or enhance its taste, appearance, or other qualities	"E-numbers", acetic acid = E260 in EU, additive 260 in other countries

Chapter 2 mostly discusses groups of chemicals in separate modules according to the *specific environmental properties in Table 1B* (Section 2.2) and *specific applications in Table 1C* (Section 2.3), according to which certain regulations apply in most cases. The property classifications can be based on (often interrelated) properties such as solubility (in water), hydrophobicity (tendency to leave the water), surface activity (tendency to accumulate at surfaces of two phases, such as for "surfactants"), polarity, neutral or ionic chemicals and reactivity. Other classifications very important for environmental toxicology are based on environmental behaviour or effects, such as persistency ("P" increasing problems with increased emissions), bioaccumulation potential ("B", up-concentration in food chains), or type of specific toxic effects ("T"). The influence of ***specific chemical structures*** such as in Table 1A is further clarified in the current introductory chapter in order to better understand the basic chemical terminology.

Structures of organic chemicals and functional groups

- *Hydrocarbons and polycyclic aromatic hydrocarbons*

As the name suggest, hydrocarbons contain only carbon and hydrogen atoms and can therefore be considered to be the simplest group of organic molecules. Nevertheless, this group covers a wide variety of aliphatic, cycloaliphatic and aromatic structures (see Figure 1 for some examples) and also a wide range of properties. What this group shares is a low solubility in water with the larger molecules being extremely insoluble and accumulating strongly in organic media such as soil organic matter.

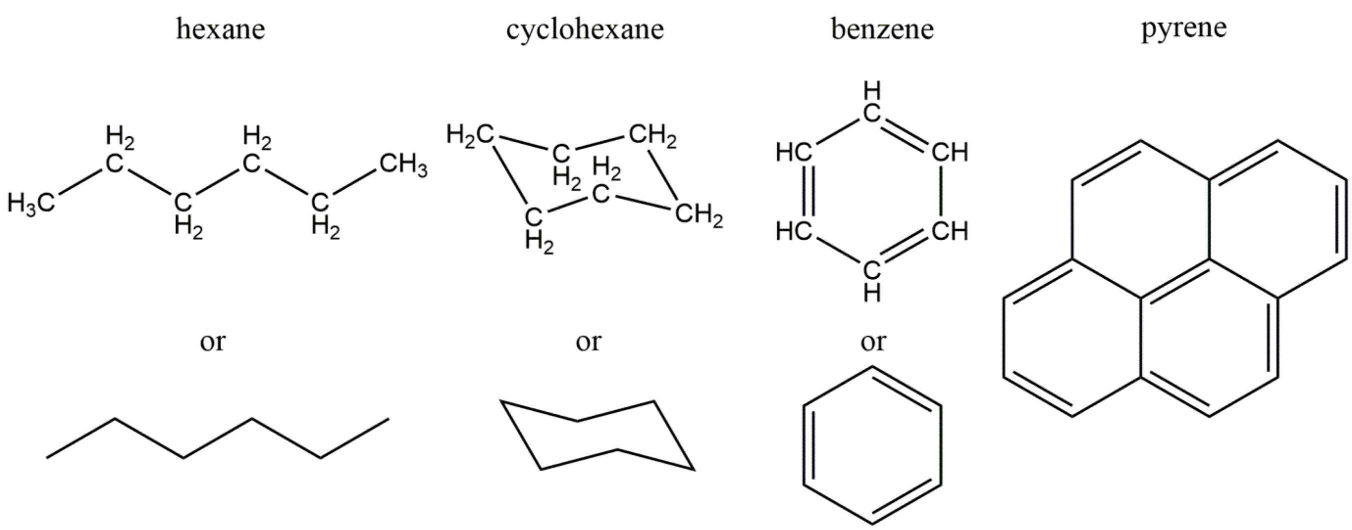


Figure 1. Examples of hydrocarbons.

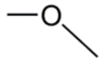
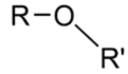
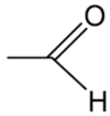
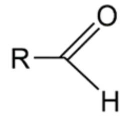
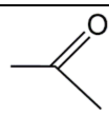
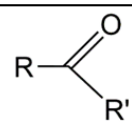
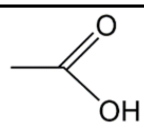
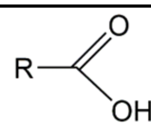
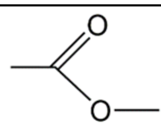
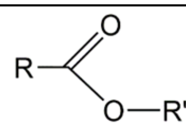
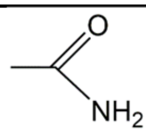
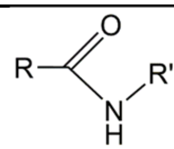
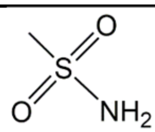
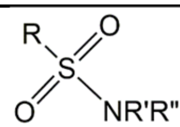
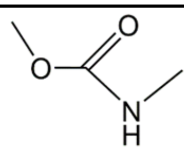
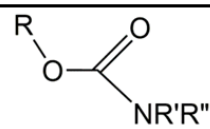
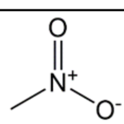
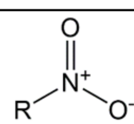
As a result of the ability of carbon to form strong bonds with itself and other atoms to form structures containing long chains or rings of carbon atoms there is a huge and increasing number (millions) of organic chemicals known. Chemicals containing only carbon and hydrogen are known as hydrocarbons. Aliphatic molecules consist of chains of carbon atoms as either straight or branched chains. Molecules containing multiple carbon-carbon bonds (C=C) are known as unsaturated molecules and can be converted to saturated molecules by addition of hydrogen.

Cyclic alkanes consist of rings or carbon atoms. These may also be unsaturated and a special class of these is known as aromatic hydrocarbons, for example benzene in Figure 1. The specific electronic structure in aromatic molecules such as benzene makes them much more stable than other hydrocarbons. Multiple aromatic rings linked together make perfectly flat molecules, such as pyrene in Figure 1, that can be polarized to some extent because of the shared electron rings. In larger sheets, these polycyclic aromatic molecules also make up the basic graphite structure in pencils, and also typically represent the strongly adsorbing surfaces of black carbon phases such as soot and activated carbon.

The structures of organic chemicals help to determine their properties as behaviour in the environment. At least as important in this regard, however, is the presence of functional groups. These are additional atoms or chemical groups that are present in the molecule that have characteristic chemical effects such as increasing or decreasing solubility in water, giving the chemical acidic or basic properties or other forms of chemical reactivity. The common functional groups are shown in Table 2.

Table 2. *Common Functional Groups, where R are carbon backbone or hydrogen units*

Class	Functional group	General Formula	Examples
Halohydrocarbons	—X (F, Cl, Br, I)	R−X	CH_3I (iodomethane)

Alcohols	—OH	R—OH	CH_3OH (methanol)
Ethers			CH_3OCH_3 (dimethylether)
Aldehydes			CH_2O (methanal)
Ketones			CH_3COCH_3 (propanone, or acetone)
Carboxylic Acids			CH_3COOH (ethanoic acid, or acetic acid)
Esters			$CH_3COOCH_2CH_3$ (ethyl acetate)
Amines	$—NH_2$	R—NR'R"	CH_3NH_2 (methylamine, or aminomethane)
Amide			$CH_3CON(CH_3)_2$ (N,N-dimethylacetamide)
Sulphonamide			CH_3SOONH_2 (methylsulfonamide)
Carbamate			X
Nitro			CH_3NOO (nitromethane)

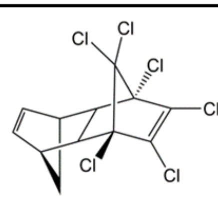
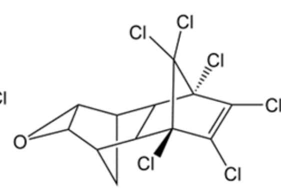
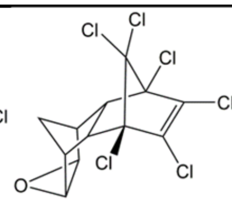
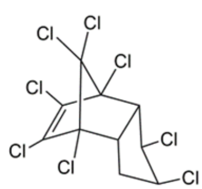
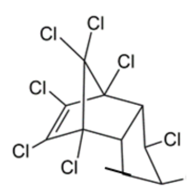
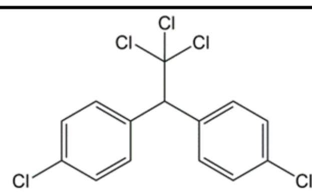
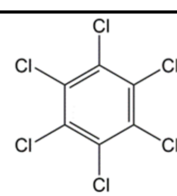
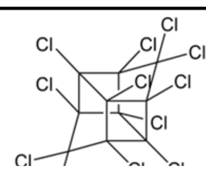
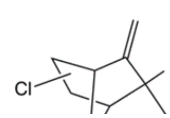
- *Halogenated hydrocarbons: first generation pesticides*

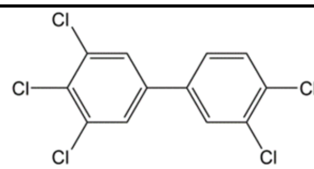
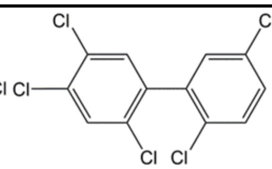
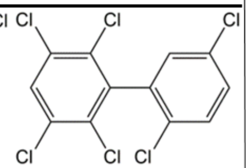
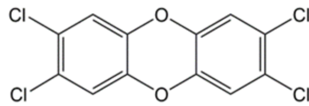
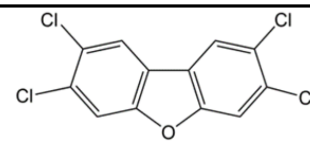
The first organic chemical recognised as an environmental pollutant was the insecticide DDT (see clip 1 at the start of this chapter). It later became clear that other organochlorine pesticides such as lindane and dieldrin (Table 3) were also widely distributed in the environment. This was also the case for polychlorinated biphenyls (PCBs) and other organochlorinated industrial chemicals. These chemicals all share a number of undesirable properties such as environmental persistence, very low solubility in water and high level of accumulation in biota to potentially toxic levels. Many organochlorines can be viewed as hydrocarbons in which hydrogen atoms have been replaced by chlorine. This makes them even less soluble than the corresponding hydrocarbon due to the large size of chlorine atoms. In addition, chlorination also makes the molecules more chemically stable and therefore contributes to their environmental persistence. Other organochlorines contain additional functional groups, such as the ether bridges in PCDDs and PCDFs (better known as dioxins and dibenzofurans) and ester groups in the 2,4-D and 2,4,5-T herbicides. Many organochlorines were applied very successfully in huge quantities as pesticides for decades before their negative effects such as persistence and accumulation in biota became apparent. It is therefore no coincidence that the initial set of Persistent Organic Pollutants (POPs) identified in the Stockholm Treaty (see below) as chemicals that should be banned were all organochlorines, as shown in Table 3.

As well as chlorine, other halogens such as bromine and fluorine are used in important groups of environmental contaminants. Organobromines are best known as flame retardants and have been applied in large quantities to improve the fire safety of plastics and textiles. They share many of the same undesirable properties of organochlorines and several classes have now been taken out of production. Organofluorines are another important class of halogenated chemicals, and part of the well-known group of ozone depleting CFCs (Section 2.3.6). In particular, per-and polyfluoralkyl substances are widely used as fire-stable surfactants in fire-fighting foams, as grease and water resistant coatings and in the production of fluoropolymers such as Teflon. Organofluorines are much more water soluble and much less bioaccumulative than organochlorines and organobromines but are extremely persistent in the environment.

The recognition of these organochlorines as harmful environmental contaminants eventually resulted in measures to restrict their manufacture and use in the Stockholm Convention on Persistent Organic Pollutants signed in 2001 to eliminate or restrict the production and use of persistent organic pollutants (POPs). This initial list of POPs has been subsequently augmented with other harmful halogenated organic pollutants up to a total of 29 chemicals, which are either to be eliminated, restricted, or required measured to reduce unintentional releases. POPs are further discussed in section 2.2.4.

Table 3. *Key persistent organic pollutants, also named POPs - the Dirty Dozen*

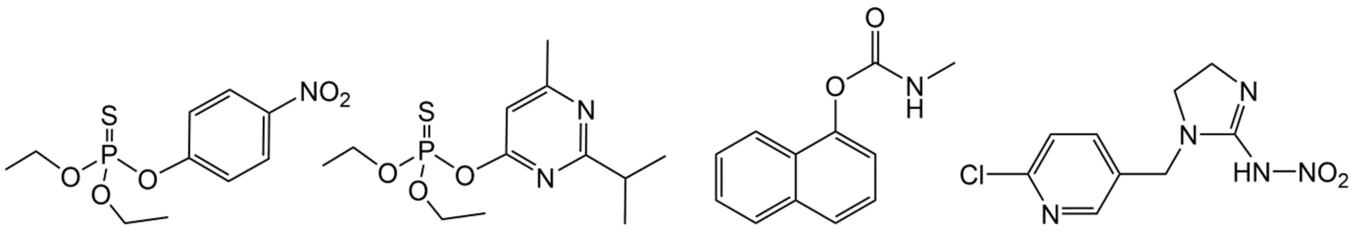
Chemical	Use	Structure
Aldrin/ Dieldrin/ Endrin	crop insecticides (corn, cotton, grains)	  
Chlordane/ Heptachlor	insecticides (potatoes, citrus vegetables, cotton/termites, soil insects)	 
DDT/ Hexachloro -benzene	crop insecticide (cotton) / fungicide for seed treatment	 
Mirex/ Toxaphene	insecticide (termites, fire ants/ livestock	 

	and crops)	
PCBs	industrial (heat exchange fluid for e.g. electrical transformers, paint and plastic additive)	 PCB 81 (co-planar structure)  PCB 101  PCB 151 (non-planar structures)
Dioxins/ Furans	unintentionally produced during combustion	 TCDD (2,3,7,8 tetrachlorodioxin)  TCDF (2,3,7,8 tetrachlorofuran)

Additional POPs to eliminate include: chlordecone, lindane (hexachlorocyclohexane), pentachlorobenzene, endosulfan, chlorinated naphthalenes, hexachlorobutadiene, tetrabromodiphenylether, and pentabromodiphenylether decabromodiphenyl ether (BDEs).

- *Alternatives for the organochlorine pesticides: effective functional groups*

Since the signing of the Stockholm Convention, organochlorine pesticides have been replaced in most countries by more modern pesticide types such as the organophosphorus and carbamate insecticides. These compounds are less persistent in the environment, but still could pose elevated risks to environments surrounding the agricultural sites, and increased levels on food produced on these agricultural sites. The very toxic organophosphorus neurotoxicant parathion has been in use since the 1940s, and has the typical two lipophilic side chains on two esters (ethyl units), as well as a polar unit. Parathion has caused hundreds of fatal and non-fatal intoxications worldwide and as a result it is banned or restricted in 23 countries. The relatively comparable organophosphate structure of diazinon has been widely used for general-purpose gardening and indoor pest control since the 1970s, but residential use was banned in the U.S. in 2004. In Californian agriculture however, 35000 kg diazinon was used in 2012. The carbamate based insecticide carbaryl is toxic to target insects, and also non-target insects such as bees, but is detoxified and eliminated rapidly in vertebrates, and not secreted in milk. Although illegal in 7 countries, carbaryl is the third-most-used insecticide in the U.S., approved for more than 100 crops. In 2012, 52000 kg carbaryl was used in California, while this was 3 times more in 2000. Neonicotinoid insecticides, with the typical aromatic ring containing nitrogen, form a third generation of pesticide structures. Imidacloprid is currently the most widely used insecticide worldwide, but as of 2018 banned in the EU, along with two other neonicotinoids clothianidin and thiamethoxam.



parathion diazinon carbaryl imidacloprid

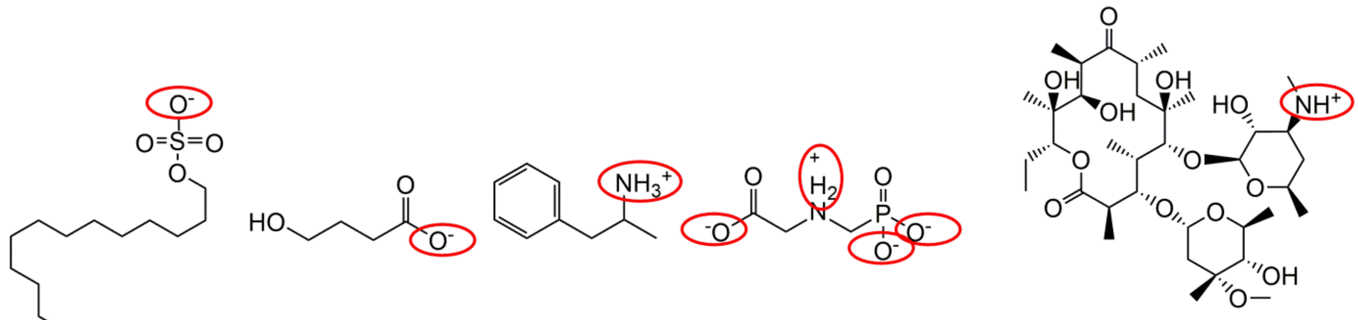
Figure 2. Some examples of second and third generation replacements of organochlorine pesticides.

- *Relatively simple and (very) complex pollutants*

As well as the pesticides discussed above, many other chemicals are brought into the environment inadvertently during their manufacture, distribution and use and the range of chemicals recognised as problematic environmental contaminants has expanded enormously. These include fossil fuel-related hydrocarbons, surfactants, pigments, biocides and chemicals used as pharmaceuticals and personal care products (PPCPs). Figure 1 in Boxall et al. (2012) gives an illustrative overview of the major routes by which PPCPs, but also many other anthropogenic contaminants other than pesticides, are released into the environment. Particularly wastewater treatment systems form the main entry point for many industrial and household products.

The wide variety of contaminant structures does not mean that most chemicals have become increasingly more complex. For risk assessment, molecular properties such as water solubility, volatility and lipophilicity are often estimated based on quantitative structure-property relationships (Section 3.4.3). With increasingly complex structures, such property-estimations based on the molecular structure become more uncertain.

The antibiotic erythromycin for example (Figure 3), is a very complex chemical structure ($C_{37}H_{67}NO_{13}$) that has 13 functional units along with a 14 member ring. In addition, the tertiary nitrogen group is an amine base group that can give the molecule a positive charge upon protonation, depending on the environmental pH. Erythromycin is on the World Health Organization's List of Essential Medicines (the most effective and safe medicines needed in a health system), and therefore widely used. Continuous emissions in waste streams pose a potential threat to many ecosystems, but many environmentally and toxicologically relevant properties are scarcely studied, and poorly estimated.



SLS GHB amphetamine glyphosate erythromycin

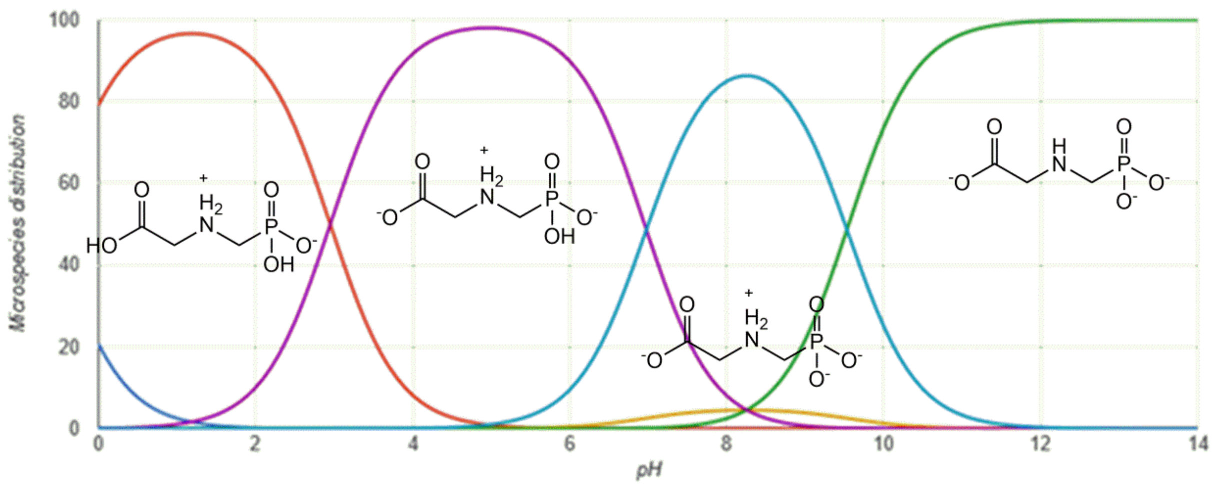


Figure 3. Relatively simple or (very) complex chemicals? Glyphosate speciation profile (chemicalize.org) for the 4 dominant glyphosate different species. Glyphosate in soil (pH4-8) predominantly occurs with 3 charged groups (net charge -1), partly with 4 charged groups (-2). The soap SLS is always negatively charged, GHB predominantly negative (pK_a 4.7), amphetamine predominantly positive (pK_a 9.9), erythromycin predominantly positive (pK_a 8.9)

There are also many contaminants or toxicants with a seemingly simple structure. Many surfactants are simple linear long chain hydrocarbons with a polar or charged headgroup (Figure 4). The illicit drug amphetamine has only a benzene ring and an amine unit, the illicit drug GHB only an alcohol and a carboxylic acid, the herbicide glyphosate only 16 atoms. Still, these 4 chemical examples also have acidic or basic units that often result in predominantly charged organic molecules, which also strongly influences their environmental and toxicological behaviour (see sections on PMOCs and Ionogenic Organic Compounds). In case of glyphosate, the chemical has 4 differently charged forms depending on the pH of the environment. At common pH of 7-9, glyphosate has all charged groups predominantly ionized, making it very difficult to derive calculations on environmental properties.

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