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ERICA
Environmental monitoRIng through Civic engAgement

Existing tools and technologies for environmental monitoring of the Fossil Fuel Industry: A review of the most relevant pollutants and low-cost and DIY sensors

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Glossary

Acute exposure: Exposure by the oral, dermal, or inhalation route for 24 hours or less.

Acute Reference Concentration (Acute RfC): An estimate of a continuous inhalation exposure for an acute duration (24 hours or less) to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Acute Reference Dose (Acute RfD): An estimate of a daily oral exposure for an acute duration (24 hours or less) to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Acute toxicity: Any poisonous effect produced within a short period of time following exposure, usually 24 to 96 hours.

Air Quality Guideline (AQG): A series of WHO publications that provide evidence-informed, non-binding recommendations for protecting public health from the adverse effects of air pollutants by eliminating or reducing exposure to hazardous air pollutants and by guiding national and local authorities in the risk management decisions.

Benchmark concentration (BMC): Dose or concentration that produces a predetermined change in response rate of an adverse effect compared to background.

Chronic Reference Dose: An estimate of a daily oral exposure for a chronic duration to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

EPA: Environmental Protection Agency in the United States.

FAO: Food and Agricultural Organization of the United Nations.

FDA: Food and Drug Administration (USA).

IARC: International Agency for Research on Cancer.

IRIS: Integrated Risk Information System.

Longer-Term Exposure: Repeated exposure by the oral, dermal, or inhalation route for more than 30 days, up to approximately 10% of the life span in humans (more than 30 days up to approximately 90 days in typically used laboratory animal species).

Lowest-Observed-adverse-effect levels (LOAELs): In a study, the lowest exposure level at which there are biologically significant increases in frequency or severity of adverse effects between the exposed population and its appropriate control group.

Lowest-Observed-Effect Level (LOEL): In a study, the lowest dose or exposure level at which a statistically or biologically significant effect is observed in the exposed population compared with an appropriate unexposed control group.

Minimal Risk Levels (MRLs): Is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs can be derived for acute, intermediate, and chronic duration exposures for inhalation and oral routes, but appropriate methodology does not exist to develop MRLs for dermal exposure.

No-observed-adverse-effect levels (NOAELs): The highest exposure level at which there are no biologically significant increases in the frequency or severity of adverse effect between the exposed population and its appropriate control; some effects may be produced at this level, but they are not considered adverse or precursors of adverse effects.

No-Observed-Effect Level (NOEL): An exposure level at which there are not statistically or biologically significant increases in the frequency or severity of any effect between the exposed population and its appropriate control.

PM: particulate matter.

Ppb: A unit of concentration expressed as parts per billion. Equivalent to 1×10^{-9}.

Ppm: A unit of concentration expressed as parts per million. Equivalent to 1×10^{-6}.

Reference Concentration (RfC): Inhalation reference concentration. An estimate of a continuous inhalation exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Reference dose (RfD): Oral reference dose. An estimate of a daily oral exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Risk (human health): The probability of adverse effects resulting from exposure to an environmental agent or mixture of agents.

Short Term Exposure: Repeated exposure by the oral, dermal, or inhalation route for more than 24 hours, up to 30 days.

Short Term Reference Concentration (Short term RfC): An of a continuous inhalation exposure for short-term duration to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Short Term Reference Dose (Short term RfD): An estimate of a daily oral exposure for a short-term duration to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime.

Threshold: The dose or exposure below which no deleterious effect is expected to occur.

TPH: Total Petroleum Hydrocarbons.

TWA: Time-weighted average.

VOCs: Volatile Organic Compounds.

WHO: World Health Organization.

Executive summary

Despite the calls for action in the context of the climate emergency, fossil fuels continue to be the main energy source in the world (82%) and the EU (71%). The fossil fuel industry, in all its three main stages – upstream, midstream, and downstream –, is one of the most polluting industries worldwide. By producing environmental data and knowledge, Citizen Science might offer a unique opportunity to improve the industry operational practices and minimize the risks posed to the health of the people living in the vicinity of the fossil fuel infrastructure. As a part of 'Environmental Monitoring through Civic Engagement' (ERICA) project, this report describes existing open-source, low-cost, DIY and user-friendly technologies useful to monitor the environmental consequences of the fossil fuel industry in EU and beyond (see Section 4. Existing low cost and DIY sensors and technologies). Technical specifications, functionalities and protocols are provided. The report also features an analysis of the most relevant pollutants related to the fossil fuel industry and how to monitor them with selected technologies (see Section 5. The most relevant parameters and pollutants for the fossil fuel industry). Among these pollutants, those that entail health risks are identified, along with a review of their related legislation on permissible levels and their toxicological profile. All this review has been conducted based on the long experience and expertise on the socio-environmental impacts of the fossil fuel industry and citizen science of the project partners, which include universities (University of Barcelona –UB-, the International Institute of Social Studies from the Erasmus University of Rotterdam –ISS-EUR-, the Adama Mickiewicza University – AMU-) and civil society organizations (Cova Contro and Source International). Furthermore, we have also collected information about sensors, pollutants and national legislation from three case studies using focus groups with the local civil society organizations.

While our analysis showed various low-cost and DIY sensors and technologies to monitor the impacts of fossil fuel industries, it also underlined a few important shortcomings. First, most low-cost and DIY sensors have been developed for monitoring air pollution *in general*, often lacking specificity to fossil fuel activities. Data quality, high detection limits, and the qualitative or semi-quantitative nature of the data are further limitations in obtaining truly actionable data. An effective way to mitigate these drawbacks is by joining forces with scientific processionals – e.g., universities and research centres – and ensure knowledge is co-created. Low-cost tools are still pivotal to raise awareness in the society, educate the public, collect the first evidence of pollution, and spark interest in political and academic actors – below, we provide a selection of the low-cost solutions we found most suitable to citizen science initiatives aimed at these goals.

A scientific review and several focus groups have allowed to provide technical information on sources, harmful effects and technological profiles to identify the most relevant parameters and the pollutants associated to fossil fuel industries (including oil, gas and coal exploration, extraction and refining). In order to provide citizen science initiatives with rigorous information, a comparative analysis of environmental and toxicological legislation is also included.

Introduction

Citizen science can be defined as the non-professional involvement of volunteers in the scientific process, including problem definition, data collection, data analysis and interpretation, and the dissemination of results (Cohn, 2008; Silvertown, 2009). Citizen science is a powerful tool for public engagement and empowerment in policy making and for raising awareness of environmental or other socially relevant issues. The potentiality of collaborative science to produce crow-sourced data is also clear. However, there are underlying tensions at the basis of citizen science, since the term has been broadly used for public participation in science, frequently meaning free or cheap labour, in an exploitative way, providing data for scientists and entrepreneurs who have set up the system: “scientists using citizens as data collectors” rather than “citizens as scientists” (Lakshminarayanan, 2007). In most initiatives that claim to be citizen science projects, participation is circumscribed to data collection (crowdsourcing. In here, we use the normal acceptation of citizen science, i.e. science by and for the citizens, aiming at the empowerment of citizens and the democratisation of science. Citizen science as a bottom-up process that seeks political action and social transformation. This acceptation of citizen science has been also named “extreme citizen science” (Haklay, 2013).

This review aims at collecting knowledge about the frugal and easy-to-use technologies and understanding how they can be used by citizen scientists to perform environmental monitoring on fossil fuel industries. It also focuses on understanding the advantages and disadvantages of these technologies. To this end, we identify the most relevant parameters and pollutants related to fossil fuel industries that pose a health risk, and we establish the toxicological profile of each pollutant. Then, international standards and the technical legislation on permissible levels for each pollutant are both reviewed. Finally, we retrieve information about sensors, pollutants and Nacional Permissible Levels gathered among the focus groups within the partnership.

All the information collected in A2.2 and A2.1 will be integrated in the ERICA E-booklet of best practices, which is the main output of Working Package 2. The ERICA (*Environmental Monitoring through Civic Engagement*) project is an Erasmus+ initiative co-funded by the European Union. It is led by the following academic and scientific institutions and environmental justice organizations: University of Barcelona (UB), The International Institute of Social Studies (ISS), The Environmental Volunteer Association Cova Contro, Adam Mickiewicz University in Poznań, Source International ONLUS, and the European Association for Local Democracy (ALDA).

Methodology

This report presents information gathered through literature reviews, both from academic and grey literature, and focus groups with local civil society organizations at the 3 pilot sites – i.e., the petrochemical complex in Tarragona (Catalonia), the oil extraction plant in Basilicata (Italy) and the coal mine in Konin (Poland). The specific methodologies applied in each section are described below.

Section 4: Existing low cost and DIY sensors and technologies

This section builds on a literature review of past or ongoing citizen science projects and in-field experiences from Source International and Cova Contro. Relevant citizen science projects were identified using the Environmental Justice Atlas (EJAtlas), Google search, Google news, Google scholar, and citizen science repositories such as Public Lab (https://publiclab.org), GLOBE (https://www.globe.gov), and Sensor Community (https://sensor.community/en/). Specific instruments, tools, and approaches adopted in other projects have been selected according to their ability to detect pollutants specific to oil, gas and coal industry (and if relevant, their performance in intercomparison tests). Furthermore, Google has been used to look for additional low-cost instruments and kits that are able to detect fossil fuel-related pollutants and can be easily used. In all cases, technical specifications on instruments and sensors were collected from suppliers' websites or from personal communication with the supplier.

Data on the sensors and tools used in citizen science initiatives have also been collected through focus groups with the local civil society organizations of the pilot sites. To undertake these sessions, the research group from AMU introduced a common methodology to be applied in all pilot sites. We conducted at least one focus group interview per pilot site. These focus groups were conducted based on a pre-agreed script that included a general structure for the session, along with guidelines for the moderator and sample specific questions. They were organized using participatory design approaches to engage participants and gather information on low-cost and DIY sensors, relevant pollutants and, also, requirements for the e-book, the e-platform and the development of the educational modules contained. The groups took the form of face-to-face or online group sessions conducted via MS Teams, Zoom or other videoconference devices. The researchers contacted individuals that met the inclusion criteria based on keywords (i.e., "NGO", "environmental protection", "environmental monitoring", "fossil fuels"). Based on such a procedure, they searched for contact information available on the web (official websites, NGO lists, public information bulletins, municipal information services, etc.). The names of environmental NGOs known to the researchers were also included, and so were the names of fossil fuel extraction companies and those of government offices. No randomization procedure was performed. The researchers contacted all those actors who displayed activities linked to environmental protection or monitoring in their online profile. Among other questions, participants were asked about any fossil fuel industry-derived pollutants they knew and whether they were negatively affecting their health or lives. They were additionally asked questions about the tools and technologies used by local communities or pro-environmental NGOs to monitor said pollutants. The detailed responses are included in a separate report.

<u>Section 5 "The most relevant parameters and pollutants"</u>

This section describes the most relevant pollutants emitted by fossil fuel industries and reflects the experience of the research team from UB. A scientific review using Science Direct and Google Scholar was performed to search for pollutants related to coal, and oil and gas extraction and petrochemical complexes. The information collected in several focus groups was also considered. Technical information about fossil fuel sources of pollutants, toxicological profile and human health risks was obtained from official institutions such as the World Health Organization (WHO), the US Environment Protection Agency (EPA), the Agency for Toxic Substances and Disease Registry (ATSDR) from US, the Centre for Disease Control and Prevention (CDC) from US, and the European Environment Agency Air quality in Europe (EEA). Regulations and International Standard were obtained from EEA.

The focus groups allowed to obtain detailed descriptions on low-cost and DIY sensors, as well as technologies employed by citizen science initiatives at partner sites. They also allowed to account for the public perception on the most harmful pollutants and other important parameters.

The appropriate legislation is presented using primary sources like the EU portal of the directives, as well as other secondary sources. The European Commission Environmental Office has been contacted to verify the validity and timeliness of the data, but they are still processing the request. For this reason, this report will be only available to the European commission, and it will only be published after data validation. <u>Disclaimer</u>: *This document will not yet be published anywhere; it will only be used to interim revision by the European Union Commission. The technical information extracted from the ATSDR, CDC, EPA, EEA and WHO should be referenced correctly and properly updated before publication.*

Existing low-cost and DIY sensors and technologies

This section describes the available low-cost and DIY sensors. A sensor is considered “low-cost” if it can be purchased for less than 2,000 €, while “DIY” means it can be easily set up and used by a citizen without the assistance of a professional technician. These available technologies are classified by their environmental matrix and the pollutants they target (Table 1).

Most low-cost and DIY sensors have been developed for monitoring air pollution, whereas low-cost technologies for water and soil include primarily colorimetric kits. Data quality (including pollutants detected, detection limits and quantitative data) is a general drawback of low-cost approaches. Therefore, we also provide a few examples of these more expensive options (5,000 – 30,000 €) that detect pollutants specific to oil and gas industry. While likely out-of-budget for individual citizens, these instruments are still affordable to communities and organizations with access to funding.

We focus on chemicals that can be considered proxies for pollution caused by the oil and gas industry (Table 1) – however, most low-cost and DIY technologies are designed to monitor *general* indicators of pollution. In air, these pollutants include carbon-based compounds like methane (CH_4), volatile organic chemicals (VOCs) like BTEX (i.e., benzene, toluene, ethylbenzene, and xylene), and hydrogen sulphide (H_2S). Being an indicator of ongoing combustion, particulate matter (PM) is also often monitored. In water and soil, total petroleum hydrocarbons (TPHs) are good proxies of pollution associated to oil and gas activities. TPHs comprise several aliphatic and aromatic compounds having 6 to 50 carbon atoms (i.e., C_6–C_{50}), including BTEX (C_6 – C_{10}; also, more generally referred to as gasoline range organic hydrocarbons), polycyclic aromatic hydrocarbons (PAHs; C_{12}–C_{22}), and other compounds (Interstate Technology & Regulatory Council, 2018; SiteLab Corporation, 2023).

Table 1. Overview of pollutants in various environmental matrixes.

Environmental matrix	Target pollutants	Other pollutants
Air	total and specific VOCs (e.g., BTEX, PAHs), CH_4, H_2S, SO_2, presence of smell	PM, NO_x, SO_2, CO, O_3, heavy metals
Water	TPHs (e.g., BTEX, PAHs), surface films or contamination	Conductivity, pH, heavy metals
Soil	TPHs (including BTEX)	Heavy metals

Target pollutants identify chemicals and general parameters whose presence is associated to oil and gas industries, while other species monitored in environmental assessments are in the third column. Legend: PM = particulate matter (including PM_1, $PM_{2.5}$, PM_{10}); H_2S = hydrogen sulphide; CH_4 = methane; VOCs = volatile organic compounds; BTEX = benzene, toluene, ethylbenzene, xylene; CO = carbon monoxide; O_3 = ozone; NO_x = nitrogen oxides (including NO and NO_2); SO_2 = sulphur dioxide; TPHs = total petroleum hydrocarbons (C_6 – C_{50}); PAHs = polycyclic aromatic hydrocarbons.

Sensors to monitor air pollution

There are many available low-cost sensors designed to monitor air pollutants, including some that are specific to the oil and gas industry. The working principle varies depending on the target species – for instance, particles are detected with optical particle counters, VOCs with photo ionization detectors, while NO_x, O_3, and CO are often measured with metal oxide or electrochemical sensors (European Commission, 2022; Gerboles, 2017).

Low-cost sensors can be purchased directly as ready-to-use devices; alternatively, one can buy the bare sensor and build a case and data logger system. Most DIY devices for air quality monitoring belong to this category. In both cases, total costs per device range from few tens to up to 2,000 € for criteria pollutants and up to 5,000 € for VOCs (Gerboles, 2017).

Data quality is a well-known drawback of low-cost air quality sensors. Both the US Environmental Protection Agency (EPA, 2024a) and the EU Joint Research Center (European Commission, 2022; Karagulian, 2019) systematically compared the performance of low-cost sensors to reference methods to identify the best products for monitoring initiatives. Along these lines, the South Coast Air Quality Management District in California established the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), a program that aims to evaluate the performance of sensors costing ≤ 2,000 USD (AQMD, n.d.-a). Their website includes a comprehensive list of products classified by supplier and target pollutant, alongside cost, technical specifications, and a report showing the sensor's response with respect to reference techniques. This website is an invaluable resource for identifying the sensor that optimizes available budget and general purpose of the citizen science initiative.

Commercial low-cost sensors

A selection of devices that showed good performance in intercomparison tests and have been (or have potential to be) used in citizen science initiatives are presented in Table 2. Given the rich offer on the market, we refer the reader to the AQ-SPEC website (AQMD, n.d.-a) for a more comprehensive list of options.

Table 2. Selection of commercial low-cost sensors for detecting pollution in air.

	Detected pollutants	Approximate cost	Info
Aeroqual S500	$PM_{2.5}$, PM_{10}, H_2S, VOCs, CH_4 (plus O_3, NO_x, SO_2, CO, CO_2, and others)[a]	1,600 € (heandable monitor) + 600 – 1,200 € (sensor head)	Table A1
Smart Citizen Kit v2.1	PM_1, $PM_{2.5}$, PM_{10}, VOCs [b] (plus CO_2, sound, and light pollution)	100 €	Table A2
PurpleAir	$PM_{2.5}$, VOCs[c]	200 – 300 €	Table A3
Airnote	PM_1, $PM_{2.5}$, PM_{10}[d]	1,700 € (10 units)	Table A4

Pollutants in parenthesis can be detected but are not identified as being specific to oil and gas activities. Tables A1 – 4 in the appendix present detailed technical information on these instruments. Costs are approximate and do not include shipping and taxes. [a] Poor response for PM_{10} and VOCs measured with a GSS sensor (but good response for the PID sensor) in AQ-SPEC tests. [b] Poor response for PM_{10} and VOCs in AQ-SPEC tests. [c] VOCs detected only by PurpleAir Zen, Touch, and Flex. [d] Poor response for PM_{10} in AQ-SPEC tests.

Aeroqual S500 is a handhold sensor that has been used in monitoring initiatives related to oil and gas pollution (e.g., in Val d'Agri; (Souce International, 2021)). By changing the sensor's head, one can detect a variety of species, including H_2S, CH_4, and total VOCs, with detection limits generally ≤ 1 ppm. According to AQ-SPEC, the photoionization detector for VOCs is one of the best low-cost options currently available on the market to detect total VOCs in air (AQMD, n.d.-c).

The **Smart Citizen Kit** (v2.1) was specifically developed for citizen science applications (see https://smartcitizen.me) and allows one to detect several species associated with air pollution. While the cost is modest, this instrument should be used primarily for collecting qualitative and semi-quantitative data, especially with respect to PM_{10} and VOCs (AQMD, n.d.-b).

PurpleAir and **Airnote** are two devices dedicated to particles that can be purchased for less than 300 €. PurpleAir is a well-established device for $PM_{2.5}$ monitoring and is a popular choice for citizen-led air quality monitoring (PurpleAir Community, n.d.). The latest available releases (e.g., PurpleAir Zen) can also detect total VOCs. Airnote is a wireless, power-free sensor ideal for deployment in remote sites that was developed in response to the Fukushima nuclear disaster (Ozzie, 2021). Like PurpleAir, data is shared in real time on a global map and is openly available to the public.

DIY sensors

Most DIY sensors for air pollution are low-cost optical counters for particulate matter ($PM_{2.5}$) encased in a shield and connected to a data logger. The **DustBox** (v2), developed in the context of the Citizen Sense initiative (https://citizensense.net/), is a good example of this setup (see Table A5 in Appendix

1). The core of this device is a low-cost PM sensor from Plantower that is placed into a 3D-printed enclosure and connected to the WiFi through a microcontroller. While their instruction manual is detailed and thorough – including also instructions for assembling electronics and performing calibrations and quality controls –, building this instrument requires confidence in electronics, soldering, and coding. The total cost is not specified but is likely around a few hundred euros (the case alone is ~ 200 €). Other examples of DIY devices for $PM_{2.5}$ include **airRohr** (developed by Sensor Community; https://sensor.community/en/) and **CanAirIO** (Hackster.io, 2018); simpler, more qualitative instruments include the **Simple Air Sensor** (Public Lab, n.d.-a) by Public Lab (https://publiclab.org) and the **GLOBE sun photometer** (The Globe Program, n.d.).

More specific for oil and gas is the **Frackbox**, always from the Citizen Sense initiative (see Table A6 in Appendix 1) (Citizen Sense, n.d.-b). The Frackbox detects VOCs, including BTEX, using a low-cost photo ionization detector, in addition to NO_x, O_3, and meteorological data. Detection limits are < 5 ppb for all species. At the time of writing, this device is still a prototype and detailed building instructions are not available (Citizen Sense, n.d.-b).

Passive samplers

An alternative low-cost option to include citizens is to perform sample collection. *Passive* samplers are particularly suitable for this purpose, as they only need to be deployed for a given amount of time; they are light and do not require power. On the other hand, *active* samplers force air through a connection bag for a set period of time, generally an hour. Once recollected, both passive and active samples are mailed to academic or accredited laboratories for analyses via standardized methods. For example, individual VOCs can be detected via gas chromatography mass spectrometry following the standard EPA method TO-15, which is designed to see 97 individual pollutants in concentration ≥ 0.5 ppb (EPA, 1999; Public Lab, n.d.-a) . Specific costs and detection limits are dictated by the analytical technique, analyte, and laboratory of analysis.

Both commercial and DIY passive samplers are suitable for citizen science initiatives. **Radiello** is a convenient choice when funding is available (~ 400 – 600 € for 20 samplers, inclusive of samples' analysis) (Radiello, n.d.). This firm offers various solutions depending on target pollutant and sampling needs. For example, a H_2S Radiello passive sampler was deployed during a month-long campaign to detect traces of this gas around the oil plant COVA in Val d'Agri (Souce International, 2021). Other Radiello samplers are designed to specifically adsorb other pollutants, including, among others, total VOCs, aldehydes, phenols, 1,3-butadiene, O_3, NO_2, and ammonia.

The **Bucket Monitor** from Public Lab is an example of a DIY active sampler for VOCs and sulphur-containing chemicals, including H_2S (Public Lab, n.d.-b). This sampler was first designed in the late 1990s by California residents worried about the health effects of nearby petrochemical and oil plants (Communities for a Better Environment & The National Oil Refinery Action Network, 1999) and has been thoroughly tested and approved by the US EPA for community-based air quality monitoring (Louisiana Bucket Brigade, 2005; Public Lab, n.d.-b). The Bucket Monitor consists of a closed 20 L food storage bucket containing a 5 L Tedlar bag. The bag is filled with air using a battery-powered camping vacuum or a bike pump and shipped for analyses within 24 – 72 hours of collection. The cost of a single bucket is around 200 €. While only qualitative, DIY passive samplers based on **copper strips** (Public Lab, n.d.-b) **or photopaper** (Horwell et al., 2004; Vera et al., 2020) can be deployed to selectively detect H_2S.

Other low-cost approaches

Additional low-cost approaches can help gather qualitative or preliminary data on air quality. For example, citizens can report presence and intensity of bad smell (as in Smell My City; https://smellmycity.org), oil-related gas flaring (Facchinelli et al., 2022) or evaluate the health of indicator plants to spot significant levels of air pollution (Citizen Sense, n.d.-c).

As more expensive instruments focusing on VOCs and oil-related species, we note the PEN3 Portable Electronic Nose (AIRSENSE Analytics, n.d.-b), OlfoSense (AIRSENSE Analytics, n.d.-a), and the WatchGas QGM multi-gas monitor (Progas Solutions s.r.l., n.d.). The latter is a professional instrument designed to detect gas-phase hydrocarbons and H_2S for applications in the petrochemical industry.

Sensors to monitor water pollution

Commercial low-cost kits

Colorimetric kits are the best option for semi-quantitative and qualitative low-cost analyses of water samples. Indeed, most citizen science programs on water quality monitoring rely on these tools (e.g., Freshwater Watch; https://www.freshwaterwatch.org/). Kits including 30 – 100 tests can be purchased for 50 – 200 € from both general chemistry (e.g., Sigma Aldrich) and specialized suppliers, such as ChemMetrics (https://www.chemetrics.com/) and SenSafe (https://sensafe.com/) and are intuitive and quick to use. They work by dipping a strip embedded with a specific dye into the sample (or by adding a dye-containing reagent to the aqueous sample). After a short waiting time, the strip's (or the sample's) colour is compared to a wheel that associates each hue to a concentration range. For some chemicals, kits are available for different concentration ranges, with detection limits that vary accordingly but are always in the ppm range.

Most kits focus on general water quality parameters (e.g., NO_3^-) and soluble metals including, among others, iron, arsenic, and lead. A handful of products are available for H_2S, and organics associated with industrial pollution. The **Sulfide CHEMets visual Kit** from ChemMetrics (CHEMetrics, n.d.-a) (see Table A7 in Appendix 1) employs methylene blue as the dye to detect H_2S/HS^-. The kit is available in several ranges from 0 – 10 to 1,200 – 12,000 ppm, with respective detection limits of 0.05 to 75 ppm. The same supplier sells also a kit for phenols, general indicators for industrial pollution, for the 0 – 1 to 0 – 350 ppm concentration ranges (CHEMetrics, n.d.-b). Also, SenSafe offers various low-cost solutions for detecting sulphides in water (Sensafe, n.d.).

There are a few more expensive options specific to TPHs contamination in water. The **Modern Water RaPID Assay** (JJS Technical Services, n.d.) quantifies total BTEX/TPH in the range 0.02 – 3 ppm through a magnetic particle immunoassay (see Table A8 in Appendix 1). The **Hanby TPH Test Kit** is a more qualitative tool where samples are first extracted with an organic solvent, then the extract's hue is compared to a colour scale to identify type of oil-based contaminant and its concentration. Both kits are also available for soil samples (Hanby Environmental, n.d.).

Commercial and DIY low-cost sensors

Low-cost sensors are mainly available for general water quality parameters. As commercial products, we note the **Hanna multiparametric field probe** (2,000 – 2,400 €) (Hanna Instruments, n.d.), a robust field instrument that records several water quality parameters (e.g., pH, temperature, conductivity, dissolved oxygen, total dissolved solids, etc.) and has already been used in community monitoring programs. If interested in selected parameters, the **Horiba LAQUAtwin Compact Meters** (Water Quality Testing, n.d.) are cheaper alternatives – these pocket-size meters are available for pH, conductivity, oxidation-reduction potential, and selected ions for 150 – 400 € each.

The **eXact iDip Photometer** (Sensafe, n.d.) is a cheap option (~ 350 €) for assessing general water chemistry and quantifying metals and other pollutants – including sulphides and hydrogen cyanide. It follows the same working principle as colorimetric kits but utilizes a photometer to quantify colour change – thus, concentrations are assessed more accurately. The SenSafe website has a rich selection of strips for selected analytes to be used in combination with this instrument.

Like commercial products, DIY sensors focus on general water parameters rather than specific oil-related pollutants. Contributors in Public Lab compiled a thorough list of low-cost sensors suitable for this purpose. As for air quality measurement, the sensors must be placed into an enclosure and connected to a data logger before deployment. Information on these steps can be found in dedicated Public Lab pages (Public Lab, n.d.-c). The book "Environmental Monitoring with Arduino" by E. Gertz and P. DiJusto is also a valuable resource. At the time of writing, we are not aware of DIY sensors to detect water pollutants specific to oil and gas activities (Gertz & Di Justo, 2012).

Other low-cost approaches

Georeferenced visual inspection or photographic records are valid low-cost alternatives that involve local communities. For example, the Public Lab describes a simple method to distinguish between natural bacterial films and oil pollution that can help identify contaminated water bodies (Public Lab, 2020). Georeferenced photos can also help localizing areas to prioritize in further environmental actions (Souto & Batalhão, 2022). Citizen science projects can make use of open satellite images to monitor oil spill, as has been done to detect oil spills in the Niger Delta region in Nigeria (Cartoscope, n.d.).

As for air, citizens can be involved in sample collections – e.g., through the deployment of passive samplers (Allan et al., 2012) or the extraction of chemicals from water samples (Cacciatori et al., 2024). Samples are then sent to professional laboratories for analysis.

Professional field probes are available for detecting pollutants associated to petrochemical activities. SiteLab (https://site-lab.com) sells field fluorimeters to detect hydrocarbons in water and soil. The **UVF-500D Handheld Analyzer** (SiteLab Corporation, n.d.) (~ 6,500 €) is a basic instrument suitable for detecting TPHs associated to oil and grease (i.e., $C_{15} – C_{50}$), with detection limits in the low ppm range (0.05 – 5 ppm). For a higher price (14,000 – 24,000 €), the **UVF-TRILOGY Benchtop Analyzer** (SiteLab Corporation, 2023) detects a range of TPHs, including BTEX ($C_6 – C_{10}$), diesel-derived organics ($C_{10} – C_{36}$), PAHs ($C_{12} – C_{22}$), and oil and grease hydrocarbons ($C_{15} – C_{50}$) with detection limits of 0.05 – 0.5 ppm. These instruments require sample extraction prior to analyses and detect only aromatic TPHs. For a similar price (~ 14,000 €), the **enviroFlu-HC 500** (TriOS Optical Sensors, n.d.) detects PAHs in water with detection limits of 0.3 ppb. This instrument can be used for real-time data and does not require sample extraction.

Sensors to monitor soil pollution

Commercial kits and technologies

Low-cost detection of oil-based pollutants in soil can be done with the kits available water but following a different sample extraction protocol prior to analyses. Indeed, the **Modern Water RaPID Assay** (JJS Technical Services, n.d.), the **Hanby TPH Test Kit** (Hanby Environmental, n.d.), the **UVF-500D Handheld Analyzer** (SiteLab Corporation, n.d.), and the **UVF-TRILOGY Benchtop Analyzer** (SiteLab Corporation, 2023) can all analyse also soil samples.

Specific for soil is the **PetroFLAG Analyzer System for TPH in Soil** (Dexsil, n.d.) (see Table A10 in Appendix 1). For approximately the same per-sample cost of the Hanby kit (~ 90 € per sample), PetroFLAG detects *both* aliphatic and aromatic TPH in the range C_8 – C_{44} based on an optimized extraction procedure and turbidimetric detection. Detection limits are in the tens of ppm range. We refer the reader to the 2021 Concawe report for a comprehensive review of tools for detecting hydrocarbons in soil (Lourenço et al., 2021).

Other low-cost approaches

Citizens can be involved in sample collection – as done, for example, by Citizen Science Community Resources (https://www.csresources.org). This project sells an "EnviroBucket" containing all necessary equipment for soil sampling and provides the possibility of sending the sample to a certified laboratory for analysis of PAHs (~ 220 € / sample), heavy metals (~ 100 € / sample) and pesticides (~ 200 €/ sample).(The Globe Program, n.d.)

Soil samples can also be tested for general chemistry parameters using the low-cost kits for water combined with a soil extraction – e.g., as outlined in the GLOBE protocol for measurement of soil pH. Soil extraction typically involves weighting a mass of soil (e.g., 40 g), place it into a clean container, add the same mass of distilled water, and stir. The suspension is then allowed to sediment and the supernatant liquid is analysed like water. Depending on the parameter, this approach provides at best semi-quantitative or qualitative results – while it works well for water-soluble species (e.g., nitrate) (Agronomy Research & Information Center of the University of California, n.d.), other contaminants require harsher extraction procedure (e.g., acids for metals and organic solvents for TPH).

The Appendix 1 includes detailed technical information on the 10 most suitable low-cost solutions for citizen science initiatives.

Are low-cost and DIY sensors appropriate to monitor fossil fuel industries?

Most low-cost sensors and technologies detect pollutants that are *not* specific to fossil fuel industries. For air, there exist a few low-cost solutions for detecting specific oil-related contaminants, including H_2S and VOCs (e.g., the **Aeroqual S500** and the **Radiello** passive samplers). Intercomparing tests by governmental labs highlighted data quality issues in some low-cost products, an issue that should not be neglected when planning initiatives that require high-quality data. For water and soil, the best low-cost options are kits based on colorimetric or magnetic assays. While intuitive and simple to use, most products provide qualitative or, at best, semi-quantitative information (e.g., a concentration range), and typically work in the ppm range.

A good alternative consists in involving citizens only in sample collection and delegating chemical analyses to a professional, accredited lab. Various options for active and passive sampling exist for air, water, and soil, either commercial or DIY. Typically, analyses cost 100 – 250 € per sample (depending on analyte and lab), but results are robust and reliable. Last, citizens can also play an active role by gathering ground-based data – in environmental justice, these "simple" crowd-sourced observations can be more impactful than data collected with expensive instruments.

<u>The best 10 DIY sensors for citizen science</u>

The Appendix includes detailed technical information on the 10 most suitable low-cost solutions for citizen science initiatives. As commercial solutions for air, we recommend the **Aeroqual S500**, the **Smart Citizen Kit v2.1**, various **PurpleAir** sensors, and **Airnote**. As DIY devices, we suggest the **DustBox (v2)** and the **Frackbox** developed in the context of the Citizen Sense initiative. These systems target primarily $PM_{2.5}$, but the Aeroqual S500 and Frackbox have specific sensors for oil-related pollutants.

Commercial kits are the best low-cost options for water and soil analyses. Specific for petrochemical activities, we note the **Sulfide CHEMets visual Kit** for water, **Modern Water RaPID Assay** for BTEX/TPH detection in water and soil, the **Hanby TPH Test Kit** for oil-based pollutants in water and soil, and **PetroFLAG Analyzer System for TPH** in soil.

Inputs from project pilot sites

One of the questions asked to the different focus groups was aimed at the different tools and technologies they knew about citizen science monitoring of fossil fuel industries in each pilot site. The corresponding information is presented in Table 3. The Basilicata focus group components mentioned the usefulness of aerial and underwater drones and a thermal camera as supporting tools in citizen science initiatives that monitor oil and gas extraction. These products can be extremely useful to control possible oil spills and petrochemical emissions – for example, thermal cameras can be deployed to monitor fugitive emissions from fossil fuel industries. This focus groups also mentioned the utility of open-source data from the Copernicus satellite, which provides, for example, daily information on the global atmospheric composition of greenhouse gases, reactive gases (e.g., carbon monoxide, oxidised nitrogen compounds, sulphur dioxide), ozone, and aerosols (https://www.copernicus.eu/en/copernicus-services/atmosphere). Any DIY technology nor sensor was mentioned by these focus groups.

Also, the focus group of Tarragona did not mentioned any DIY sensor. In this case, the main citizen science initiatives involved the collaboration of citizens with governmental institutions and technology centres. Therefore, citizens collaborated by, for example, gathering data on bad odours, while technology centres developed the tools to collect, analyse and monitor the pollutants like 1,3-butadiene.

Likewise, in Poland, focus group participants mentioned no technologies nor sensors. All citizen science initiatives to monitor the impact of coal extraction focused on biological sampling and qualitative assessment through visual examination of water parameters and observation of animal behaviour. In addition, involving scientific institutions and experts was again crucial to sharing knowledge and achieving the best results.

Table 3. NGOs Engaged in Citizen Science for Monitoring Fossil Fuel Environmental Impact, Analyzed Pollutants, and Tools Used at Each Pilot Site.

Pilot site	Citizen science organisations	Pollutants analysed	Environmental Monitoring Techniques
Basilicata (Italy)	× COVA Contro × Movimento Tutela Val Basento (http://movimentovalbasento.altervista.org/) × Osservatorio Popolare Val d'Agri (https://www.facebook.com/osservatoriopopolarevaldagri/?locale=it_IT)	× Identification of bad odours and their sources × Remote sensing for methane into the air column - https://covacontro.org/a-stigliano-aumenta-la-presenza-di-metano-nella-colonna-daria-valori-quintuplicati-tra-il-2018-ed-il-2021/ × Analysis of hydrocarbons and heavy metals; × Analysis of H_2S, NO_2; hydrocarbons, heavy metals and new contaminants such as DCPA and PFOS in drinking and underground waters;	× Real-time air quality meters × Aerial and underwater drones × Flir thermal camera × Copernicus open source/Envi remote sensing software
Tarragona (Spain)	× Cel Net × Enginyers sense fronteres × INSTA × Ecologistes en acció × GEPEC × Good Karma Project × La Canonge 3: https://lacanonja3.wordpress.com/ × Neighbourhood associations × Ones Mediterrània: https://www.mare-terra.org/ca/inici/ × L'Escurçó: https://m.facebook.com/p/Organizaci%C3%B3n-Ecologista-LEscur%C3%A7%C3%B3-100070104726960/ × Surfrider foundation: https://www.surfrider.eu/learn/news/les-microplastiques-pollution-invisible-ocean/	× Identification of the main volatile organic compounds (VOCs) present in Tarragona's air. × Identification of VOCs associated with bad odours. × Determination of petrochemical or chemical companies responsible for pollution. × Identification of toxic VOCs produced by the petrochemical industry not covered by current regulations. × Identification of bad odours and their sources × Analysis of 200 volatile organic compounds (VOCs), with notable pollutants including benzene, 1,3-butadiene, acetic acid, and ethylene oxide following the IQOXE chemical accident in 2020. × Measurement of PM10 (particulate matter with a diameter of 10 micrometres or less) × Assessment of polycyclic aromatic hydrocarbons (PAHs), with significant pollutants including benzo(a)pyrene, benzo(a)anthracene, benzo(b+j)fluoranthene,	×Radiello® passive samplers and 24-hour active air sampling using multi-sorbent bed tubes. ×Interactive mapping technology for microplastics ×None of the mentioned citizen organizations have utilized do-it-yourself (DIY) monitoring tools. However, there have been other initiatives proposing the use of experimental tools such as the PurpleAir map. ×sensors specifically designed to detect 1,3-butadiene and monitor episodes of VOC pollution and elevated levels (installed by municipality El Morell)

Pilot site	Citizen science organisations	Pollutants analysed	Environmental Monitoring Techniques
	× La Sínia: https://www.riugaia.cat/ × Associació per a la Conservació dels Ecosistemes Naturals (CEN): www.assoc-cen.org	benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene, and dibenzo(a,h)anthracene. × (Reference: https://www.celnet.cat/estudis.html) × Analysis of microplastics	
Konin (Poland)	× Ecological Association Eko-Przyjezierze (http://www.przyjezierze.org/) × The Foundation Rozwój TAK – Odkrywki NIE (Development YES – Open-Pit Mines NO, RT-ON Foundation) (https://rt-on.pl/en/) × Greenpeace Poland (https://www.greenpeace.org/poland/) × EKO-Unia Association (https://eko-unia.org.pl/)	× Biological sampling and assessment through visual examination (siltation and water colour) × Observation of the behavior of animal species × Expertise performed by Adam Mickiewicz University and Greenpeace on the association's request, concerning biodiversity (fish, amphibians, reptiles) and pollutants (heavy metals). × slope stability and landslide risk	n/a

The most relevant parameters and pollutants

Fossil-fuel industries produce toxic pollutants that are associated to various health effects as well as ecosystem degradation. Coal mining has been related to increased cardiopulmonary, lung, and kidney disease, increased rates of lung cancer mortality, and adverse in-utero effects in pregnant women, including low-birthweight (Ahern et al., 2011; Ahern & Hendryx, 2008; ATSDR, 2016; Hendryx et al., 2010; Hendryx & Luo, 2015). Oil and gas industries have been related to reproductive problems, hormonal effects, allergies, asthma and other respiratory problems, leukaemia and other haematological malignancies, lung and bladder cancer, as well as an excess mortality linked to problems in bone, brain, liver, pleural, larynx and pancreas. Moreover, the higher sound levels in the vicinity of these industries have been related with increase stress, headache, impatience, annoyance, hypersensitivity, violence and anxiety (Kursunoglu & Kursunoglu, 2021; Marquès et al., 2020; Pan et al., 2022).

One of the challenges that citizen involved in environmental monitoring campaigns face is to find those target pollutants most related with FF industries as well as to interpret and understand data about chemical concentration and compare it with international standards and recommendations. Understanding international environmental legislation is a challenge, as it is important to distinguish between mandatory data and those that are international recommendations. Therefore, it is important to differentiate between environmental quality standards (EQS) and environmental guidelines. Both are essential tools in environmental management and public health protection but present distinct characteristics and applications. EQS provide the maximum permissible levels (MPL) of pollutants in specific environmental matrices and ensure regulatory compliance and public safety. They are based on requirements from nationwide laws and regulations as those from the European Community Directives or Environmental Protection Agency (EPA) from US., but also from the corresponding regulations from each country or region with sufficient juridical powers. There exist also MPL for occupational exposure (workers), but they are not discussed here.

In air monitoring, one other aspect to consider when we compare our field data with the existing standards or recommendations is if we are talking about immission or emission values. Immision is a related to the air one can breathe – thus, it refers to a mixture of components and pollutants – whereas emission data refers directly to emission sources – e.g., industries. Sometimes these concepts can be related, but sometimes not. Therefore, immision refers to the number of pollutants present in the atmosphere and the corresponding standards or limits are designated to protect human and environment health, while emission is referred to sources that can be localized (like a wastewater pipe or a combustion torch).

Several international organizations underscore the controversy between environmental quality policies and recommendations to protect human health. Most international environmental guidelines regarding pollutants emitted by fossil fuel industries are likely underestimated, as recent epidemiological studies have reported health impacts at levels below the recommended thresholds. The EU Ambient Air Quality Directives and the World Health Organization (WHO) define air quality standards and guidelines, respectively, to protect human health from both short- and long-term effects, varying according to the pollutant and its health impacts. Although the Directives consider relevant World Health Organisation standards, guidelines and programmes, usually values differ, with the WHO air quality guidelines generally being more stringent. The EU standards represent a political compromise, balancing economic feasibility with optimal protection.

Examples of European regulations to obtain EQS related fossil-fuel pollutants covered in this report are the following.

- The Directive on Ambient Air Quality and cleaner air for Europe (. Directive 2008/50/EC), which sets EU air quality standards for 12 air pollutants. Limit values have been expressed for one hour, eight hours, 24-hour and annual mean maximum concentration to protect human health.
- The Drinking Water Directive, which includes water quality standards that are in line (or, in some cases, even more stringent) than the WHO recommendations. This Directive tackles also emerging pollutants, such as endocrine disruptors, PFAs, and microplastics.
- The Water Framework Directive (WFD), which includes the list of priority substances that Member States must monitor in surface waters. The standards for these chemicals are set in the Environmental Quality Standards Directive (EQSD) and the Groundwater Directive (GWD).
- Specifically regarding industrial emissions, there is also the Industrial Emissions Directive (IED), which is the EU instrument that regulates emissions from industrial installations, including combustion plants. However, it is not covered in this report.

Environmental guidelines offer flexible, science-based recommendations for managing environmental risks. They are basically recommendations or advisory limits rather than legally enforceable standards and sometimes they may cover also emerging pollutants or pollutants not yet regulated by law. Examples of environmental guidelines of interest to fossil fuel industries are the following.

- The World Health Organization (WHO) air quality guidelines, first and second edition which provide global targets for national, regional, and local governments to reduce air pollution.
- The WHO Guidelines for drinking-water quality and Guidelines on Recreational Water Quality, which These guidelines are focused on water quality management, establishing health-based targets, catchment-to-consumer water safety plans and independent surveillance and protect public health on coastal and freshwater environments respectively.
- The US Environmental Protection Agency (EPA) guidelines for exposure to specific chemicals, such as reference doses (RfD) or reference concentrations (RfC).

List of fossil fuel-related pollutants

In this section, the most relevant pollutants related to fossil-fuel industries have been described. Each contaminant or chemical group of pollutants have structured in three sub-sections.

a. Introduction of the pollutants describing the natural earth concentrations (p.ex. metals) and/or the main anthropogenic sources related to fossil-fuel industries
b. Toxicity and health effects. This section includes information about the possible health effects of each pollutant, related to long-term exposure and short-term exposure.
c. EU Regulations and International health Standards. This section presented some recommended international standards related basically to the human health protection. The information presented consisted in:

-WHO recommended guidelines for human protection

-International Agency for Research on Cancer (IARC) classification of each pollutant according to its carcinogenic potential. https://monographs.iarc.who.int/list-of-classifications/:

Group 1: carcinogenic to humans

Group 2A: probably carcinogenic to humans

Group 2B: possibly carcinogenic to humans

Group 3: not classifiable as to its carcinogenicity to humans

- The toxicological profile from US Agency for Toxic Substances and Disease Registry (ATSDR). It has been described the derived maximum risk level (MRL) for acute, intermediate and chronic inhalation and oral exposure. (definitions are described in Glossary).
- Integrated Risk Information System (IRIS) of US EPA: related inhalation reference (Rfc) and oral reference (RfD) have also included.

Concentrations are usually expressed as parts per million (ppm) by volume, parts per billion (ppb) by volume, or micrograms per cubic meter of air (µg/m^3).

Nitrogen dioxide (NO_X)

Nitrogen oxides, including nitric oxide and nitrogen dioxide, are released from burning fossil fuels (coal, oil and natural gas), as well as motor vehicle exhaust and various industrial processes. They are commercially produced by reacting nitric acid with metals or cellulose and are used in the production of nitric acid, lacquers, dyes, rocket fuels, organic nitration, and explosives (ATSDR, 2021).

Toxicity and Health Risks

Human exposure to NOx is related mainly to respiratory effects: Short-term exposure is related to bronchial responsiveness in asthmatic people and long-term exposure causes respiratory outcomes as respiratory effects on children[68] (WHO, 2000).

EU Regulations and International Standards

A short-term (24hour) nitrogen dioxide AQG level recommendation: 25 µg/m^3. An interim target 1 of 120 µg/m^3 and an interim target 2 of 50 µg/m^3 are also proposed (ATSDR, 2021).

A long-term annual nitrogen dioxide AQG level recommendation: 10 µg/m^3. An interim target 2 of 30 µg/m^3 and an interim target 3 of 20 µg/m^3 are also proposed (WHO, 2021).

Sulphur Dioxide (SO_X)

Sulphur dioxide is derived from the combustion of sulphur-containing fossil fuels and is a major air pollutant in many parts of the world (WHO, 2021).

Toxicity and Health Risks

Short-term exposure to SO_2 is related to all-age mortality and childhood respiratory disease, and long-term exposure is related to respiratory disease (WHO, 2021).

EU Regulations and International Standards

A short-term (24hour) sulphur dioxide AQG level recommendation: 40 µg/m^3. An interim target 1 of 125 µg/m^3 and an interim target 2 of 50 µg/m^3 are also proposed (WHO, 2021).

Particulate matter (PM)

Particulate matter (PM) encompasses diverse solid particles and liquid droplets in the air, originating from both anthropogenic sources like coal-fired power plants or vehicles and from natural sources like dust storms. PM can also form in the atmosphere via reactions involving chemicals like sulphur dioxide (SO_2) and nitrogen dioxide (NO_2). It consists of various components (e.g., metals, elemental carbon, organic compounds) with properties that vary by time, region, meteorology, and source (EPA, 2024e).

PM is classified into three categories according to its size: Ultrafine particles (UFP): ≤ 0.1 µm diameter; Fine particles (PM2.5): ≤ 2.5 µm diameter; and Thoracic particles (PM10): ≤ 10 µm diameter.

Toxicity and Health Risks

Long-term exposure to **particulate matter** above AQG has been linked to:

- Acute health conditions trigger in highly sensitive and sensitive individuals, even over exposure periods of less than 24 hours (ATSDR, 2024).
- Increase the risk of harm for individuals with pre-existing health conditions, such as cardiopulmonary disease, even with exposure periods of less than 24 hours (ATSDR, 2024).
- Cardiovascular outcomes like higher risk of developing hypertension or coronary heart disease and stroke (Dong et al., 2013; Foraster et al., 2014; Fuks et al., 2014; Go et al., 2013).
- Neurological and cognitive disorders (ATSDR, 2024). .

Increases in **PM2.5** levels or long-term exposure to PM2.5 is associated with:

- Irritation of eyes, nose, throat and lungs (ATSDR, 2024) and exacerbates asthma symptoms by causing oxidative stress that inflames the airways (Guarnieri & Balmes, 2014).
-
- Increases relative risk of acute cardiovascular events: cerebrovascular accident (Brook et al., 2018), heart attack and overall increases in blood pressure, including hypertension (Coogan et al., 2012; Giorgini et al., 2015; Lee et al., 2020).
- Increased morbidity and mortality in persons diagnosed with cancer, including lung cancer (Dockery & Pope, 1994; Jerrett et al., 2013), liver cancer (Deng et al., 2017), paediatric lymphomas, and CNS tumours (Ou et al., 2020).

- Significant association between higher PM2.5 levels and increased hyperactivity and inattention scores in children (Fuertes et al., 2016).
- Oxidative stress and inflammation, leading to impairments in insulin signalling associated with diabetes (Meo et al., 2015).
- Prenatal exposure to air pollutants and PM2.5 have been considered risk factors for increase in preterm birth, low birth weight at term or autism spectrum disorder (ASD) (Lam et al., 2016; Lyall et al., 2017; F. P. Perera et al., 2018).

EU Regulations and International Standards

No sub-acute AQG exists for exposures that occur for less than 24 hours, but some studies demonstrated changes in the blood of healthy subjects or patients with coronary artery disease at ≤24-hour exposures (ATSDR, 2024; WHO, 2021).

Table 4. WHO and ATSDR PM Screening Values.

PM Air Pollutant	WHO	ATSDR CV
PM10	45 µg/m^3 (24-hour) 15 µg/m^3 (annual)	NA
PM2,5	15 µg/m^3 (24-hour) 5 µg/m^3 (annual)	NA

CV- Comparison value – micrograms per cubic meter; PM – Particulate Matter. NA – Not Available: ATSDR does not have CV for PM.

*WHO 2021

*These screening levels reflect the numeric value of the WHO AQGs for 24-hours

Metals/metalloids

Toxic metals can be found in or attached to particulate matter (PM), allowing them to be transported over long distances and persist in the environment. Humans are primarily exposed to toxic metals through the ingestion of food and water, while inhalation and direct contact are minor exposure routes (Ortiz et al., 2019).

Humans living surrounding fossil fuel industries can be exposed to different heavy metals as a consequence of coal and oil processing. Vanadium (V), nickel (Ni), chromium (Cr), arsenic (As), mercury (Hg) and lead (Pb) have been found in significant concentrations in soils, vegetation, sediments, wastewater or urine samples in different studies (Nadal et al., 2004a)(Relić et al., 2019), (Yi et al., 2022). Therefore, according to this, we concluded that the target metals/metalloids most related with petrochemical areas are the following: **arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), manganese (Mn), lead (Pb),** and **vanadium (V).**

Based on the toxicological experiments, As, Cr, and Pb are known to be human carcinogens; Cd, Ni, and Co are also probable human carcinogens through an inhalation route.

Table 5. Air quality standards for protecting human health from toxic metals

Pollutant	Averaging period	Standard type and concentration	Comments
Pb	Calendar year	EU limit value: 0.5 µg/m^3	Measured as content in PM_{10}
		WHO AQG: 0.5 µg/m^3	
As	Calendar year	EU limit value: 6 ng/m^3	Measured as content in PM_{10}
		RL: 6.6 ng/m^3	
Cd	Calendar year	EU limit value: 5 ng/m^3	Measured as content in PM_{10}
		WHO AQG: 5 ng/m^3	
Ni	Calendar year	EU limit value: 20 ng/m^3	Measured as content in PM_{10}
		RL: 25 ng/m^3	

Source: (EEA, 2019)

Arsenic (As)

Natural arsenic levels in soil typically range from 1 to 40 mg/kg, averaging 5 mg/kg, with higher levels in mining areas. In the U.S., data published about arsenic levels in ambient air range from <1 to 3 ng/m^3 in remote areas and 20 to 30 ng/m^3 in urban areas. Regarding surface water, arsenic levels are usually <1 µg/L in seas and oceans but can range from 0.29 to 34.0 µg/L and in case of groundwater, arsenic levels average 1–2 µg/L, but can reach up to 3,400 µg/L in areas with volcanic rock and sulfidic mineral deposits (ATSDR, 2007b).

Toxicity and Health Risks

The principal route of human exposure to arsenic is the oral route, although inhalation of arsenic dusts or dermal contact with contaminated soil or water can also occur. Arsenic is a known human carcinogen by both the inhalation and oral exposure routes.

The long-term exposure to As inhalation have been related with:

- Increased risk of lung cancer and increased incidence of tumours at other sites, including the liver, skin, and digestive tract.
- Respiratory irritation
- Nausea
- Skin effects
- Neurological effects

The long-term exposure to As through food or drinking water have reported:

- Cardiovascular effects as high blood pressure and circulatory problems.
- Reproductive problems as miscarriages, stillbirths, preterm births or low birth weights.
- Skin tumours and increases the risk of internal tumours (mainly of bladder and lung, and to a lesser extent, liver, kidney, and prostate).

EU Regulations and International Standards

The IARC classifies arsenic as carcinogenic to humans (Group 1) (IARC, 2024).

The US EPA defines a cancer slope factor of 1.5 mg/kg/day and a drinking water unit risk of $5x10^{-5}$ µg/L and lowered the arsenic standard for drinking water from 50 µg/L to 10 µg/L. The inhalation unit risk is 0.0043 µg/m^3. The EPA's chronic oral reference dose (RfD) for inorganic arsenic is 0.0003 mg/kg/day for dermal effects and potential vascular complications. There is no reference concentration (RfC) for chronic inhalation exposure(EPA, 2024d).

ATSDR defined an MRL of 0.005 mg As/kg/day for acute-duration (14 days or less) for oral exposure to inorganic arsenic for gastrointestinal effects and facial oedema and an MRL of 0.0003 mg As/kg/day for chronic-duration (365 days or more) for oral exposure to inorganic arsenic based for dermal effects. No inhalation MRLs were derived for organic arsenic (ATSDR, 2007b).

Table 6. Regulations and Guidelines Applicable to Arsenic Compounds.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification for arsenic and arsenic compounds	Group 1 (inorganic As)	IARC 2024
WHO	Air quality guidelines	0.0066 µg/m^3	WHO 2000
	Drinking water quality guidelines	0.01mg/L	WHO 2022
EU	Air quality standards	6 ng/m^3	Directive 2008/50/EC

Cadmium (Cd)

Cadmium occurs in the earth's crust often associated with zinc, lead, and copper ores. Ocean water levels range from <5 to 110 ng/L, and natural surface water and groundwater usually have <1 µg/L. Surface soil concentrations vary. The main anthropogenic sources of cadmium in the environment are non-ferrous metal mining and refining, phosphate fertilizer production and use, fossil fuel combustion, and waste incineration and disposal (ATSDR, 2015a).

Toxicity and Health Risks

The major source of exposure of Cd is through oral exposure. There is evidence to suggest that cadmium is a human carcinogen, and also has been related with decrease in renal function, reproductive toxicity, and hepatic, haematological and immunological effects (ATSDR, 2015a).

Acute inhalation exposure to Cd at concentrations above about 5 mg/m^3 has been related with pulmonary oedema, tracheobronchitis, and pneumonitis and long-term inhalation of low-level cadmium in workers has been associated with decrease lung function, emphysema, and damage olfactory function and nasal epithelium (ATSDR, 2015a).

EU Regulations and International Standards

EPA has established a RfD of 5×10^{-4} mg/kg/day in water and 1×10^{-3} mg/kg/day in food, but a RfC has not established (EPA, 1989).

ATSDR has derived an acute-duration inhalation MRL of 0.03 µg Cd/m^3, a chronic-duration inhalation MRL of 0.01 µg Cd/m^3, an intermediate-duration oral MRL of 0.5 µg Cd/kg/day and a chronic-duration oral MRL of 0.1 µg Cd/kg/day.

IARC classifies cadmium as carcinogen for humans (Group I) (IARC, 2024).

Table 7. Regulations, Advisors, and Guidelines Applicable to Cadmium.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of Cadmium and cadmium compounds	Group 1	IARC 2024
WHO	Air quality guidelines	5 ng/m^3	WHO 2000
	Drinking water quality guidelines	0.003mg/L	WHO 2022
EC	Air quality standards	5 ng/m^3	Directive 2008/50/EC

Chromium (Cr)

The atmospheric concentrations of chromium can range from 5 to 525 ng/m^3 between urban and non-urban areas. In fresh waters, it can range from <1 to 30 µg/L, with a median value of 10 µg/L (US references), and in ocean water, the mean chromium concentration is 0.3 µg/L. Drinking water supplies contain total chromium levels within a range of 0.2–35 µg/L (ATSDR, 2016).

Toxicity and Health Risks

Chromium (VI) compounds are more toxic than chromium (III) compounds; therefore, only chromium (VI) is considered in this report (ATSDR, 2016).

The most sensitive noncancer effects of exposure to chromium (VI) compounds are:

- Respiratory effects as nasal and lung irritation and altered pulmonary function.
- Gastrointestinal effects as irritation, ulceration and nonneoplastic lesions of the stomach and small intestine.
- Anaemia
- Reproductive effects as decreased sperm count.
- Immunological and developmental effects.
- Dermal and ocular irritation may occur from direct contact.

EU Regulations and International Standards

ATSDR has derived an MRL of $5x10^{-6}$ mg chromium (VI)/m^3 for intermediate- and chronic-duration inhalation and an MRL of 0.0003 mg chromium (VI)/m^3 for intermediate-duration inhalation exposure (ATSDR, 2004). It has derived an MRL of 0.005 mg chromium(VI)/kg/day for intermediate-duration oral exposure for haematological effects and an MRL of 0.0009 mg chromium(VI)/kg/day for chronic-duration oral exposure (ATSDR, 2004).

EPA has derived a chronic RfD of 0.003 mg chromium(VI)/kg/day for soluble salts of chromium(VI); a chronic inhalation RfC of 0.008 µg chromium (VI)/m^3 for chromic acid mists and dissolved chromium (VI) aerosols, and a chronic inhalation RfC of 0.0001 mg chromium(VI)/m^3 for chromium(VI) particulates (EPA, 1998).

IARC classifies Chromium(VI) as Carcinogenic to humans (Group 1) and Chromium(III), not classifiable as to its carcinogenicity to humans (Group 3) (IARC, 2024).

Table 8. Regulations, Advisors, and Guidelines Applicable to Chromium.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification	Chromium (VI) Group 1 Chromium (III) Group 3	IARC 2024
WHO	Air quality guidelines	1 $\mu g/m^3$ for a lifetime risk of $4x10^{-2}$	WHO 2000
	Drinking water quality guidelines (total Cr)	0.05mg/L	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

Lead (Pb)

Lead (Pb) is widely dispersed in the environment due to human activities such as combustion of coal and oil, and waste incineration. In the air, Pb exists as particles that are removed by rain or settling. Soil and sediment are major sinks for Pb, which is strongly adsorbed to soil and minimally transported to surface water or groundwater, except under acidic conditions (ATSDR, 2020).

Toxicity and Health Risks

Lead (Pb) exposure primarily occurs through ingestion, with some inhalation exposure. Occupational exposure to organic Pb compounds may also involve significant dermal absorption (ATSDR, 2020)

Exposure to Pb have been related with (ATSDR, 2020):

- Neurological Effects as decreased cognitive function, altered mood and behaviour or peripheral neuropathy and encephalopathy in children.
- Renal Effects.
- Cardiovascular Effects like increased blood pressure, increased risk of hypertension, atherosclerosis, altered cardiac conduction or increased risk of heart disease.
- Haematological Effects
- Immunological Effects that can cause decreased resistance to disease.
- Reproductive Effects as alterations in semen quality, decreased fertility, spontaneous abortion, preterm birth, and earlier age at the onset of menopause.
- Developmental Effects that can cause decreased birth weight and size.
- Respiratory Effects as decreased lung function increased risk of asthma, and obstructive lung disease.
- Hepatic Effects as possible increases in plasma liver enzymes and cholesterol.
- Endocrine Effects affecting thyroid hormones, cortisol ,growth factors, and vitamin D levels.
- Gastrointestinal Effects causing nausea, vomiting, and diarrhoea and/or constipation.
- Musculoskeletal Effects as bone loss, osteoporosis, dental caries, tooth loss, and periodontitis.
- Ocular Effects as possible macular degeneration and cataracts.
- Increased risk of cancer of the respiratory and intestinal tract.

EU Regulations and International Standards

The primary measure of internal lead (Pb) exposure is the concentration of Pb in blood (PbB), typically measured in µg/dL. PbB serves as a biomarker for Pb exposure, reflecting its diverse toxic effects on every organ system. Effects on neurological, renal, cardiovascular, haematological, immunological, reproductive, and developmental systems have been observed at PbB levels as low as ≤5 µg/dL. No specific exposure thresholds have been identified for organ system effects, indicating no safe level of exposure. Cognitive deficits in children are the most well-documented effects occurring at these low PbB levels. Due to the serious adverse effects associated with even low PbB levels, minimum risk levels (MRLs) for Pb have not been established (ATSDR, 2020).

IARC considers lead as Possibly carcinogen to humans (Group 2B) (IARC, 2024).

Table 9. Regulations and guidelines Applicable to Lead (Pb).

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of	Lead: group 2B Inorganic lead compounds: group 2A Organic lead compounds: group 3	IARC 2024
WHO	Air quality guidelines	0.5 µg/m^3	WHO 2000
	Drinking water quality guidelines	0.01 mg/L	WHO 2022
EC	Air quality standards	0.5 µg/m^3	Directive 2008/50/EC

Mercury (Hg)

Atmospheric mercury is mainly in the form of gaseous elemental mercury (Hg0), which can travel long distances. When deposited into water bodies, mercury can be methylated by anaerobic bacteria, forming methylmercury, a highly bioaccumulative organic form that increases in concentration up the aquatic food chain. As a result, mercury is often found at elevated levels in fish, other aquatic organisms, rice, and other vegetation (ATSDR, 2022b).

Toxicity and Health Risks

The general population is exposed to various forms of mercury, with primary exposure to organic mercury from foods contaminated with methylmercury. Exposure to inorganic mercury compounds is minimal, compared to organic and elemental forms being inhalation of mercury vapor the most significant route of exposure to elemental mercury. Workers in occupations such as chloralkali processing have historically faced exposure to elemental mercury vapor (ATSDR, 2022).

Toxicological effects observed due to the exposure to all forms of mercury have been:

- Neurological and neurodevelopmental effects.
- Renal effects.
- Respiratory effects, including lung inflammation, pneumonitis, and respiratory failure due to pulmonary oedema (acute exposure).

EU Regulations and International Standards

ATSDR has derived a provisional MRL of 0.3 µg Hg/m^3 for chronic inhalation exposure to elemental mercury. No MRLs have been defined for acute and intermediate inhalation exposure and insufficient data for MRL derivation has been defined for oral exposure to elemental mercury (ATSDR, 2022).

ATSDR has derived a provisional MRL of 2 µg Hg/kg/day and an MRL of 0.01 µg Hg/kg/day for acute oral exposure and intermediate oral exposure respectively to inorganic mercury salts. Insufficient data have been to define MRLs inhalation exposure and chronic oral exposure to inorganic mercury salts (ATSDR, 2022).

For methylmercury, ATRSDR has derived a provisional MRL of 0.1 µg Hg/kg/day for chronic oral exposure and no MRLs have been defined for inhalation exposure and for acute and intermediate oral exposure (ATSDR, 2022).

The IARC concluded that elemental mercury and inorganic mercury compounds are not classifiable as to their carcinogenicity to humans (Group 3) and methylmercury compounds are possibly carcinogenic to humans (Group 2B) (IARC, 2024).

Table 10. Regulations and Guidelines Applicable to Mercury (Hg).

Agency	Description	Information	Reference
IARC	Carcinogenicity classification	Mercury and inorganic mercury compounds: Group 3 Methylmercury compounds: Group 2B	IARC 2024
WHO	Air quality guidelines	1 µg/m^3 annual average (0.0001 ppm)	WHO 2000
	Drinking water quality guideline	0.006 mg/L	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

Nickel (Ni)

Nickel is widely used in industry and used in equipment and parts for chemical plants, petroleum refineries, jet engines, power generation facilities, and offshore installations(ATSDR 2024). Food and water intake are the main exposures routs for general population.

Toxicity and Health Risks

Acute and chronic exposure to nickel has been related to:

- Respiratory effects as respiratory irritation, alterations in lung function tests, and increased risk of pulmonary fibrosis.
- Immunological effects as increase in allergic response.
- Reproductive effects in very few studies relating nickel exposure with increased risk of abortions.
- Increased risks of lung and nasal cancers specially nickel refinery workers.

EU Regulations and International Standards

Agency	Description	Information	Reference
IARC	Carcinogenicity classification	Nickel compounds: Group 1 Nickel, metallic: Group 2B	IARC 2024
WHO	Air quality guidelines	Incremental risk for 1 µg/m^3 nickel in air	WHO 2000
	Drinking water quality guideline	0.07 mg/L	WHO 2022
EC	Air quality standards	20 ng/m^3	Directive 2008/50/EC

Vanadium (V)

Vanadium is widely distributed in the earth's crust at an average concentration of approximately 100 mg/kg and is a constituent of nearly all coal and petroleum crude oils (Merian, 1991). Therefore, heavy fuel combustion, particularly in oil-fired power plants, refineries, industrial boilers, and coal combustion, are major contributors to anthropogenic emissions of vanadium into the atmosphere (ATSDR, 2015b).

Toxicity and Health Risks

The general population is exposed to vanadium primarily through ingestion of food and to vanadium oxides through inhalation in industrial or urban areas. Although, few studies exist about vanadium effects in humans, animal studies provide additional evidence that vanadium compounds are respiratory toxicants (ATSDR, 2015b). Therefore, signs about respiratory distress, impaired lung function, increased pulmonary reactivity and histological alterations in the lungs, larynx, and nasal cavity have been observed in laboratory animals exposed to vanadium.

No studies were located regarding the carcinogenicity in humans after inhalation exposure to vanadium, but studies in rats and mice showed increase in the incidence of alveolar/bronchiolar adenoma, carcinoma, or the combined incidences of adenoma and carcinoma in male rats.

EU Regulations and International Standards

ATSDR has derived an acute-duration inhalation MRL of 0.0008 mg vanadium/m^3 (ATSDR, 2015b), a chronic-duration inhalation MRL of 0.0001 mg vanadium/m^3 and an intermediate-duration oral MRL of 0.01 mg vanadium/kg/day (ATSDR, 2015b).

US EPA has derived an oral reference dose (RfD) of 0.009 mg/kg/day for vanadium and has not derived an inhalation reference concentration (RfC) for vanadium and vanadium compounds (IRIS, 2012).

IARC classifies Vanadium pentoxide as Possibly carcinogenic to humans (Group 2B) (IARC, 2024).

Table 11. Regulations, Advisories and Guidelines Applicable to Vanadium and Compounds.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of lead	Vanadium pentoxide: Group 2B	IARC 2024
WHO	Air quality guidelines	1 $\mu g/m^3$	WHO 2000
	Drinking water quality guidelines	n.a.	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

VOLATILE ORGANIC COMPOUNDS (VOCs)

Volatile organic compounds (VOCs) are carbon-containing chemicals largely present as gases at common pressures and temperatures, and can be considered as the main air pollutants specific to fossil fuel industries, although sometimes can also be found in soil or water.

Methane

Methane is a VOC closely related with a large number of human activities including fossil fuel industry, gas leaks from distribution networks, and landfill waste. Once released into soil or water, methane slowly escapes into the air, where it degrades over time (CCAC, n.d.; European Commission, 2021; Public Health England, 2019).

Toxicity and Health Risks

People may be exposed to very low levels of methane when breathing resulting in (CCAC, n.d.; European Commission, 2021; Public Health England, 2019):

- Neurological effects as mood changes, slurred speech, vision problems, memory loss, headache
- Nausea, vomiting, facial flushing
- In severe cases, changes in breathing and heart rate, unconsciousness or death.

EU Regulations and International Standards

Methane is not thought to cause cancer in humans.

In November 2023, the European Union agreed on a new regulation known as the Global Methane Pledge aimed at reducing global methane emissions by at least 30% from 2020 levels by 2030. This regulation mandates the fossil gas, oil, and coal industries to monitor, report, and verify methane emissions. It includes stringent measures to detect and repair methane leaks, limit venting and flaring, and introduces global monitoring tools for transparent reporting of methane emissions from oil, gas, and coal imports into the EU. These measures enable the Commission to consider additional actions in the future to further reduce methane emissions.

1,3 Butadiene

1,3-butadiene is a non-methane volatile organic compound (NMVOC) which is an important product of crude oil and gas that can be emitted to the atmosphere from several sources, but especially by petrochemical industries (Fukusaki et al., 2021; Gallego et al., 2018; Sun & Wristers, 2002). It is manufactured primarily as a coproduct of steam cracking to produce ethylene and it is specially of concern in the industry of rubber, nylon, neoprene, some latexes, resins and as an intermediate, 1,3-butadiene is used in the production of various chemicals and fungicides (NIOSH, 1984).

Toxicity and Health Risks

1,3-butadiene exposure is associated to an increased risk of (Han et al., 2024; Symanski et al., 2016):

- Some cancers as acute lymphocytic leukaemia and other lymphatic neoplasms, lymphohematopoietic cancers, lymphosarcoma, and oesophageal and stomach cancer.
- Irritation of the eyes, nasal passages, throat, and lungs.
- Hearing loss due to its ototoxicity

Moreover, animal experiments have reported(ATSDR, 2011; National Toxicology Program, 1993):

- Increased mortality, primarily due to cancer after chronic exposure.
- Reproductive effects as early foetal deaths or increase in the number of foetuses with irregular ossification.

EU Regulations and International Standards

EPA has established an inhalation reference concentration (RfC) for 1,3-butadiene of 0.9 ppb for ovarian atrophy in female mice (EPA, 2002). EPA has not established an oral reference dose (RfD) for 1,3-butadiene (EPA, 2024d).

According to the US National Institute for Occupational Safety and Health (NIOSH), it is recommended that 1,3-butadiene be regarded as a potential occupational carcinogen, teratogen, and as a possible reproductive hazard, as well as that the present Occupational Safety and Health Administration (OSHA) from US standard of 1,000 ppm for exposure to 1,3-butadiene be re-examined (NIOSH, 1984).

Table 12. Regulations, Advisories, and Guidelines Applicable to 1,3-Butadiene.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of lead	carcinogenic to humans (Group 1)	IARC 2024
WHO	Air quality guidelines	n.a.	WHO 2000
	Drinking water quality guidelines	n.a.	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC
ONTARIO MINISTRY OF ENVIRONMENT	Maximum annual mean in air	2 µg/m^3	Ontario's legislation

Ethylene oxide (C_2H_4O)

Ethylene oxide (C_2H_4O) is a non-methane volatile organic compound (NMVOC), flammable gas with a slightly sweet odour, primarily used to produce chemicals like ethylene glycol (antifreeze). A smaller portion is used for sterilizing medical devices, cosmetics, and food, thanks to its ability to penetrate packaging and destroy bacteria and viruses (ATSDR, 2022a; EPA, 2024c; NIOSH, 2022).

Toxicity and Health Risks

Inhalation is the main route of exposure to ethylene oxide in occupational and environmental settings. Children may be at higher risk due to underdeveloped detoxification pathways, higher respiratory rates, and increased outdoor activities (ATSDR, 2018) (ATSDR 2020).

Exposure to ethylene oxide has related to (ATSDR, 2018, 2022a; EPA, 2016, 2024c):

- Neurological effects as headache, dizziness, nausea, lethargy, fatigue, muscle weakness, numbness, memory loss or incoordination.
- Respiratory effects as coughing, shortness of breath, wheezing, and bronchial constriction and hyperreactivity
- Excessive thirst and dry mouth, and gastrointestinal effects.
- Eye irritation.
- Skin rashes.
- Haemoglobin adducts of ethylene oxide in blood
- Evidence of DNA damage
- Haematological effects
- Increased risk of lymphohematopoietic cancers, including non-Hodgkin lymphoma, myeloma, and lymphocytic leukaemia and breast cancer in females.

Moreover, animal studies have shown the developing foetus to be sensitive to ethylene oxide exposure (ATSDR, 2018, 2022a).

EU Regulations and International Standards

Ethylene oxide is characterized as “carcinogenic to humans” by the inhalation route of exposure based on the total weight of evidence, in accordance with the EPA’s 2005 Guidelines for Carcinogen Risk Assessment (EPA, 2016). Also, IARC concluded that ethylene oxide is carcinogenic to humans (Group 1) (IARC, 2018).

The lowest odour threshold of ethylene oxide is 260 ppm (470 mg/m^3).

Table 13. Regulations and Guidelines Applicable to Ethylene Oxide (C_2H_4O).

Agency	Description	Information	Reference
IARC	Carcinogenicity classification	Carcinogenicity to humans (Group 1)	IARC 2024
WHO	Air quality guidelines	n.a.	WHO 2000
	Drinking water quality guidelines	n.a.	WHO 2022

Agency	Description	Information	Reference
EC	Air quality standards	n.a.	Directive 2008/50/EC
ONTARIO MINISTRY OF ENVIRONMENT	Maximum annual mean in air	0.04 µg/m^3	Ontario's legislation

Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are a class of organic compounds many of them found in coal and oil deposits. There are more than a thousand PAHs identified, but not all of them present the same environmental importance. According to the literature review, the potential toxicity, and potential for human and environment exposure, only some of them are considered in this report.

Toxicity and Health Risks

People are typically exposed to a mixture of PAHs through inhalation, ingestion of contaminated food, water, soil, or dust. PAHs accumulate mainly in the kidneys, liver, and fat, with smaller amounts in the spleen, adrenal glands, and ovaries. They are usually excreted within a few days through faeces and urine and are generally not detected in human tissue surveys due to rapid metabolism. Phenanthrene was the only PAH found in the 1982 National Human Adipose Tissue Survey (ATSDR, 2014; EEA, 2023).

Childhood studies of prenatal exposure to PAH has been associated with developmental problems, anxiety, depression, and inattention, attention-Deficit/Hyperactivity Disorder (ADHD), deficient maturation of emotional self–regulation capacity or poorer social responsiveness in childhood (F. Perera, 2017) (ATSDR, 2014).

Benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, and indeno[1,2,3-c,d]pyrene have been shown to cause tumours in laboratory animals through inhalation, ingestion, or prolonged skin contact. Human studies indicate that long-term exposure to mixtures containing PAHs and other compounds via inhalation or skin contact can also lead to cancer (ATSDR, 2014).

According the IARC, the potential carcinogenesis of PAHs has determined (IARC,2024):

- Benz[a]anthracene and benzo[a]pyrene are probably carcinogenic to humans (Group 2A).
- Benzo[b]fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, and indeno[1,2,3-c,d]pyrene are possibly carcinogenic to humans (Group 2B).
- Anthracene, benzo[g,h,i]perylene, benzo[e]pyrene, chrysene, fluoranthene, fluorene, phenanthrene, and pyrene are not classifiable as to their carcinogenicity to humans.

EPA has determined that benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, and indeno[1,2,3-c,d]pyrene are probable human carcinogens and that acenaphthylene, anthracene, benzo[g,h,i]perylene, fluoranthene, fluorene, phenanthrene, and pyrene are not classifiable as to human carcinogenicity (EPA, 1984) .

EU Regulations and International Standards

For acenaphthene, ATSDR has derived an MRL of 0.6 mg/kg/day for intermediate-duration oral exposure (15-364 days) (ATSDR, 2014).

For fluoranthene, ATSDR has derived an MRL of 0.4 mg/kg/day for intermediate-duration oral exposure (15-364 days) (ATSDR, 2014).

For fluorene, ATSDR has derived an MRL of 0.4 mg/kg/day for intermediate-duration oral exposure (15-364 days) (ATSDR, 2014).

Reference doses have been developed by EPA for anthracene (0.3 mg/kg/day), acenaphthene (0.06 mg/kg/day), fluoranthene (0.04 mg/kg/day), fluorene (0.04 mg/kg/day), and pyrene (0.03 mg/kg/day). No reference concentrations exist for any of the PAHs (ATSDR, 2014).

Benzo[*a*]pyrene (BaP) is the only PAH with reference levels (EEA, 2023):

- EU air limit for BaP (1 ng/m^3)
- WHO has not set an AQG for BaP but defines a reference level of 0.12ng/m^3

Table 14. Regulations and Guidelines Applicable to Polycyclic Hydrocarbons.

Agency	Description	Information	
IARC	Carcinogenicity classification	(B[a]A; B[a]P): Group 2AB	IARC 2024
		(B[b]F; B[j]; B[k]F; I[123cd]P): Group 2B	IARC 2024
		Anthracene; B[ghi]P; B[e]P; Chrysene, Fluoranthene; Fluorene; Phenanthrene; Pyrene: Group 3	IARC 2024
WHO Feu clic o toqueu aquí per escriure text.	Air quality guidelines	0.12 ng/m^3	WHO 2000
	European standard for drinking water	B(a)P: 0,7 µg/L	WHO 2022
EC	Air quality standards	1 ng/m^3	Directive 2008/50/EC

BTEX

BTEX refers to the acronyms of benzene, toluene, ethylbenzene, and xylenes, all aromatic hydrocarbons that are constituents of petroleum products, particularly gasoline, jet fuels, and kerosene. The four chemicals are volatile and have good solvent properties, so they can contaminate air, water, and soil. Contamination of groundwater and subsurface soil can result in migration of these chemicals into basements as soil gas (ATSDR, 2004).

Benzene (C_6H_6)

Benzene is commercially recovered from both coal and petroleum sources, with most of its production coming from the petrochemical and petroleum refining industries. Key sources include refinery streams such as catalytic reformats, pyrolysis gasoline, and toluene hydrodealkylation (ATSDR, 2015c)

Toxicity and Health Risks

Benzene is widely distributed in the environment, with the primary concern for the public being low-level inhalation over extended periods(ATSDR, 2015c). The long-term exposure to benzene is related to (ATSDR, 2015c; F. P. Perera et al., 2018):

- Carcinogenesis producing acute myelogenous leukaemia (AML).
- Haematotoxicity effects as anaemia, leukopenia, or thrombocytopenia.
- Immunotoxicity.
- Neurotoxicity after high-level exposure to benzene in short-term.
- Reproductive effects reported only in animal studies that showed that inhaling benzene during pregnancy can delay bone formation and damage bone marrow.

EU Regulations and International Standards

ATSDR has derived an acute-duration inhalation MRL of 30 µg/m^3, a chronic-duration inhalation MRL of 10 µg/m^3 and a chronic-duration oral MRL of 0.0005 mg/kg/day for benzene (ATSDR, 2015c).

EPA derived an inhalation RfC for benzene of 0.03 mg/m^3 (0.009 ppm) and an oral RfD for benzene of 0.004 mg/kg/day (EPA, 2024d). The same organism has a current maximum contaminant level (MCL) of 0.005 mg/L for benzene in drinking water (EPA 2002a).

Table 15. Air quality standards for protecting human health from benzene C_6H_6.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of lead	carcinogenic to humans (Group 1)	IARC 2024
WHO	Air quality guidelines	RL: 1.7 µg/m^{3*}	WHO 2000
	Drinking water quality guidelines	0.01 mg/L	WHO 2022
EC	Air quality standards	EU limit value: 5 µg/m^3	Directive 2008/50/EC

* with an excess lifetime risk of 1/ 100 000

Toluene

Toluene is an effective solvent that occurs naturally in crude oil and the tolu tree. It is produced during gasoline and fuel production from crude oil and coke from coal, and it is used in a wide variety of petroleum derivates (ATSDR, 2017).

Toluene can be released into air, water, and soil where it is produced or used. It can enter surface waters and groundwater through solvent and petroleum spills, and leak from underground storage tanks at gasoline stations. Toluene is not commonly found in drinking water (ATSDR, 2017).

Toxicity and Health Risks

Short term exposure to toluene has related to (ATSDR, 2017):

- Neurologic effects as headaches, sleepiness, dizziness, or unconsciousness in short-term exposure, and more severe effects such as incoordination, cognitive impairment vision and hearing loss, tiredness, confusion, weakness, drunken-type actions, memory loss or nausea, in long-term exposure.
- Reproductive effects related to developmental effects.
- Immunotoxicity.
- Kidney and liver effects.

EU Regulations and International Standards

ATSDR has derived an acute-duration inhalation MRL of 2 ppm (7.6 mg/m^3) and a chronic-duration inhalation MRL of 1 ppm (3.8 mg/m^3) for neurological effects, an acute-duration oral MRL of 0.8 mg/kg/day and an intermediate-duration oral MRL of 0.2 mg/kg/day (ATSDR, 2017).

The EPA's reference concentration (RfC) for toluene is 5 mg/m^3 and the EPA's reference dose (RfD) is 0.08 mg/kg/day (EPA, 2005). EPA states that there is inadequate data on which to classify toluene in terms of its carcinogenicity in humans or animals (EPA, 2005).

Table 16. Regulations, Advisories, and Guidelines Applicable to Toluene.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of lead	not classifiable as to its carcinogenicity to humans (Group 3	IARC 2024
WHO	Air quality guidelines	should be kept below the odour detection threshold level of 1 mg/m^3 as a 30-minute average.	WHO 2000
	Drinking water quality guidelines	0.7 mg/L	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

Ethylbenzene

Ethylbenzene is a colourless liquid with a gasoline-like smell, naturally found in oil and used to produce styrene, fuels, and solvents. It easily moves into the air from water and soil and can contaminate groundwater. Ethylbenzene is released into the air from burning oil, gas, coal, and industrial processes using the compound (ATSDR, 2015d)

Toxicity and Health Risks

Short-term exposure to high levels of ethylbenzene is related to (ATSDR, 2015d):

- Eye and throat irritation in humans (air exposure)
- Vertigo and dizziness.
- Eye damage and skin irritation (liquid ethylbenzene in animal experiments).

Long-term exposure to ethylbenzene in animal experiments, has related to (ATSDR, 2015d):

- Potentially irreversible damage to the inner ear and hearing
- Kidney damage and kidney tumours
- Liver tumours

EU Regulations and International Standards

ATSDR has derived an acute-duration inhalation MRL of 5 ppm for ethylbenzene and an intermediate-duration inhalation MRL of 2 ppm for ethylbenzene based on auditory threshold shifts observed in rats. It has derived a chronic-duration inhalation MRL of 0.06 ppm for ethylbenzene based on increase in the severity of nephropathy in female rats exposed (ATSDR, 2015d). An intermediate-duration oral MRL of 0.4 mg/kg/day for hepatotoxicity in male rats.

The EPA inhalation reference concentration (RfC) for ethylbenzene is 1 mg/m^3 (equivalent to 0.23 ppm), based on developmental toxicity seen in rats and rabbits., and the oral reference dose (RfD) is 0.1 mg/kg/day (EPA, 2024d)

IARC determined that long-term exposure to ethylbenzene may cause cancer in humans (Group 2B) (IARC, 2024).

Table 17. Regulations, Advisories, and Guidelines Applicable to Ethylbenzene.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification of lead	Possibly carcinogenic in humans (Group 2B)	IARC 2024
WHO	Air quality guidelines	n.a.	WHO 2000
	Drinking water quality guidelines	0.3 mg/L	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

Xylenes

Xylene is primarily a synthetic chemical produced from petroleum but also occurs naturally in petroleum, coal tar, and, to a small extent, during forest fires. It is a material used in the chemical, plastics manufacturing, synthetic fibre industries, in coating fabrics and papers, and found in small amounts in airplane fuel and gasoline (ATSDR, 2007a). Xylene, a liquid, can leak into soil, surface water, or groundwater. Most accidentally released xylene evaporates into the air, but some enters rivers or lakes. Due to its rapid evaporation, xylene is rarely found in high concentrations in topsoil or surface water unless there is a recent spill or ongoing contamination (ATSDR, 2007a).

Toxicity and Health Risks

People is most likely to be exposed to xylene by breathing it in contaminated air, but it may also enter the body eating or drinking xylene-contaminated food or water. Less often, xylene enters the body through the skin following direct contact. Xylene is rapidly absorbed by lungs after breathing air containing it (ATSDR, 2007a).

Short-term exposure to high levels of xylene can cause (ATSDR, 2007a):

- Irritation of the skin, eyes, nose, and throat.
- Difficulty in breathing and impaired function of the lungs.
- Delayed response to a visual stimulus or impaired memory.
- Stomach discomfort and possible changes in the liver and kidneys.

Long-term exposure to high concentrations of xylene can cause (ATSDR, 2007a):

- Effects on the nervous system: headaches, lack of muscle coordination, dizziness, confusion, and changes in one's sense of balance.
- Changes in the liver and harmful effects on the kidneys, lungs, heart, and nervous system in animal experiments.

EU Regulations and International Standards

Based on animal experiments, ATSDR has derived an acute-duration inhalation MRL of 2 ppm and an intermediate-duration inhalation MRL of 0.6 ppm. A chronic-duration inhalation MRL of 0.05 ppm has defined for mild subjective respiratory and neurological symptoms in workers. Also in animal studies, ATSDR has derived an acute-duration oral MRL of 1 mg/kg/day; an intermediate-duration oral MRL of 0.4 mg/kg/day, and a chronic-duration oral MRL of 0.2 mg/kg/day (ATSDR, 2007a).

Also based in animal studies, EPA has derived an inhalation reference concentration (RfC) for mixed xylenes of 0.1 mg/m^3 (0.02 ppm) and an oral reference dose (RfD) for mixed xylenes of 0.2 mg/kg/day (ATSDR, 2007a). (EPA, 2003)

IARC concluded that xylenes are Not classifiable as to its carcinogenicity to humans (Group 3).

Table 18. Regulations and Guidelines Applicable to Xylenes.

Agency	Description	Information	Reference
IARC	Carcinogenicity classification	Not classifiable as to its carcinogenicity to humans (Group 3).	IARC 2024
WHO	Air quality guidelines	n.a.	WHO 2000
	Drinking water quality guidelines	0.5 mg/L	WHO 2022
EC	Air quality standards	n.a.	Directive 2008/50/EC

Inputs from project pilot sites

Particulate matter, nitrogen oxides, sulfur oxides, heavy metals, Volatile Organic Compounds (VOCs), and hydrocarbons (including non-methane hydrocarbons, NMHCs, and polycyclic aromatic hydrocarbons, PAHs) were the main chemical groups discussed in the focus group sessions across the three pilot sites. Within the VOCs, BTEX (benzene, toluene, ethylbenzene, and xylenes) was particularly highlighted in the Basilicata and Tarragona pilot sites. Benzene was the primary pollutant of concern, being mentioned for air in both Basilicata and Tarragona, and for both air and water in Tarragona. In the Basilicata focus group, toluene in water and general VOCs in soil were also noted.

Particulate matter was identified as an air contaminant of concern in Basilicata and Konin, while heavy metals were a major concern in water in both Basilicata and Poland, and in soil in Basilicata. The Italian focus group listed manganese (Mn), iron (Fe), lead (Pb), cadmium (Cd), antimony (Sb), mercury (Hg), vanadium (V), barium (Ba), nickel (Ni), and cobalt (Co) as the most significant heavy metals affecting human health. Nitrogen and sulphur-derived gases were recognized as air pollutants across all three pilot sites, with methane and carbon oxides being also of particular concern in Basilicata and Konin, respectively.

Regarding water pollution, specific pollutants from fossil fuel industries relevant to each pilot site were considered, such as chemical solvents in Italy and synthesized chemicals (PFAs) in Spain. Parameters related to water consumption, chemical discharges, and chemical leaching were commonly mentioned across all pilot sites. Soil impact concerns included parameters such as soil erosion and ecosystem destruction. Table 19 provides summary answers to mentioned questions.

Table 19. Contaminants identified during the focus groups meetings classified by pilot sites and matrix.

Pilot site	Air	Water	Soil
Basilicata (Italy)	× Benzene × methane × non methane hydrocarbons (NMHC) × nitrogen dioxide (NO2) × sulphur dioxide (SO2) × volatile organic compounds (VOC) × hydrogen sulphide(H2S) × particulate matter	× hydrocarbons × btex (toluene) × solvents (sulfolane) × heavy metals (manganese, iron, lead, cadmium, antimuonium, mercury, vanadium barium, nickel, cobalt) × Tri- chloroethylene, Tetra- chloroethylene, Dichloroethylene × underground hidden drainage/drainage networks × Water consumption × obsolete industrial sewage network	× heavy metals (manganese, iron, lead, cadmium, antimuonium, mercury, vanadium barium, nickel, cobalt) × Organic compounds, highly volatile and difficult to detect × hydrocarbons × subsidence
Tarragona (Spain)	× Benzene × Ethylene oxide × 1-3 butadiene × Ethylene (due to the production volume) × Vinyl chloride (there are some doubts regarding its presence in Tarragona) × Acrylonitrile × Chlorohydric × Nitric acid (Nitricomax factory)	× Naphtha × Benzene × Anti foaming × PFA: PFA (Perfluoroalkyl substances) are chemical compounds that can persist in the environment for long periods of time due to their stability and low reactivity. While some PFAS may degrade slowly over time, many of them are known for their persistence in the environment and their ability to bioaccumulate in living organisms. Therefore, while they may degrade, their degradation is generally very slow. While EU legislation currently addresses around 20 of these compounds, it's important to note that there are approximately 10,000 different PFAs in existence, posing a significant challenge for regulation and management. Four of these “forever chemicals” are the most problematic. × Tri- chloroethylene and Tetra- chloroethylene × Plastic pellets × Water consumption	× Plastic pellets × Organic compounds, highly volatile and difficult to detect × Tri- chloroethylene and Tetra- chloroethylene × Soil erosion and soil works across Francolí riversides

Pilot site	Air	Water	Soil
		× Discharges through drainage channels following heavy rain episodes	
Konin (Poland)	× Sulphur Dioxide (SO_2) × Nitrogen Oxides (NO_x) × Particulate Matter (PM10, PM2.5) × Carbon Oxides (CO, CO_2) × Emission of suspended particles during the extraction and transportation process	× Leaching of chemicals used in the extraction process into rivers and lakes × Soluble Organic Compounds (TOC), × Heavy Metals × the cone of depression	× Destruction of forest ecosystems and changes in landscape structure. × the cone of depression × potential landslides associated with open-pit brown coal mining.

7. Analysis of the technical legislation on permissible levels - international standards

This section aims to make a compendium of the legislation included in this report in terms of fossil-fuel related pollutants, which could be crucial for citizen science initiatives in order to obtain actionable data. European directives and WHO guidelines have been the priority, but some recommendations from other institutions as US EPA have also been considered.

AIR

European Union’s air quality standards

Directive 2008/50/EC

The European Union's *Directive 2008/50/EC* on air quality and cleaner air sets standards to limit air pollutants across member states. It establishes air quality objectives, including limit values and target levels for pollutants. The directive requires member states to monitor air quality, reduce exposure to harmful pollutants, and prepare action plans if standards are exceeded. The aim is to protect human health and the environment, creating a baseline for cleaner air across Europe.

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedances each year
Fine particles ($PM_{2.5}$)	25 µg/m^3	1 year	Target value to be met as of 1.1.2010	n/a
Fine particles ($PM_{2.5}$)	20 µg/m^3	1 year	Stage 2 limit value to be met as of 1.1.2020 ***	n/a
Sulphur dioxide (SO_2)	350 µg/m^3	1 hour	Limit value to be met as of 1.1.2005	24
Sulphur dioxide (SO_2)	125 µg/m^3	24 hours	Limit value to be met as of 1.1.2005	3
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	Limit value to be met as of 1.1.2010	18
Nitrogen dioxide (NO_2)	40 µg/m^3	1 year	Limit value to be met as of 1.1.2010 *	n/a
Particulate matter (PM_{10})	50 µg/m^3	24 hours	Limit value to be met as of 1.1.2005 **	35
Particulate matter (PM_{10})	40 µg/m^3	1 year	Limit value to be met as of 1.1.2005 **	n/a
Lead (Pb)	0.5 µg/m^3	1 year	Limit value to be met as of 1.1.2005 (or 1.1.2010 in the immediate vicinity of specific, notified industrial sources; and a 1.0 µg/m^3	n/a

			limit value applied from 1.1.2005 to 31.12.2009)	
Carbon monoxide (CO)	10 mg/m^3	Maximum daily 8 hour mean	Limit value to be met as of 1.1.2005	n/a
Benzene	5 µg/m^3	1 year	Limit value to be met as of 1.1.2010 **	n/a
Ozone	120 µg/m^3	Maximum daily 8 hour mean	Target value to be met as of 1.1.2010	25 days averaged over 3 years
Arsenic (As)	6 ng/m^3	1 year	Target value to be met as of 31.12.2012	n/a
Cadmium (Cd)	5 ng/m^3	1 year	Target value to be met as of 31.12.2012	n/a
Nickel (Ni)	20 ng/m^3	1 year	Target value to be met as of 31.12.2012	n/a
Polycyclic Aromatic Hydrocarbons	1 ng/m^3	1 year	Target value to be met as of 31.12.2012	n/a
	(expressed as concentration of Benzo(a)pyrene)			

** Under Directive 2008/50/EU, the Member State could apply for an extension of up to five years (i.e. maximum up to 2015) in a specific zone. The request is subject to an assessment by the Commission. In such cases within the time extension period the limit value applies at the level of the limit value + maximum margin of tolerance (*48 µg/m^3 for annual NO_2 limit value).

*** Under Directive 2008/50/EU, the Member State was able to apply for an extension until three years after the date of entry into force of the new Directive (i.e. May 2011) in a specific zone. The request was subject to assessment by the Commission. In such cases within the time extension period the limit value applies at the level of the limit value + maximum margin of tolerance (35 days at 75*µg/m^3 for daily PM_{10} limit value, 48 µg/m^3 for annual Pm_{10} limit value).

*** Stage 2: indicative limit value as referred to in Directive 2008/50/EU.

WHO's air quality standards

The World Health Organization (WHO) Air Quality Guidelines (AQGs) provide evidence-based recommendations to protect human health from adverse effects of air pollution. They define safe levels of key pollutants, such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone, based on current scientific understanding. WHO's AQGs set reference levels (RLs) as targets for reducing pollution exposure, with stricter thresholds than many national standards to reflect health risks even at low exposure levels. The guidelines aim to guide policymakers globally in setting air quality policies that minimize health risks.

Pollutant	Averaging period	AQG	RL	Comments
PM_{10}	1 day Calendar year	$45µg/m^3$ 15µg/m3		99th percentile (3-4 exceedance days per year). Updated 2021 guideline Updated 2021 guideline
$PM_{2.5}$	1 day Calendar year	$15µg/m^3$ $5µg/m^3$		99th percentile (3-4 exceedance days per year). Updated 2021 guideline Updated 2021 guideline
O_3	Maximum daily 8-hour mean Peak season (b)	$100µg/m^3$ $60µg/m^3$		99th percentile (3-4 exceedance days per year). New 2021 guideline New 2021 guideline
NO_2	1 hour 1 day Calendar year	$200µg/m^3$ $25µg/m^3$ $10µg/m^3$		99th percentile (3-4 exceedance days per year). New 2021 guideline Updated 2021 guideline
BaP	Calendar year		$0.12ng/m^3$	
SO_2	10 minutes 1 day	$500µg/m^3$ $40µg/m^3$		99th percentile (3-4 exceedance days per year). New 2021 guideline
CO	1 hour Maximum daily 8-hour mean	$30mg/m^3$ $10mg/m^3$		

	1 day	4mg/m^3		99th percentile (3-4 exceedance days per year). New 2021 guideline
C_6H_6	Calendar year		1.7µg/m^3	
Pb	Calendar year	0.5µg/m^3		
As	Calendar year		6.6ng/m^3	
Cd	Calendar year	5ng/m^3 (c)		
Ni	Calendar year		25ng/m^3	

Notes:

(a) As WHO has not set an AQG for BaP, C6H6, As and Ni, the RL was estimated assuming an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000.

(b) Average of daily maximum 8-hour mean concentration in the six consecutive months with the highest six-month running average O_3 concentration.

(c) AQG set to prevent any further increase of Cd in agricultural soil, likely to increase the dietary intake of future generations.

Ontario's Ambient Air Criteria

Some fossil fuel related pollutants like 1,3-buthadiene or ethylene oxide have not threshold values neither in EU directives nor WHO guidelines. In this case, it may be interesting and recommending to resort to specific legislation from other countries extra European. The Ontario's Ambient Air Criteria has been considered a very useful document to obtain extra quality standards. This document provides a list of the Ambient Air Quality Criteria (AAQCs) developed by the Ontario Ministry of the Environment (MOE).

WATER

European Union’s water quality standards

[**Environmental Quality Standards Directive 2008/105/EC**]: This directive, also known as the *Priority Substances Directive*, sets specific limits for hazardous substances in surface waters. It defines priority substances and establishes maximum concentrations for pollutants to reduce their impact on aquatic ecosystems and human health.

Environmental quality standards (EQS) of some fossil-fuel related pollutants

AA : annual average;
MAC : maximum allowable concentration.
Unit : [µg/l]

Name of substance	AA-EQS (2) Inland surface waters (3)	AA-EQS (2) Other surface waters	MAC-EQS (4) Inland surface waters (3)	MAC-EQS (4) Other surface waters
Benzene	10	8	50	50
Cadmium and its compounds (depending on water hardness classes) (6)	≤ 0,08 (Class 1)	0,2	≤ 0,45 (Class 1)	≤ 0,45 (Class 1)
	0,08 (Class 2)		0,45 (Class 2)	0,45 (Class 2)
	0,09 (Class 3)		0,6 (Class 3)	0,6 (Class 3)
	0,15 (Class 4)		0,9 (Class 4)	0,9 (Class 4)
	0,25 (Class 5)		1,5 (Class 5)	1,5 (Class 5)
Hexachloro-benzene	0,01 (9)	0,01 (9)	0,05	0,05
Hexachloro-butadiene	0,1 (9)	0,1 (9)	0,6	0,6
Hexachloro-cyclohexane	0,02	0,002	0,04	0,02
Lead and its compounds	7,2	7,2	not applicable	not applicable
Mercury and its compounds	0,05 (9)	0,05 (9)	0,07	0,07
Naphthalene	2,4	1,2	not applicable	not applicable
Nickel and its compounds	20	20	not applicable	not applicable
Pentachloro-benzene	0,007	0,0007	not applicable	not applicable
Polyaromatic hydrocarbons (PAH) (10)	not applicable	not applicable	not applicable	not applicable
Benzo(a)pyrene	0,05	0,05	0,1	0,1
Benzo(b)fluor-anthene	Σ = 0,03	Σ = 0,03	not applicable	not applicable
Benzo(k)fluor-anthene				
Benzo(g,h,i)-perylene	Σ = 0,002	Σ = 0,002	not applicable	not applicable
Tetrachloro-ethylene (7)	10	10	not applicable	not applicable
Trichloro-ethylene (7)	10	10	not applicable	not applicable

Notes: 1) CAS: Chemical Abstracts Service. (2) This parameter is the EQS expressed as an annual average value (AA-EQS). Unless otherwise specified, it applies to the total concentration of all isomers. (3) Inland surface waters encompass rivers and lakes and related artificial or heavily modified water bodies. (4) This parameter is the EQS expressed as a maximum allowable concentration (MAC-EQS). Where the MAC-EQS are marked as 'not applicable', the AA-EQS values are considered protective against short-term pollution peaks in continuous discharges since they are significantly lower than the values derived on the basis of acute toxicity. (5) For the group of priority substances covered by brominated diphenylethers (No 5) listed in Decision No 2455/2001/EC, an EQS is established only for congener numbers 28, 47, 99, 100, 153 and 154. (6) For cadmium and its compounds (No 6) the EQS values vary depending on the hardness of the water as specified in five class categories (Class 1: < 40 mg CaCO3/l, Class 2: 40 to < 50 mg CaCO3/l, Class 3: 50 to < 100 mg CaCO3/l, Class 4: 100 to < 200 mg CaCO3/l and Class 5: ≥ 200 mg CaCO3/l). (7) This substance is not a priority substance but one of the other pollutants for which the EQS are identical to those laid down in the legislation that applied prior to 13 January 2009. (8) DDT total comprises the sum of the isomers 1,1,1-trichloro-2,2 bis (p-chlorophenyl) ethane (CAS number 50-29-3; EU number 200-024-3); 1,1,1-trichloro-2 (o-chlorophenyl)-2-(p-chlorophenyl) ethane (CAS number 789-02-6; EU number 212-332-5); 1,1-dichloro-2,2 bis (p-chlorophenyl) ethylene (CAS number 72- 55-9; EU number 200-784-6); and 1,1-dichloro-2,2 bis (p-chlorophenyl) ethane (CAS number 72-54-8; EU number 200-783-0). (9) If Member States do not apply EQS for biota they shall introduce stricter EQS for water in order to achieve the same level of protection as the EQS for biota set out in Article 3(2) of this Directive. They shall notify the Commission and other Member States, through the Committee referred to in Article 21 of Directive 2000/60/EC, of the reasons and basis for using this approach, the alternative EQS for water established, including the data and the methodology by which the alternative EQS were derived, and the categories of surface water to which they would apply. (10) For the group of priority substances of polyaromatic hydrocarbons (PAH) (No 28), each individual EQS is applicable, i.e. the EQS for Benzo(a)pyrene, the EQS for the sum of Benzo(b)fluoranthene and Benzo(k)fluoranthene and the EQS for the sum of Benzo(g,h,i)perylene and Indeno(1,2,3-cd)pyrene must be met.

Groundwater Directive 2006/118/EC: This directive complements the WFD with standards specifically for groundwater, including parameters for chemical quality and requirements to prevent pollution and deterioration. It provides guidance on pollutants like nitrates and pesticides, ensuring groundwater quality is maintained across member states.

WHO's water quality standards

The World Health Organization (WHO) provides Guidelines for Drinking Water Quality, which cover standards for both surface water and groundwater, primarily focusing on health-based values for safe drinking water. WHO has defined different sets of guideline values for individual chemicals, by source category. For matters of space, in the following table we report only the values related to the chemicals from industrial sources and human dwellings.

The World Health Organization (WHO) also provides the Guidelines on Recreational Water Quality, which are focused on water quality management for coastal and freshwater environments to protect public health. The guidelines describe the current state of knowledge about the possible adverse health impacts of various forms of water pollution and set out recommendations for setting national health-based targets, conducting surveillance and risk assessments, putting in place systems to monitor and control risks, and providing timely advice to users on water safety.

EPA's parameters of drinking water quality

The U.S. Environmental Protection Agency (EPA) establishes the *Drinking Water Requirements for States and Public Water Systems* to ensure safe drinking water across the United States. These requirements are defined under the *Safe Drinking Water Act* (SDWA) and include enforceable regulations for contaminants in public water systems, as well as guidelines for monitoring, reporting, and maintaining water quality. EPA's online portal (https://www.epa.gov/dwreginfo) provides detailed regulatory information, resources for compliance, and specific limits for each regulated contaminant in drinking water.

SOIL

European Union's soil quality standards

The European Union does not have a single comprehensive directive dedicated to soil quality, but it incorporates soil protection and quality standards into broader environmental policies and regulations. Key EU policies, like the *Thematic Strategy for Soil Protection* (2006), aim to prevent soil degradation, reduce contamination, and promote sustainable land use. While binding soil standards are still under development, current policies set guidelines to address issues such as soil erosion, loss of organic matter, contamination, and soil sealing.

Several related directives—such as those on nitrates (Nitrates Directive 91/676/EEC) and industrial pollution (Industrial Emissions Directive 2010/75/EU)—provide parameters to limit pollutants impacting soil quality.

8. Obstacles and Limits of Citizen Science for the environmental monitoring of the Fossil Fuel industry

Citizen science is a powerful approach to environmental monitoring. It encourages public engagement, fosters citizen empowerment, and can be crucial for raising awareness about activities impacting nature and human health. When applied to the monitoring of fossil fuel industries, citizen science can help improve existing practices and industries' accountability, raise environmental standards, and even foster progress in legislation. However, the effectiveness of this approach heavily depends on data quality.

This review collected information about the frugal technologies that allow citizen scientists to monitor the impacts of fossil fuel industries. We have examined DIY and low-cost sensors and tools to point out their advantages and limitations in participatory environmental monitoring. While they can be successfully used for specific purposes, most technologies suffer from one or several of these three limitations: (1) lack of specificity; (2) limited data quality; (3) unsuitable detection limits.

Regarding the first limitation, most low-cost tools detect general indicators of pollution that can be also caused by traffic or other fuel combustion activities. In the best case-scenario, they can detect methane (CH_4), total volatile organic chemicals (VOCs), which also include BTEX, H_2S, and SO_2, which can be specific to fossil fuel exploitation. However, they are not designed to detect specific markers of fossil fuel industries, such as individual VOCs like 1,3-butadiene, ethylene oxide, or benzo(a)pyrene: these chemicals generally require state-of-the-art techniques that are accessible only to professional laboratories.

Data quality is another shortcoming of these approaches. This is particularly evident for water and soil, whose low-cost analyses rely primarily on colorimetric kits. Colorimetric kits are extremely useful for educational and awareness raising goals but are not ideal for community projects prioritizing data quality for subsequent legal actions – these communities should consider buying more expensive instruments or teaming with professional scientists. Indeed, collaborations between citizens and professionals represent an effective strategy to obtain actionable data. This collaboration can take various shapes – for example, citizens can still be involved in sample collection, data interpretation, and dissemination of results, and help collect "simple" observations that are more easily accessible to locals (e.g., occurrence of bad small).

Too high detection limits are a third disadvantage of low-cost technologies, representing a further reason to engage scientists or accredited laboratories in data collection. This collaboration ensures environmental samples are analysed with the best available technologies, yielding quantitative data at the lowest detection limits. Furthermore, low-cost commercial devices often do not provide detection limits in their tutorials or websites, which makes it hard to select the best tool to purchase.

Despite these shortcomings, frugal technologies represent a useful addition to citizen science projects, as they help educate and engage the public, raise awareness, and attract the attention of professionals for further studies. As commercial low-cost solutions to monitor air pollution we recommend the Aeroqual S500, the Smart Citizen Kit v2.1, various PurpleAir sensors, and Airnote, whereas for DIY devices we recommend the DustBox and the Frackbox. Furthermore, citizens can take part in sample collection using Radiello passive samplers or active samplers like the "Bucket Monitor", and by collecting ground-based data such as the occurrence of bad smells. For water and soil, we suggest the Modern Water RaPID Assay for BTEX and TPHs and the PetroFLAG Analyzer System (soil only). Low-cost colorimetric kits are also available for a series of water pollutants from CHEMets visual Kits and SenSense. For general water quality parameters, we suggest the Hanna multiparametric field probe, the Horiba LAQUAtwin Compact Meters, and the eXact iDip Photometer As for air, citizens can be involved in water and soil sample collection and then sent them to a certified laboratory for analysis, perform biomonitoring, or report incidences of pollution through georeferenced photos. Focus groups interviews highlighted the usefulness of open-source tools such as the Copernicus satellite data, which provides daily information on global atmospheric composition in a certain region. Citizen scientists can also report changes in animal behavior or ecosystem degradation.

We argue that the more information is available and precise, the more the benefits of citizen science for environmental monitoring can be reaped. Indeed, technical and financial requirements for data collection have effects on data quality, timeliness and consistency, and therefore on legal actionability. Potential citizen scientists can thus be equipped with the necessary information to recognize the technical obstacles at stake and how these relate to the environmental pollution in their area. This could help them overcome existing problems, such as the high cost of sensors or lack of specific monitoring training by focusing their efforts on reaching out to external partnerships, for their efforts to have more repercussion.

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Appendix 1: Technical specification on selected low-cost technologies

[NOTE: Costs are approximate and may change depending on shipping location and taxes. Assembly guide and building instructions are not provided for commercial sensors and kits. The supplier is not indicated for DIY devices (n.a. = not available).]

Table A1	
Sensor reference	**Aeroqual S500**
Parameters analysed	$PM_{2.5}$, PM_{10}, H_2S, VOCs, CH_4 (plus O_3, NO_x, SO_2, CO, CO_2, etc.)
Sensor functionalities	• $PM_{2.5}$, PM_{10}: laser particle counter • H_2S: gas sensitive electrode • VOCs: photo ionization detector • CH_4: gas sensitive semiconductor [see here for a complete overview]
Detection limits	• $PM_{2.5}$, PM_{10}: 1 µg/m^3 • H_2S: 0.04 ppm (0 – 10 ppm sensor range) • VOCs: 0.01 ppm (PID, 0 – 30 ppm sensor range) • CH_4: 10 ppm [see here for a complete overview]
Environmental matrix	Air
Other technical specifications	Powered with light lithium batteries. Data is stored in the monitor and retried via USB cable.
DIY system?	No
Cost	1'600 € (handable monitor) + 600 – 1'200 € (head sensor; changes depending on pollutant) = 2'200 – 2'800 € • $PM_{2.5}$, PM_{10} head sensor: 1085 € • H_2S head sensor: 610 € • VOCs head sensor: 790 € • CH_4 head sensor: 610 €
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Designed for researchers, air quality professionals, and community groups to conduct outdoor air quality testing. Example of applications include wide area air quality surveys, checking pollution "hotspots", community air pollution monitoring, educational projects in schools.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	n.a.

Advantages	Real-time response. Small, portable device ideal for field projects. The swappable head allows the measurement of several pollutants using the same monitor.
Limitations	The memory store only 8’188 data. Data are downloaded via USB. Poor response for PM_{10} as compared to standard methods (according to AQ-SPEC).

Table A2	
Sensor reference	**Smart Citizen Kit v2.1**
Parameters analysed	PM_1, $PM_{2.5}$, PM_{10}, VOCs equivalents (plus CO_2 equivalents, weather parameters, sound pollution, light pollution)
Sensor functionalities	• PM_1, $PM_{2.5}$, PM_{10}: laser particle counter (PMS 5003) • VOCs: metal oxide sensor (AMS CCS811)
Detection limits	Not available in website
Environmental matrix	Air
Other technical specifications	Sends data to an online platform.
DIY system?	No
Cost	100 €
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Designed for citizen science to measure and collect data on air and noise pollution.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Open source and customizable. Data are shared in a dedicated online platform. Detects various environmental health parameters, including sound and light pollution. Data can be stored in a SD card in WiFi is not available. Small and light.
Limitations	Poor response for PM_{10} and VOCs as compared to standard methods (according to AQ-SPEC). Detects only total VOCs equivalents. Requires WiFi connection to share data. ~ 12 h battery life (all sensors connected).

Table A3	
Sensor reference	**PurpleAir** (various products)
Parameters analysed	$PM_{2.5}$, VOCs equivalents (only PurpleAir Zen, Touch, and Flex)
Sensor functionalities	• $PM_{2.5}$: laser particle counter (PMS 1003, 5003, or 1003)

	• VOCs: metal oxide sensor (BME688)
Detection limits	• $PM_{2.5}$: ± 10 µg/m^3 (for readings between 0 – 100 µg/m^3) • VOCs: not specified in website
Environmental matrix	Air
Other technical specifications	All products include temperature, relative humidity, and pressure sensors and send data to the PurpleAir platform map via WiFi. Some products change color depending on overall air quality. Some sensors have a double set of laser particle counters to help determine the sensors' health.
DIY system?	No
Cost	200 – 300 €
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Simple and easy-to-use system designed for community monitoring.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Compact, economic, easy to install and use both indoor and outdoor. It shows good response in intercomparison tests for $PM_{2.5}$ (although corrections are needed for research-quality data[57]). Provides real-time, continuous data. Data are sent directly to the online platform and can be accessed with any mobile device.
Limitations	It generally requires a WiFi connection for data download (some products can record data on a SD card). Only some versions detect VOCs as VOCs equivalents (PurpleAir Zen, PurpleAir Touch, PurpleAir Flex).

Table A4	
Sensor reference	**Airnote**
Parameters analysed	PM_1, $PM_{2.5}$, PM_{10}
Sensor functionalities	Laser particle counter (PMS 7003M)
Detection limits	Not available in website
Environmental matrix	Air
Other technical specifications	Includes a temperature, relative humidity, pressure, and radiation sensor. It is powered through a small solar panel; if needed can be charged also via a micro-USB cable. Data is sent to Safecast network and shared globally via cellular connection.

DIY system?	No
Cost	1’700 € (10 pieces)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Ideal for non-expert users.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here and here
Advantages	Compact, wireless, portable, autonomous. Designed for continuous long-term monitoring outdoor and off-grid. No software configuration required. Data are uploaded directly on an online database (Safecast network).
Limitations	Poor response for PM_{10} as compared to standard methods (according to AQ-SPEC). Detection limits not specified.

Table A5	
Sensor reference	**DustBox (v2)**
Parameters analysed	$PM_{2.5}$
Sensor functionalities	Laser particle counter (PMS 5003)
Detection limits	Not available in website
Environmental matrix	Air
Other technical specifications	Includes a sensor for temperature and humidity. The case is 3D-printed in the shape of a pollen grain or a virus. It can be connected to a WiFi network for data download; data can be uploaded to the shared Airsift map.
DIY system?	Yes
Cost	200 € (enclosure) + cost of sensor, PCB, and equipment (not specified in website)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Construction requires time and some knowledge of electronics and coding.
Where to buy it?	n.a.
Assembly guide and building instructions	here
User technical handbooks and protocols	here and here

Advantages	Very thorough instruction manual that includes also calibration, quality control instructions, and data interpretation. Eye-catching design.
Limitations	Construction and setting require a long list of steps and some knowledge of electronics and coding. Detection limits not specified.

Table A6	
Sensor reference	**Frackbox**
Parameters analysed	VOCs, NO_x, O_3
Sensor functionalities	• VOCs: photo ionization detector • NO_x and O_3: gas sensitive electrode
Detection limits	• VOCs: < 5 ppb • NO_x and O_3: < 5 ppb
Environmental matrix	Air
Other technical specifications	Includes a sensor for temperature, relative humidity, and wind direction. It is housed in a US mailbox. Data is periodically uploaded to the Citizen Sense platform through a cell phone connection. It runs on Linux. The system can be upgraded to measure also $PM_{2.5}$ and CH_4.
DIY system?	Yes
Cost	800 €
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Construction requires time and some knowledge of electronics and coding. Instruction manual is not as detailed as for the DustBox.
Where to buy it?	n.a.
Assembly guide and building instructions	here
User technical handbooks and protocols	here; here for data analysis
Advantages	Possible to contact the developers and borrow a copy. Possible to add sensors for $PM_{2.5}$ and CH_4. Developed for community monitoring of the effect oil and gas industry on residents. Detailed shopping list.
Limitations	Still a prototype. The instruction manual is not detailed (but the shopping list is). PID is not selective for BTEX. There are cross-interferences for NO_2 and O_3. Calibration is required for accurate readings of all pollutants (it requires a source of zero air).

Table A7	
Sensor reference	**Sulfide Test Kit – CHEMets visual Kit**
Parameters analysed	H_2S/HS^-
Sensor functionalities	Colorimetric reaction
Detection limits	0.5 ppm (0 – 1 and 1 – 10 ppm kit)
Environmental matrix	Water
Other technical specifications	Kits available for 5 concentration ranges (from 0 – 10 ppm to 1’200 – 12’000 ppm). Results available in 5 min.
DIY system?	No
Cost	150 € (30 tests)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Simple, rapid method for qualitative and semi-quantitative results.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Rapid analysis (5 min). Simple and straightforward procedure clearly outlined in the instruction manual. Appropriate for field measurements.
Limitations	Semi-quantitative or qualitative method. Samples must be analyzed immediately after collection (H_2S is readily volatile).

Table A8	
Sensor reference	**Modern Water RaPID Assay**
Parameters analysed	BTEX/TPH
Sensor functionalities	Magnetic particle immunoassay
Detection limits	Measurement range 0.02 – 3 ppm (as total BTEX); detection limits in the ppm range.
Environmental matrix	Water and soil
Other technical specifications	A separate extraction kit is sold for analyses of soil samples. Results available in 60 min.
DIY system?	No
Cost	1’500 € (100 tests)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Requires moderate skills to operate.
Where to buy it?	here

Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Suitable for field or lab analyses. Relatively rapid results (within 1 h). Limited price per sample. Three kit calibrator levels, in units comparable to GC standard methods.
Limitations	Qualitative or semi-quantitative method. Knowledge of fuel source is required (unable to differentiate between BTEX and similar compounds). The website does not provide clear instruction for analyses nor a clear list of all equipment and material needed. Minimum order of 5 kits.

Table A9	
Sensor reference	**Hanby TPH Test Kit**
Parameters analysed	TPH
Sensor functionalities	Extraction + reaction with a catalyst to produce a unique color
Detection limits	0.1 – 20 ppm (water); 1 – 1’000 ppm (soil)
Environmental matrix	Water and soil
Other technical specifications	Each kit contains all material necessary for analyses. Results in 5 min.
DIY system?	No
Cost	~ 2’000 € (15 tests)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Quick and easy to use.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Easy to use and quick. Appropriate for field sampling. The kit includes all equipment to perform analyses, including glassware. Clear instructions. No calibration required.
Limitations	Qualitative or semi-quantitative method. If the sample has a dark color, results may not be accurate. The kit is unable to distinguish different hydrocarbon fractions.

Table A10	
Sensor reference	**PetroFLAG Analyzer System for TPH in Soil**
Parameters analysed	TPH (aromatic and aliphatic fractions, $C_8 – C_{44}$)
Sensor functionalities	Turbidimetric detection
Detection limits	15 – 2’000 ppm depending on the analyte
Environmental matrix	Soil
Other technical specifications	Results available in 15 min. Different response factors are applied depending on the contaminants. Calibration required.
DIY system?	No
Cost	~ 900 € (10 samples)
Assessment of intuitiveness, attractivity of the format, usability, and accessibility for end users	Requires moderate skills to operate. Appropriate for field measurements.
Where to buy it?	here
Assembly guide and building instructions	n.a.
User technical handbooks and protocols	here
Advantages	Responds to a broad range of petroleum products. Requires moderate skills to operate. Results available within minutes. Appropriate for field measurements.
Limitations	Qualitative or semi-quantitative method. Gasoline hydrocarbons (< C_8) are not detected. Possible interference with natural-occurring hydrocarbons and soil moisture. Some prior knowledge of the contaminant required.

Appendix 2 : National Maximum Permissible Limits

Table 20. Maximum Permissible Limits in Poland.

Name of the substance	Period of averaging measurement results	The acceptable level µg/m³	Permissible frequency of exceeding the permissible level in the calendar year	The Margin of Tolerance µg/m³					The deadline for reaching the permissible level
				2010	2011	2012	2013	2014	
Benzene (C_6H_6)	The calendar year	**5**	-	0	0	0	0	0	2010
Nitrogen Dioxide (NO_2) 2)	1 hour	**200**	18 times	0	0	0	0	0	2010
	The calendar year	**40**	-	0	0	0	0	0	2010
Sulphur dioxide (SO_2) 2)	1 hour	**350**	24 times	0	0	0	0	0	2005
	24 hours	**125**	3 times	0	0	0	0	0	2005
Carbon monoxide (CO) 1)	8 hours	**10 000**	-	0	0	0	0	0	2005
The PM10 2)	24 hours	**50**	35 times	0	0	0	0	0	2005
	The calendar year	**40**	-	0	0	0	0	0	2005
The dust PM2.5 3)	The calendar year	**25**	-	4	3	2	1	1	2015
	The calendar year	**20** 4)	-	0	0	0	0	0	2020

Name of the substance	Period of averaging measurement results	The acceptable level µg/m^3	Permissible frequency of exceeding the permissible level in the calendar year	The Margin of Tolerance µg/m^3					The deadline for reaching the permissible level
				2010	2011	2012	2013	2014	
The lead (Pb)	The calendar year	**0.5** 5)	-	0 0	0 0	0 0	0 0	0 0	2005

1) The maximum eight-hour average of the moving average calculated every hour from eight average one-hours in a day. Each such calculated average of an 8-hour is assigned to the era in which it ends. The first calculation period for each day is the period from 17 00 previous day to 01 00 a given day. The last calculation period for each day is the period from 16 00 to 24 00 on the CET Central European time.

2) Dust concentrations with aerodynamic diameter of grains up to 10 m (PM10) measured by the fractional separation method or methods considered equivalent.

3) Dust concentration with aerodynamic diameter of grains up to 2.5 m (PM2.5) measured by weight-by-separation method or methods considered equivalent.

4) Limit for PM2.5 suspended particulate matter from 1 January 2020 (phase II).

5) The sum of metal and its compounds in the dust suspended PM10.

The levels of the substance in the air for gaseous pollutants are determined under conditions: temperature 293 K, pressure 101,3 kPa. The levels for particulate matter in the air shall be determined under real conditions. Limit values for sulphur dioxide (SO $_2$2), nitrogen oxides (NO $_x$) in the air due to plant protection, dates of achievement and periods for which measurement results are averaging.

Name of the substance	Period of averaging measurement results	The acceptable level µg/m^3	The deadline for reaching the permissible level
Nitrogen oxides (NO_x)[1)]	The calendar year	**30**	2003
Sulphur dioxide (SO_2)[2)]	The calendar year	**20**	2003
	The Winter Time (period from 01 X to 31 III)	**20**	2003

(1) The sum of nitrogen dioxide and nitric oxide on the basis of nitrogen dioxide.

The levels of the substance in the air for gaseous pollutants are determined under conditions: temperature 293 K, pressure 101,3 kPa.

See also Regulation of the Minister of Family, Labour And Social Politics of June 12, 2018 on the highest permissible concentrations and intensities of factors harmful to health in the working environment:

https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20180001286/O/D20181286.pdf

https://powietrze.gios.gov.pl/pjp/content/annual_assessment_air_acceptable_level#

Appendix 3: Standards and Guidelines for Air Quality and Hazardous Substances

Table 21. Minimal Risk Levels (MRLs) for Hazardous Substances.

Route	Duration	MRL	Factors*	Endpoint
ACENAPHTHENE				
Oral	Int.	0.6 mg/kg/day	300	Hepatic
ALUMINUM				
Oral	Int.	1 mg/kg/day	30	Neurol.
Oral	Chr.	1 mg/kg/day	90	Neurol.
AMMONIA				
Inh.	Acute	1.7 ppm	30	Resp.
Inh.	Chr.	0.1 ppm	30	Resp.
ANTHRACENE				
Oral	Int.	10 mg/kg/day	100	Hepatic
ARSENIC				
Oral	Acute	0.005 mg/kg/day	10	Gastro.
Oral	Chr.	0.0003 mg/kg/day	3	Dermal
Benzene				
Inh.	Acute	0.009 ppm	300	Immuno.
Inh.	Int.	0.006 ppm	300	Immuno.
Inh.	Chr.	0.003 ppm	10	Immuno.
Oral	Chr.	0.0005 mg/kg/day	30	Immuno.
Cadmium				
Inh.	Acute	0.00003 mg/m^3	300	Resp.
Inh.	Chr.	0.00001 mg/m^3	9	Renal

Route	Duration	MRL	Factors*	Endpoint
Oral	Int.	0.0005 mg/kg/day	100	Musculo.
Oral	Chr.	0.0001 mg/kg/day	3	Renal
CHLOROBENZENE				
Oral	Int.	0.07 mg/kg/day	100	Hepatic
CHROMIUM(III) INSOL. PARTICULATES				
Inh.	Int.	0.005 mg/m^3	90	Resp.
CHROMIUM(III) SOLUBLE PARTICULATES				
Inh.	Int.	0.0001 mg/m^3	300	Resp.
CHROMIUM(VI)				
Oral	Int.	0.005 mg/kg/day	100	Hemato.
Oral	Chr	0.0009 mg/kg/day	100	Gastro.
CHROMIUM(VI), AEROSOL MISTS				
Inh.	Int.	0.000005 mg/m^3	100	Resp.
Inh.	Chr.	0.000005 mg/m^3	100	Resp.
CHROMIUM(VI), PARTICULATES				
Inh.	Int.	0.0003 mg/m^3	30	Resp.
ETHYLBENZENE				
Inh.	Acute	5 ppm	30	Neurol.
Inh.	Int.	2 ppm	30	Neurol.
Inh.	Chr.	0.06 ppm	300	Renal
Oral	Int.	0.4 mg/kg/day	30	Hepatic
ETHYLENE OXIDE				
Inh.	Acute	0.4 ppm	30	Develop.
Inh.	Int.	0.07 ppm	30	Develop.

Route	Duration	MRL	Factors*	Endpoint
MERCURY				
Inh.	Chr.	0.3 µg/m^3	10	Neurol.
MERCURY, INORGANIC SALTS (MERCURIC CHLORIDE, ETC.)				
Oral	Acute	2 µg/kg/day	100	Renal
Oral	Int.	0.01 µg/kg/day	1000	Renal
NAPHTHALENE				
Inh.	Acute	0.06 ppb	30	Resp.
Oral	Acute	0.2 mg/kg/day	300	Neurol.
Oral	Int.	0.6 mg/kg/day	300	Neurol.
NICKEL				
Inh.	Int.	0.03 µg/m^3	30	Resp.
Inh.	Chr.	0.01 µg/m^3	30	Resp.
NITROBENZENE				
Inh.	Acute	0.1 ppm	30	Hemato.
Inh.	Int.	3 ppb	300	Hemato.
Inh.	Chr.	0.2 ppb	300	Resp.
Oral	Acute	0.05 mg/kg/day	100	Hemato.
Oral	Int.	0.02 mg/kg/day	100	Hemato.
PERFLUOROOCTANE SULFONIC ACID (PFOS)				
Oral	Int.	2 ng/kg/day	300	Develop.
PERFLUOROOCTANOIC ACID (PFOA)				
Oral	Int.	3 ng/kg/day	300	Develop.
SULFUR DIOXIDE				
Inh.	Acute	0.01 ppm	9	Resp.
TOLUENE				
Inh.	Acute	2 ppm	9	Neurol.
Inh.	Chr.	1 ppm	10	Neurol.
Oral	Acute	0.8 mg/kg/day	300	Neurol.

Route	Duration	MRL	Factors*	Endpoint
Oral	Int.	0.2 mg/kg/day	100	Immuno.
VANADIUM				
Inh.	Acute	0.0008 mg/m^3	90	Resp.
Inh.	Chr.	0.0001 mg/m^3	30	Resp.
Oral	Int.	0.01 mg/kg/day	10	Hemato.
XYLENES, MIXED				
Inh.	Acute	2 ppm	30	Neurol.
Inh.	Int.	0.6 ppm	90	Neurol.
Inh.	Chr.	0.05 ppm	300	Neurol.
Oral	Acute	1 mg/kg/day	100	Neurol.
Oral	Int.	0.4 mg/kg/day	1000	Neurol.
Oral	Chr.	0.2 mg/kg/day	1000	Neurol.
ZINC				
Oral	Int.	0.3 mg/kg/day	3	Hemato.
Oral	Chr.	0.3 mg/kg/day	3	Hemato.

*For Duration, Acute = 1 to 14 days, Intermediate = 15 to 364 days, and Chronic = 1 year or longer. * Total Factors: Final value of all uncertainty and modifying factors, multiplied together.*

https://wwwn.cdc.gov/TSP/MRLS/mrlsListing.aspx

Table 22. Air Quality Standards.

Pollutant	Concentration		Permitted exceedances each year
Fine particles ($PM_{2.5}$)	25 µg/m^3	1 year [1]	n/a
Fine particles ($PM_{2.5}$)	20 µg/m^3	1 year [2]	n/a
Sulphur dioxide (SO_2)	350 µg/m^3	1 hour	24
Sulphur dioxide (SO_2)	125 µg/m^3	24 hours	3
Nitrogen dioxide (NO_2)	200 µg/m^3	1 hour	18
Nitrogen dioxide (NO_2)	40 µg/m^3	1 year	n/a
Particulate matter (PM_{10})	50 µg/m^3	24 hours	35

Pollutant	Concentration		Permitted exceedances each year
Particulate matter (PM_{10})	40 µg/m^3	1 year	n/a
Lead (Pb)	0.5 µg/m^3	1 year	n/a
Carbon monoxide (CO)	10 mg/m^3	Maximum daily 8 hour mean	n/a
Benzene	5 µg/m^3	1 year	n/a
Ozone	120 µg/m^3	Maximum daily 8 hour mean	25 days averaged over 3 years
Arsenic (As)	6 ng/m^3	1 year	n/a
Cadmium (Cd)	5 ng/m^3	1 year	n/a
Nickel (Ni)	20 ng/m^3	1 year	n/a
Polycyclic Aromatic Hydrocarbons	1 ng/m^3 (expressed as concentration of Benzo(a)pyrene)	1 year	n/a

[1] *Target value to be met as of 1.1.2010; Limit value to be met as of 1.1.2015.* [2] *Stage 2 limit value to be met as of 1.1.2020 ****

* *Under Directive 2008/50/EU, the Member State could apply for an extension of up to five years (i.e. maximum up to 2015) in a specific zone. The request is subject to an assessment by the Commission. In such cases within the time extension period the limit value applies at the level of the limit value + maximum margin of tolerance (48 µg/m^3 for annual NO2 limit value).*

** *Under Directive 2008/50/EU, the Member State was able to apply for an extension until three years after the date of entry into force of the new Directive (i.e. May 2011) in a specific zone. The request was subject to assessment by the Commission. In such cases within the time extension period the limit value applies at the level of the limit value + maximum margin of tolerance (35 days at 75µg/m^3 for daily PM10 limit value, 48 µg/m^3 for annual Pm10 limit value).*

*** *Stage 2: indicative limit value as referred to in Directive 2008/50/EU.*

Table 23. World Health Organization (WHO) air quality guidelines (AQGs) and estimated reference levels (RLs)[(a)]

Pollutant	Averaging period	AQG	RL	Comments
PM_{10}	1 day Calendar year	45µg/m^3 15µg/m^3		99th percentile (3-4 exceedance days per year). Updated 2021 guideline Updated 2021 guideline
$PM_{2.5}$	1 day Calendar year	15µg/m^3 5µg/m^3		99th percentile (3-4 exceedance days per year). Updated 2021 guideline Updated 2021 guideline
O_3	Maximum daily 8-hour mean Peak season [(b)]	100µg/m^3 60µg/m^3		99th percentile (3-4 exceedance days per year). New 2021 guideline New 2021 guideline
NO_2	1 hour 1 day Calendar year	200µg/m^3 25µg/m^3 10µg/m^3		99th percentile (3-4 exceedance days per year). New 2021 guideline Updated 2021 guideline
BaP	Calendar year		0.12ng/m^3	
SO_2	10 minutes 1 day	500µg/m^3 40µg/m^3		99th percentile (3-4 exceedance days per year). New 2021 guideline
CO	1 hour Maximum daily 8-hour mean 1 day	30mg/m^3 10mg/m^3 4mg/m^3		99th percentile (3-4 exceedance days per year). New 2021 guideline
C_6H_6	Calendar year		1.7µg/m^3	
Pb	Calendar year	0.5µg/m^3		
As	Calendar year		6.6ng/m^3	

Pollutant	Averaging period	AQG	RL	Comments
Cd	Calendar year	5ng/m^3 (c)		
Ni	Calendar year		25ng/m^3	

(a) As WHO has not set an AQG for BaP, C6H6, As and Ni, the RL was estimated assuming an acceptable risk of additional lifetime cancer risk of approximately 1 in 100 000.

(b) Average of daily maximum 8-hour mean concentration in the six consecutive months with the highest six-month running average O3 concentration.

(c) AQG set to prevent any further increase of Cd in agricultural soil, likely to increase the dietary intake of future generations.

Sources: WHO (2000, 2006, 2021).

Table 24. Directive 2008/50/EC introduced additional PM2.5 objectives targeting the exposure of the population to fine particles.

Title	Concentration	Averaging period	Permitted exceedances each year
$PM_{2.5}$ Exposure concentration obligation	20 µg/m^3 (AEI)	Based on 3-year average	n/a
$PM_{2.5}$ Exposure reduction target	Percentage reduction* + all measures to reach 18 µg/m^3 (AEI)	Based on 3-year average	n/a

** Depending on the value of AEI in 2010, a percentage reduction requirement (0,10,15, or 20%) is set in the Directive. If AEI in 2010 is assessed to be over 22 µg/m^3, all appropriate measures need to be taken to achieve 18 µg/m^3 by 2020.Di*

Source: EC, European Commission, EU air quality standards, available at: https://environment.ec.europa.eu/topics/air/air-quality/eu-air-quality-standards_en

Air pollutants and health outcomes. Source: WHO, 2021

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