

arag^{sun}rn



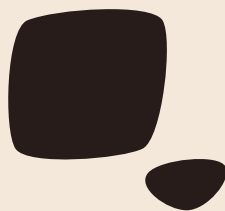
Funded by the
European Union



Factsheets on the four groups
of persistent pollutants:

Metals	OCBs	PETCO	← PFAS →
--------	------	-------	----------

Per- and polyfluoroalkyl substances



This factsheet is designed to help anyone interested in learning about the most persistent pollutants affecting local land and water.

It explains what these contaminants are, why they matter, and how landowners and other stakeholders can learn how to assess and manage them responsibly.



Table of contents

Page 4

What are these contaminants and what are they used for?

Page 6

Why are we concerned?

Page 8

Environmental fate, transport, effects

Page 10

Regulation and guidelines

Page 12

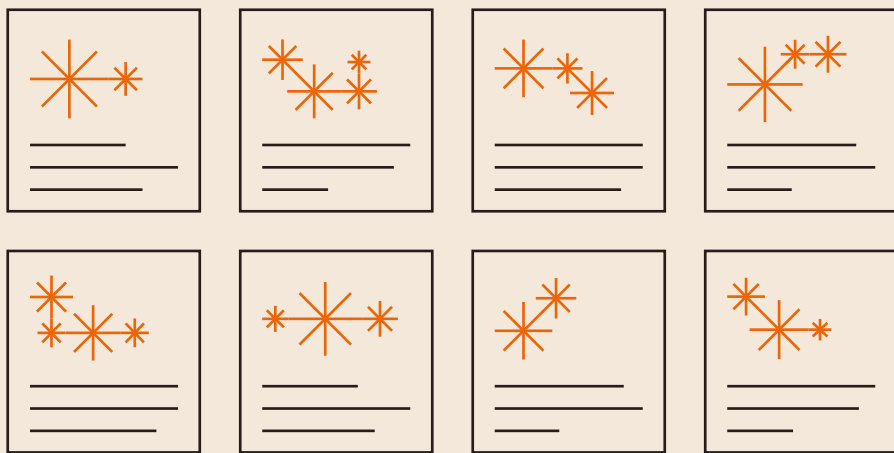
Soil testing and analysis

Page 14

Remediation options

Page 16

Initial steps to assess a potentially contaminated site



What are these contaminants and what are they used for?

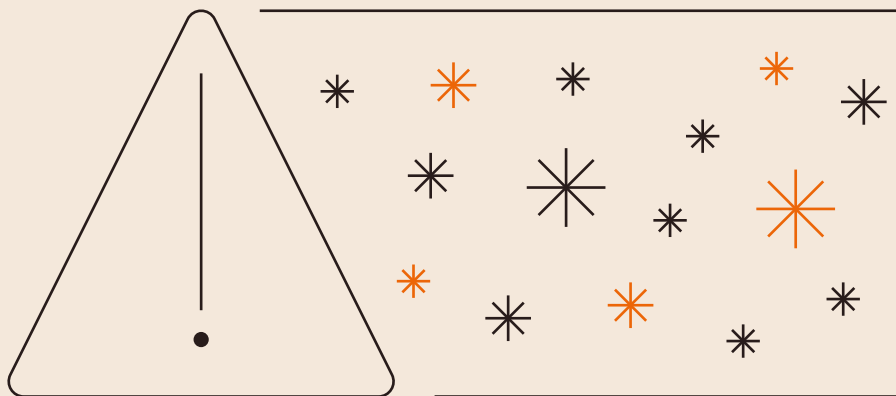
Per- and polyfluoroalkyl substances, commonly referred to as PFAS, are a **large family of man-made chemicals** that have been manufactured since the 1940s. They include thousands of individual compounds that **share one key feature: a chain of carbon atoms in which some or all of the hydrogen atoms are replaced by fluorine**. There are multiple definitions of PFAS and the OECD defined PFAS in 2021 ([oecd.org](https://www.oecd.org)) as compounds containing at least one part of their molecule where a carbon atom is joined to two or more fluorine atoms ($-CF_2-$ or $-CF_3$ groups). This carbon-fluorine bond is one of the strongest in chemistry, **making PFAS extremely resistant to heat, water, oil, and chemical reactions**. For this reason, they are often called “**forever chemicals**” because they don’t completely break down easily in the environment or the human body, which means they can build up over time.

PFAS have been used in a wide variety of consumer and industrial products. They are found in firefighting foams, non-stick cookware,

waterproof clothing, stain-resistant carpets, food packaging, paints, and many industrial applications where resistance to heat, grease, or water is important. PFAS can be broadly divided into polymeric and non-polymeric PFAS. **Polymeric PFAS** are very large molecules made by joining together many smaller 'building blocks' (called monomers) that contain fluorinated carbon chains or have fluorinated side-chains. One example is polytetrafluoroethylene (PTFE, also called Teflon®).

Non-polymeric PFAS are smaller molecules and can be divided into several subgroups. **Precursor PFAS** is a term relating to PFAS that more easily transforms to more stable PFAS that persists over long time. These are typically the **perfluoroalkyl acids** (PFAAs). Two broad categories are often mentioned, **long-chain PFAS**, such as PFOS (perfluorooctane sulfonic acid) and PFOA (perfluorooctanoic acid) and their precursors, were widely produced and used until concerns about persistence and health effects led to international restrictions. **Short-chain PFAS**, their precursors, and fluorinated alternatives have since been developed, but many of these also persist in the environment and raise concerns about their toxicity and how easily they are spread (mobility).

For soils, **the main sources of PFAS contamination include the historical use of firefighting foams** at airports, military bases, and training grounds, **various industrial emissions** such as paper, textile, fluorochemical/polymer, chrome plating, paints, and in general where PFAS have been manufactured or applied when in processes and products. Waste handling, recycling, and landfilling, and the application of sewage sludge or contaminated composts to farmland are also known sources. Increasingly PFAS are also found to occur near F-gas, semi-conductor/electronics, pharmaceutical and pesticides production sites. **Because PFAS do not break down completely, soils that received such inputs decades ago can still contain measurable levels today.**



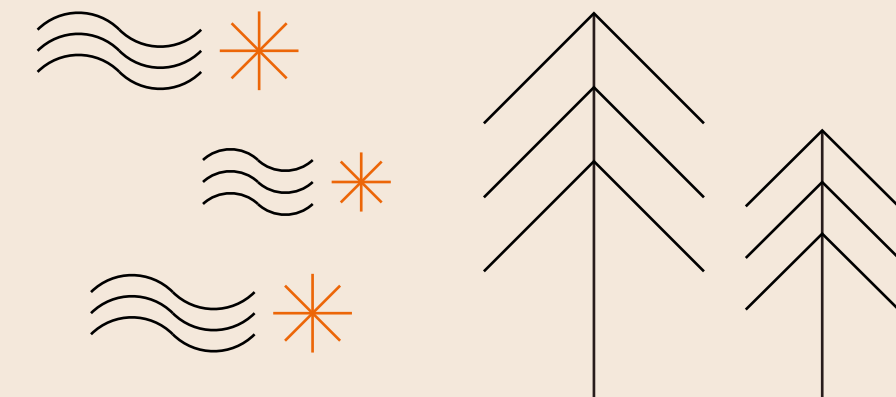
Why are we concerned?

The concern about PFAS in soil is **because of their persistence and mobility**, together with their **toxicological effects**.

Persistence means that **once PFAS enter the soil, they do not readily degrade** into harmless compounds. Unlike petroleum hydrocarbons or pesticides that can slowly break down by microbial action or chemical reactions, the perfluorinated PFAS do not degrade further under normal environmental conditions. The polyfluorinated PFAS will degrade slowly over time and will form the perfluorinated PFAS. **This means that contamination is essentially cumulative:** every input adds to the legacy burden in soils and sediments.

Mobility is another major issue. Many PFAS, particularly the short-chain ones, are water-soluble and can leach from soil into groundwater. Others, particularly the long-chain PFAS, bind strongly to soil organic matter or mineral surfaces, creating a long-term source that can release contaminants slowly over decades. This dual behavior makes management difficult: **soils can act both as a sink**, holding PFAS in place, **and as a source**, gradually releasing them to groundwater or surface water.

Exposure to PFAS has been linked to immune effects, developmental problems in children, certain cancers, liver and kidney damage, and changes in cholesterol, with evidence coming from both lab studies and population surveys. **Even though only a few PFAS are well-studied, many share properties of persistence, bioaccumulation, and toxicity**, raising concern for the entire group.



Environmental fate, transport, effects

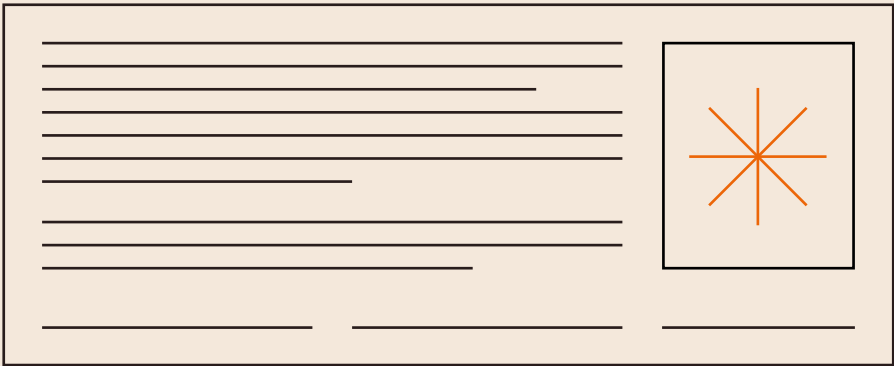
Understanding how PFAS behave in the environment is essential for assessing risks and designing remediation strategies. **In soils, PFAS behavior depends on their chemical structure.** Long-chain compounds such as PFOS and PFOA tend to bind strongly to soil particles, especially those rich in organic carbon, and are therefore relatively immobile. However, **they can still be transported if soil particles are eroded or moved.** This can create long plumes of contamination in soil, from the source and several hundreds of meters away. Short-chain PFAS, by contrast, are more soluble in water and much more mobile. They can move downward through the soil profile and reach groundwater, where they are difficult to remove once contamination occurs.

PFAS also tend to distribute between soil, water, and air depending on their volatility. Some volatile precursors can evaporate from soil surfaces and later transform into persistent PFAS in the atmosphere or after settling down with dust or rain. Others are transformation products of more complex fluorinated substances used in products; over time, these precursors degrade to yield stable PFAS.

The transport pathways from soil to the wider environment are varied. **PFAS can leach into groundwater** and spread with the groundwater flow, potentially reaching drinking-water wells. They can be washed off by surface runoff into rivers and lakes. They can also **accumulate in plants**, particularly short chain PFAS can be taken up in edible crops if the soil or irrigation water is contaminated. Long-chain PFAS that bind to soil can also be taken up by root plants and other plants containing soils. **Livestock exposed via feed or water may accumulate PFAS in tissues**, leading to human dietary exposure. This wide range of pathways explains why PFAS are detected globally, even in remote regions far from known sources.

Contaminated soils may represent a long-term source of pollution to groundwater, making water treatment plants or private wells vulnerable to decades of contamination. Agricultural soils amended with PFAS-containing biosolids have shown uptake of PFAS into crops, raising concerns for food safety. **Ecologically, PFAS can accumulate** in plants, invertebrates, fish, worms, birds and higher trophic level animals, **leading to biomagnification through food chains**.

From a health perspective, **exposure to PFAS has been linked to a variety of adverse effects**. The evidence comes both from laboratory tests on soils, animals, and even on people and from large populations in epidemiological surveys. The effects include impacts on the immune system, developmental effects in children, certain cancers, liver and kidney damage, and changes in cholesterol levels. While very few PFAS have been studied in detail, **many shows similar properties of bioaccumulation, toxicity, and cocktail effects** which raises concern across the whole chemical family.



Regulation and guidelines

European framework for soil legislation

The European Union introduced legislation on soil health in the **Soil Monitoring and Resilience Directive (SMRD)** that mandates the monitoring and assessment of soil quality. However, most threshold limit values and procedural rules are set and enforced by Member States and often at regional/local level. EU sets frameworks, principles and reporting/monitoring obligations, and **Member States translate these into national laws** (setting site-identification, screening values, risk assessment methods and mandatory remediation duties); local authorities typically implement, inspect and require remediation on the ground.

There are two common approaches used by Member States:

- ☀ **Generic screening/threshold values** (soil screening values, intervention values) that trigger further action when exceeded.
- ☀ **Risk-based site assessment** where exposure pathways and site-specific conditions determine whether remediation is required and what measures are appropriate.

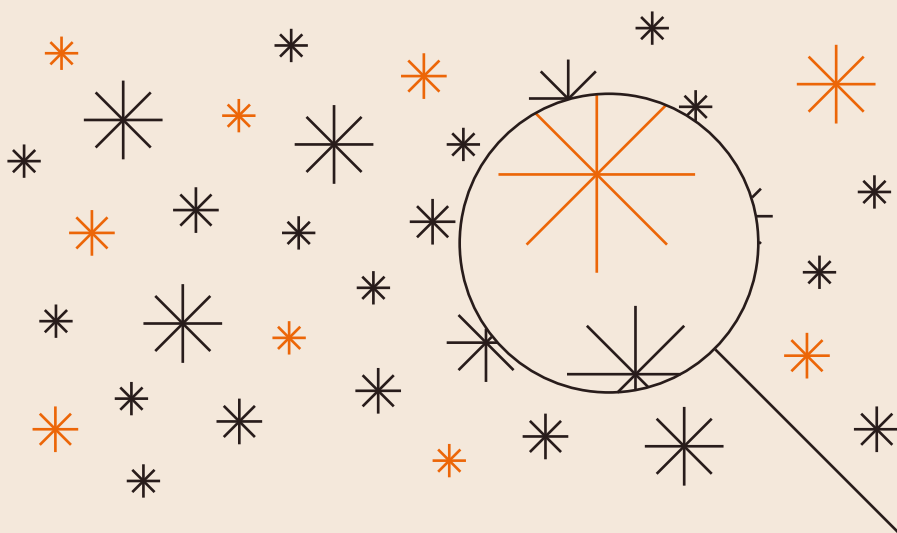
For specific Member States approaches, the specific **Member State's environment ministry** or **national environmental agency** (e.g., UK: Environment Agency; Germany: Länder Umweltämter; Sweden: Naturvårdsverket) may contain information on national soil law, contaminated-land guidance, national screening values or risk assessment protocols.

Links to other European regulations

Soil rules may be affected and can affect other EU rules such as groundwater/surface-water protection under the Water Framework Directive and dangerous substances rules, waste and landfill legislation (affecting historical waste-derived contamination), and permitting under the Industrial Emissions Directive. These links mean that **EU law can impose soil-protective outcomes** through water protection, waste rules or pollution permitting.

International frameworks and conventions

While EU and national laws provide binding rules within specific jurisdictions, **international treaties and organizations provide global standards**, obligations, and guidance that influence national regulations, enable cross-border cooperation, and address chemicals that persist and move beyond one country's borders. Examples are the Stockholm Convention on Persistent Organic Pollutants (POPs), Minamata Convention on Mercury, and the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes (including contaminated soils).



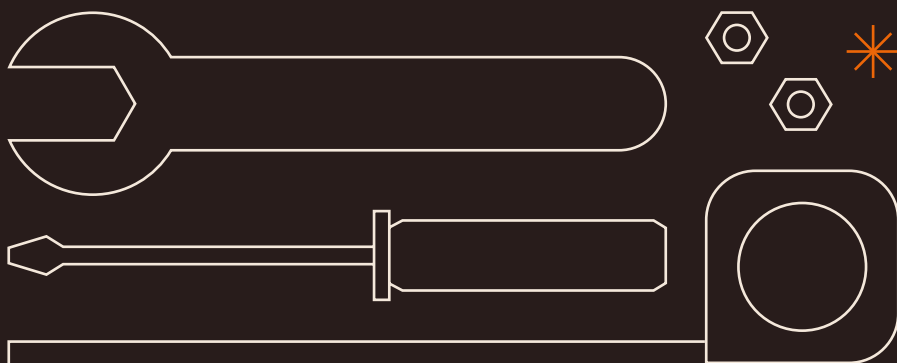
Soil testing and analysis

When investigating contaminated land or groundwater, the way samples are taken is just as important as the laboratory analysis. To get reliable results, samples need to be collected carefully, preserved immediately, and transported under controlled conditions. There are standardized methods for environmental characterization of soil and related matrices, for example the European Committee for Standardization CEN/TC 444, with the goal of **harmonizing how environmental data are collected and reported across Europe**. Also, national or regional guidance might specify how and when soil or groundwater should be tested, and what analytical standards to use. Sampling protocols therefore often need to be conducted or supervised by accredited laboratories.

The group of PFAS consists of **substances with a wide range of different physicochemical properties** and general considerations will not apply to all PFAS or every situation. **PFAS are easily spread by contact** with common items containing PFAS like waterproof

clothing, food wrappers, or Teflon-coated tools, so all equipment and sampling methods must be specially chosen and cleaned with for example ethanol to avoid false results. Many PFAS have surface active properties which can influence their distribution in soil and water bodies, and sorption behavior over time if samples are stored. As **PFAS also can move from soil into water**, it may be necessary to test groundwater or nearby surface water. **The results will not only show whether contamination is present but also help decide on next steps.**

Water-soluble (polar) PFAS are extracted from soil by organic solvents like methanol and acetonitrile, and from water by passing the sample through solid-phase sorbents that traps PFAS which are then washed off and concentrated. Poorly water-soluble ('neutral') PFAS may need extraction with non-polar solvents such as ethyl acetate. Highly sensitive instruments, most often liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS) are used to simultaneously detect up to around 50 PFAS at low concentrations. Neutral PFAS will often require analysis by gas chromatography mass spectrometry (GC-MS). In addition to these methods that only look for a few specific PFAS, other methods can be used to screen for the class of PFAS (often called 'PFAS total'), or to look for individual unknown PFAS, by so-called 'non-target screening' (NTS). **None of the methods will find all PFAS, so often a combined analysis strategy is recommended to get a full overview**, starting with screening and moving to more precise analysis.



Remediation options

If your land is contaminated, **remediation means cleaning it up or managing the pollution**, to sufficiently reduce the risk to people, water, or the ecosystem animals and plants. Remediation does not always mean physically removing all the contaminated soil, it can also involve isolating the pollution or treating it on site. **Costs can vary widely depending on the contamination and chosen method.** **Conventional treatments** such as incineration, soil washing, or chemical oxidation are not always effective for PFAS, and **may generate secondary waste streams still containing PFAS.**

Research into treatments are ongoing and several technologies where the science is ready have not yet been field proven. Destructive technologies, such as supercritical water oxidation, plasma treatment, or advanced electrochemical processes, is being developed but not yet widely applied. Instead, **soil washing followed by concentration of PFAS** (by foam fractionation, granular activated carbon (GAC), membrane technologies) **are often applied.** The table below provides an overview of different remediation principles together with specific methods that are fully available or “near commercially available” (limited field application but ready for deployment) and their advantages and limitations.



Physical removal or isolation of contaminants

Excavation:

Remove contaminated soil

Soil washing:

Removing PFAS using solvents and chemical additives

Thermal desorption:

Apply heating to volatilize PFAS

Sorption:

Using activated carbon, biochar, commercial sorbents mixed with soil to sorb PFAS

Stabilization:

Mix with binding agents or additives to lock PFAS in place

Advantages:

- Immediate removal
- Removes several PFAS
- Reduces PFAS leaching

Limitations:

- High costs and few options for disposal
- Depends on soil properties, high cost, secondary contaminated effluent needs to be treated
- High energy output, secondary pollution of air
- Less efficient for short chain PFAS, does not remove PFAS
- Less efficient for short chain PFAS, does not remove PFAS, long-term limitations



Biological processes remove, degrade, or contain contaminants

Phytoremediation:

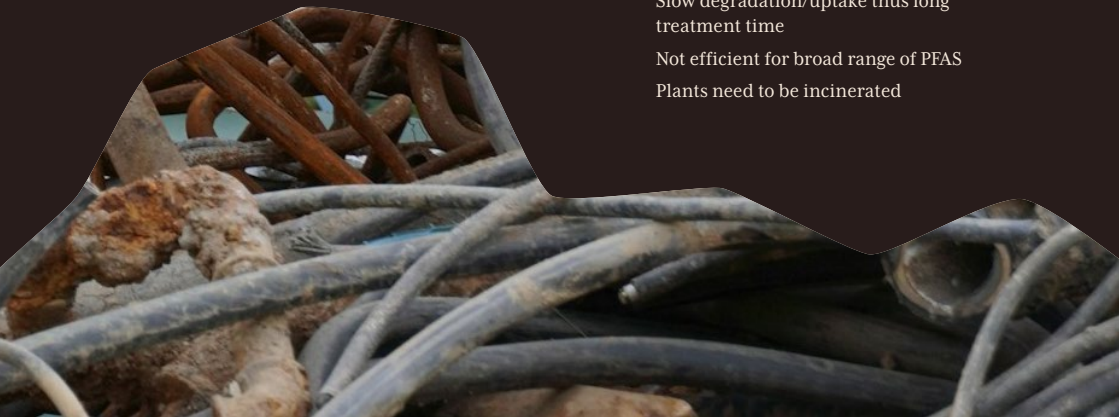
Plant growth

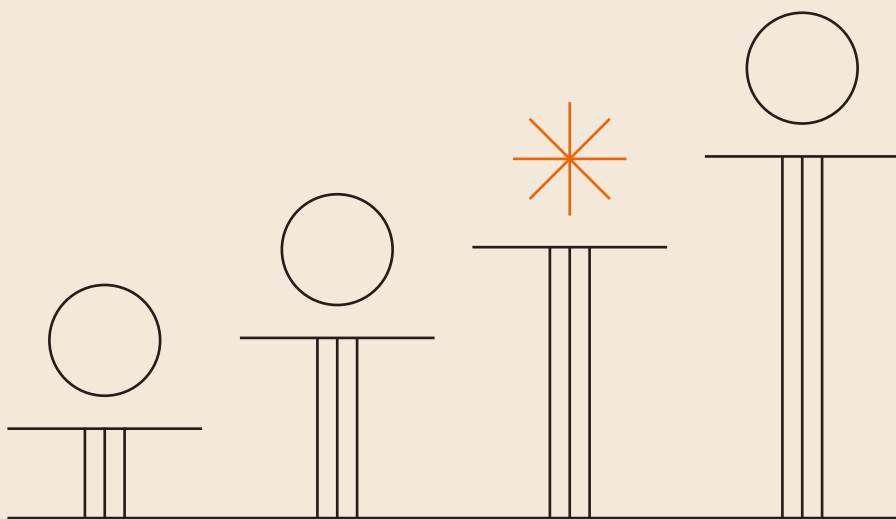
Advantages:

- Low-cost and sustainable
- Environmentally friendly

Limitations:

- Slow degradation/uptake thus long treatment time
- Not efficient for broad range of PFAS
- Plants need to be incinerated





Initial steps to assess a potentially contaminated site

Gather information about the site

Before any work or decisions can begin it's important to build a complete picture of the site. This means gathering different kinds of information about the land itself, its history, and its surroundings. Each piece helps us understand how pollution might spread and who or what could be affected.

- ☀ **Collect site history**, such as uses, know sources of pollution, old maps, news on special events, environmental permits, as past uses often helps explain what types of pollution might be present.
- ☀ **Topographical data**, including shape of the land and location of buildings, helps predict pathways of pollution via water and air including spreading of dust.

- ☀ **Geological data** on type of soil or rock and how deep the layers are, matters since some solids trap pollution while others let it spread quickly.
- ☀ **Hydrogeology**, such as depth of water and direction of groundwater flow is important since contamination can move with groundwater and reach wells, rivers, or lakes, creating health and environmental risks.
- ☀ **Meteorological data** (climate and weather) can wash pollutants deeper into the soil or spread them to water bodies. Wind can carry dust or vapours to nearby areas.
- ☀ **Contamination data** (what is in the soil and water) show how serious the problem is and whether it poses a direct risk.
- ☀ **Surrounding exposure pathways** (how people or nature could come into contact) determines the risks. Even if pollution is present, it only becomes dangerous if it has a “pathway” to reach people, animals, or ecosystems.

Gathering of the background information should be followed by field verification – sampling of soil, groundwater, surface water, as well as on-site screening using portable instruments. This data will be the basis for the risk assessment.

Assess the economic and logistic factors



Budget:

Cost of treatment, monitoring, and long-term management.



Infrastructure:

Availability of equipment and skilled personnel.



Timeframe:

Urgency of remediation (e.g., emergency vs. long-term project).

Set the remediation goals



Containment vs. destruction:

Whether the goal is to immobilize or eliminate the contamination.



Reuse potential:

Whether the soil needs to be reused (e.g., agriculture, construction).



Risk reduction:

Immediate vs. long-term health and environmental risk mitigation.

Understand the rules and responsibilities

It is of importance to clarify **who is legally responsible for the contamination** (landowner, business provider, etc.), **who caused the contamination** and **when it may create different obligations**. Check whether the site or soil use falls under any EU directive obligations (water, industrial emissions, waste), as these also can bring binding obligations.

Most often it is the Member State's contaminated-land regime: national law, agency guidance, and any regional technical guidance on soil use and contamination, that are the most important rules to be aware of.

Some regions or municipalities have additional rules for construction, excavation, or soil movement even if national or EU rules do not explicitly require action. Certain contamination incidents may require **mandatory reporting to environmental authorities and potential restrictions on land use**.

Consult experts and find information

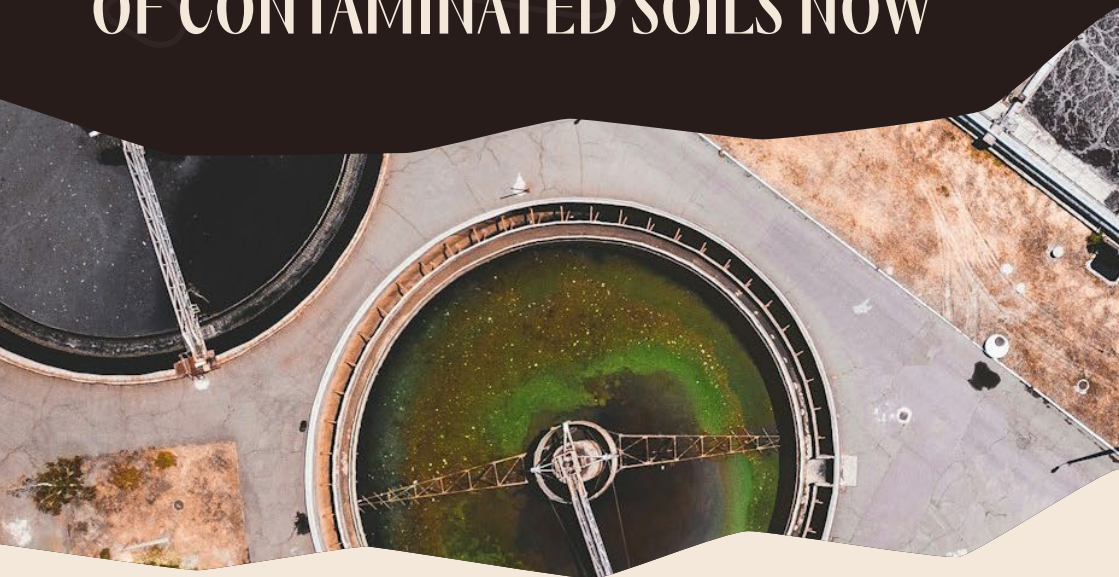
Remediation and restoration depend on the risk level and intended use of the land. Therefore, it is advisable to consult experts to perform risk assessments and recommend actions in line with the current legislation. Seeking expert advice early can also be cost saving, as early misguided actions can become expensive over time. Environmental consultants can help with performing basic screening for initial assessment, doing legal compliance check, and develop remediation plans. They should also be very familiar with local and national regulations and able to translate them into practical guidance for landowners.

There are many useful resources for anyone seeking more information on pollutants and soil remediation. Because knowledge in this field is constantly evolving, it is recommended to consult both national and regional knowledge hubs as well as European sources. For example, the **Common Forum** (commonforum.eu) brings together expertise and facilitates information exchange on contaminated land and groundwater management. The **EU Soil Observatory (EUSO)** (joint-research-centre.ec.europa.eu) provides soil data, supports research and innovation, and raises awareness of the importance of soils. The **European Food Safety Authority (EFSA)** (efsa.europa.eu) offers scientific advice to risk managers, especially on risks linked to the food chain.

The **European Chemical Agency (ECHA)** manages the implementation of the EU's chemicals legislation and promotes the safe use of chemicals to protect human health and the environment (echa.europa.eu).



ACHIEVING REMEDIATION AND GOVERNING RESTORATION OF CONTAMINATED SOILS NOW



Visit our website:

aragorn-horizon.eu

And don't forget to follow
us on social media:



ARAGORN EU



Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them.