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Deliverable D3.2

# Guidelines for Pilot City Labs to set-up indoor pollutant monitoring stations

Work Package 3

Science

Version: Final

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## Deliverable Overview

The report describes all the steps needed to set up a city lab for identification and characterisation of sources and routes of exposure and dispersion of chemical and biological indoor air pollution, e.g., indoor air microbiome and allergens, viral pathogens, household chemicals, biocides in building materials, particulate matter, radon, as well as emerging pollutants and the activities to involve local actors. This deliverable covers the information on a demonstrator for involving local actors, our stakeholders: the T3.2 QR code experiment, supported by the T3.2 Observatory.

## Additional Information

Type: DEM – Demonstrator, pilot, prototype

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## Disclaimer



## Document Revision History

| Version | Date | Description | Partners |
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| V0.2 | 29th of March 2024 | 2nd draft of deliverable | TROPOS |
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## Statement of Originality

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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## List of Terms and Abbreviations

| Abbreviation | Description |
|---|---|
| **AIR** | German Committee on Indoor Air Guide Values |
| **BC** | Black carbon |
| **BMS** | building management systems |
| **$Bqm^{-3}$** | Becquerels per cubic metre of air |
| **CO** | Carbon monoxide |
| **$CO_2$** | Carbon dioxide |
| **Device/LCS device** | A unit composed of several sensors and other physical components |
| **DNA** | Deoxyribonucleic acid |
| **EDIAQI** | Evidence Driven Indoor Air Quality Improvement |
| **IAP** | Indoor air pollutant |
| **IAQ** | Indoor air quality |
| **IEQ** | Indoor environment quality |
| **IoT** | Internet of things |
| **IT** | Information Technology |
| **ISO** | International Organization for Standardization |
| **KNOW** | The KNOW CENTER |
| **LCS** | Low cost sensors |
| **MPSS** | Mobility particle size spectrometer |
| **NO** | Nitric oxide |
| **$NO_2$** | Nitrogen dioxide |
| **$O_3$** | ozone |
| **OPSS** | Optical particle size spectrometer |
| **PAH** | Polycyclic aromatic hydrocarbons |
| **PM** | Particulate matter |
| **PNSD** | Particle number size distributions |
| **ppb** | Parts per billion |
| **ppm** | Parts per million |
| **RH** | Relative humidity |

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| | |
|---|---|
| **QR** | Quick response |
| **SCH** | Srebrnjak Children's Hospital |
| **Sensor** | A singular component capable of detecting a signal |
| **System set-up** | A complete setup combining, mist- and fog-computing, IoT and Cloud system set up for IAQ monitoring |
| **T** | Temperature |
| **TUG** | Graz University of Technology |
| **TVOC** | Total volatile organic compounds |
| **U.S. EPA** | United States Environment Protection Agency |
| **UBA** | Umweltbundesamt (German Federal Environment Agency) |
| **UFP** | Ultrafine particles |
| **VOC** | Volatile organic compounds |
| **WHO** | World Health Organization |
| **WMO** | World Meteorological Organization |

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## Executive Summary

The main objective of this deliverable is to provide a set of guidelines on how to set-up indoor pollutant monitoring stations from measurements to visualisation, including the description of a demonstrator for the activities to involve local actors via physical-digital platforms, T3.2 observatory. In this document, EDIAQI provides the following:

1. Chapter 1: Introduction.
2. Chapter 2: Report of the different measurement approaches the 4 pilots and campaigns (Ferrara, Estonia, Zagreb, and Vilnius) have done to characterise indoor air pollution including emerging pollutants.
3. Chapter 3: Description of the setup of the physical-digital platforms and how the pilot City Labs (Ferrara, Estonia, and Vilnius) set-up the quick-response (QR) code experiments and engagement of local actors from schools, kindergartens, laboratories, restaurants, gyms, offices and residential buildings. This chapter covers the description of the T3.2 Observatory and QR code experiment (demonstrator);
4. Chapter 4: Guidelines (based on lessons learned in EDIAQI) on indoor air pollution monitoring covering low-cost sensor device deployment, measuring of emerging pollutants not covered by sensors, visualisation of data, and involving local actors.

On the 6$^{th}$ month of the project (M6), the first version (v 1.0) of this deliverable was disseminated within the project as a set of guidelines to help pilots and campaigns in setting up their measurement activities with a focus on Low-Cost Sensor device deployment. The guidelines shared on M6 were based on existing ones (U.S. EPA, WHO, etc.) and are briefly presented in Chapter 1. This version presents the expanded guidelines covering measurements of emerging pollutants and indoor air quality data visualisation strategies, both of which are complimented by the publicly available tools described in D3.1 Indoor Air Pollution Observation Toolkit. As the pilots and campaigns progress beyond M18 (deadline of D3.2) up to M32, this deliverable will be updated through additions on and refining of the guidelines and biological characterization of IAP to complete the demonstrator covering identification and characterisation of sources and routes of exposure and dispersion of chemical and biological indoor air pollution, e.g. indoor air microbiome and allergens, viral pathogens, household chemicals, biocides in building materials, particulate matter, radon, as well as emerging pollutants. Ultimately, the goal is for this deliverable to outlive the

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project and continue to guide different stakeholders in monitoring their indoor air quality leading to increased awareness and improvement of quality of life in indoor spaces.

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# 1 Introduction

Within the EDIAQI project, the role of WP3-SCIENCE is to design and develop the characterisation of indoor air pollution (IAP) from measurement approaches, system set-up to visualisation of indoor air quality (IAQ) data together with stakeholders. This deliverable reports on a demonstrator: the T3.2 QR code experiment which is a system to involve local actors into testing EDIAQI solutions. To paint a full picture in the making of the T3.2 observatory, this deliverable begins with the selected guidelines in Chapter 1 which was provided to the pilots and campaigns at M6 to help them setup their activities. To describe the approach of EDIAQI presented in Figure 1, results from the WP3, T3.1 and T3.2 "Mapping interaction between indoor and outdoor air quality and deployment of monitoring technologies with cities" are presented in this deliverable in Chapters 2 and 3, respectively. In Chapter 3, the T3.2 Observatory for checking subjective IAQ perception versus objective IAQ measured values is introduced and the real-world application of this demonstrator in three pilot city labs is described. Chapter 4 contains an updated version of the guidelines building on lessons learned from the pilots and campaigns. Chapter 4 will be updated in the future to include results of the biological characterisation of IAP and how this can be integrated into the KNOW data platform, a DEM that will be submitted from T3.1c and T3.1d in a later version of D3.2. For readability, we would like to define the following terminologies and how they are used in this document:

- "**sensor**" – a singular component capable of detecting a signal;
- "**device**" or "**LCS device**" – a unit or a "low-cost" unit composed of multiple sensors and other physical components, the actual instrument;
- "**system set-up**" – a complete setup combining, mist- and fog-computing, IoT and Cloud system set up for IAQ monitoring.

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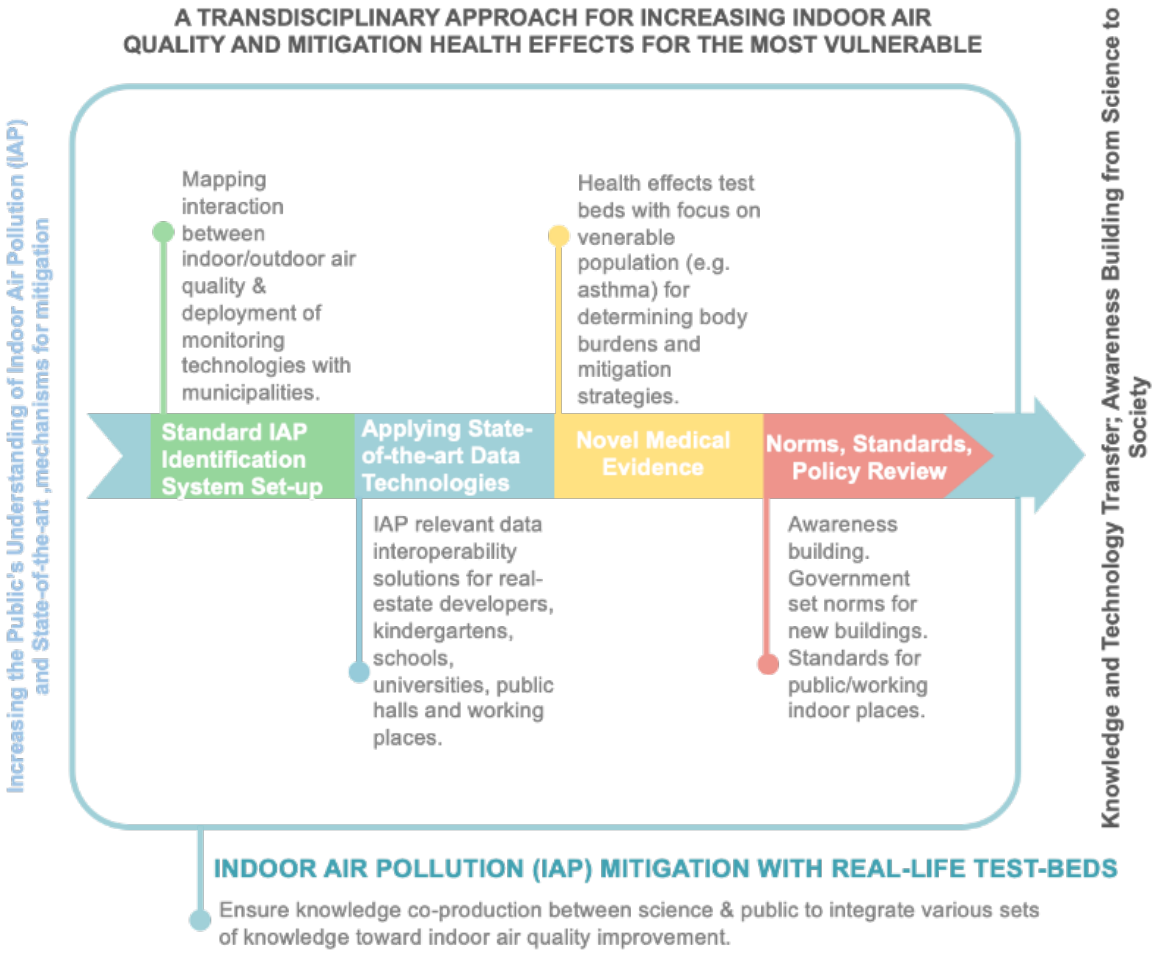


Figure 1 WP3 Science for Standard IAP identification system setup

## 1.1 Existing guidelines for indoor air pollutants

Most of the guidelines that exist for IAQ provide limit values for selected chemical compounds and inhalable particulate matter (WHO, 2010, 2014). In the European Union, IAQ standards are currently at the member state level. For instance, the German Committee on Indoor Air Guide Values (AIR) of the German Environment Agency (UBA) published in 2023 guide values for several substances and carcinogenic chemicals in indoor air (AIR, 2023). These include aldehydes, aliphatic hydrocarbons, alcohols, aromatic hydrocarbons, carboxylic acids, esters, glycols/glycol ethers/glycol esters, halogenated hydrocarbons, ketones, terpenes, CO, $PM_{2.5}$, TVOC, vinyl chloride, benzo[α]pyrene, and others. For a full list with corresponding limit values, please see Annex 1 – Indoor Air Guide Values from UBA, 2023.

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Table 1 Summary of the WHO Guidelines for Indoor Air Quality for Selected pollutants (2010) and Household Fuel Combustion (2014)

| Pollutant | Guidelines |
|---|---|
| Benzene | No safe level of exposure can be recommended |
| Carbon monoxide (CO) | • 15 minutes – 100 mg/m$^3$<br>• 1 hour – 35 mg/m$^3$<br>• 8 hours – 10 mg/m$^3$<br>• 24 hours – 7 mg/m$^3$ |
| Formaldehyde | 0.1 mg/m$^3$ – 30-minute average |
| Naphthalene | 0.01 mg/m$^3$ – annual average |
| Nitrogen dioxide ($NO_2$) | • 200 µg/m$^3$ – 1-hour average<br>• 40 µg/m$^3$ – annual average |
| Polycyclic aromatic hydrocarbons (PAH) | No threshold can be determined, and all indoor exposures are considered relevant to health |
| Radon | The radon concentrations associated with an excess lifetime risk of 1/100 and 1/1000 are 67 and 6.7 Bq/m$^3$ for current smokers and 1670 and 167 Bq/m$^3$ for lifelong non-smokers, respectively |
| Trichloroethylene | Unit risk estimate of 4.3 × 10–7 per µg/m$^3$ |
| Tetrachloroethylene | 0.25 mg/m$^3$ – annual average |
| $PM_{2.5}$ (Emission rates from household fuel combustion) | $PM_{2.5}$ (unvented) - 0.23 (mg/min)<br>$PM_{2.5}$ (vented) - 0.80 (mg/min) |
| CO (Emission rates from household fuel combustion) | CO (unvented) - 0.16 (g/min)<br>CO (vented) - 0.59 (g/min) |

With regards to monitoring these pollutants, the International Organization for Standardization (ISO) developed the ISO 16000 in 2010 which evolved into a series of ISO documents for standards for indoor air measurements (Parts 1-40) and are regularly updated to this day. However, the ISO standards do not include measuring indoor air pollutants with low-cost sensors (LCS). On the other hand, the U.S. Environment Protection Agency (EPA) has provided, with their Air Sensor Toolbox, a guide on siting and installing air sensors. These existing guidelines together with the gathered expert opinions shape parts of this deliverable focused on target pollutants and new and emerging parameters (black carbon (BC), ultrafine particles (UFPs), microplastics, etc.), utilizing advances in sensor technology in indoor air monitoring.

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## 1.2 Low-cost sensors (LCS) and indoor air monitoring applications

In recent years, there has been a rapid development and interest in the use of LCS to monitor air pollution. Due to their many advantages, LCS present opportunities in terms of increasing the spatial coverage of pollution measurements and increasing engagement with the public to raise awareness on air pollution. In 2021, the World Meteorological Organization (WMO) published "An update on low-cost sensors for the measurement of atmospheric composition" together with an expert consensus based on published peer-reviewed literature as of August 2020 (Núria Castell, 2021). The following points summarise the expert consensus in the WMO report:

- The growth of LCS in monitoring indoor air pollution relies on manufacturers and system providers.
- Transparency in providing information on sensor characterization, design, performance, and data correction algorithms is crucial.
- Users should define their specific goals, calibrate or validate sensor measurements against reference instruments, and acknowledge that LCS cannot fully replace existing regulatory monitoring frameworks.
- LCS offer new possibilities for environmental assessment but require improved validation and verification efforts.
- Evaluation programmes and centres should be established globally to support diverse user communities interested in adopting LCS approaches.

Despite highlighting that the LCS are still not a direct substitute for reference instruments, and hence, should not be used for AQ auditing, toxicology, and any assessments of legal compliance, the WMO suggests supporting further developments and expansion of the application of LCS.

One of the emerging applications of LCS is the deployment in indoor environments. Since, aside from being affordable, most LCS are compact, have low power consumption, produce less noise, and are often operationally safe (use no radioactive materials or chemical consumables), they can be deployed at a large scale to various indoor scenarios – getting to places reference instruments often cannot.

## 1.3 Recommended parameters to monitor

To gain more insight into the IAQ research, a survey was distributed to several experts included in the stakeholder profile creation (T3.2.1). The results from the survey are displayed in Figure 2 as presented at the Air Protection 2023 Conference with slight alterations:

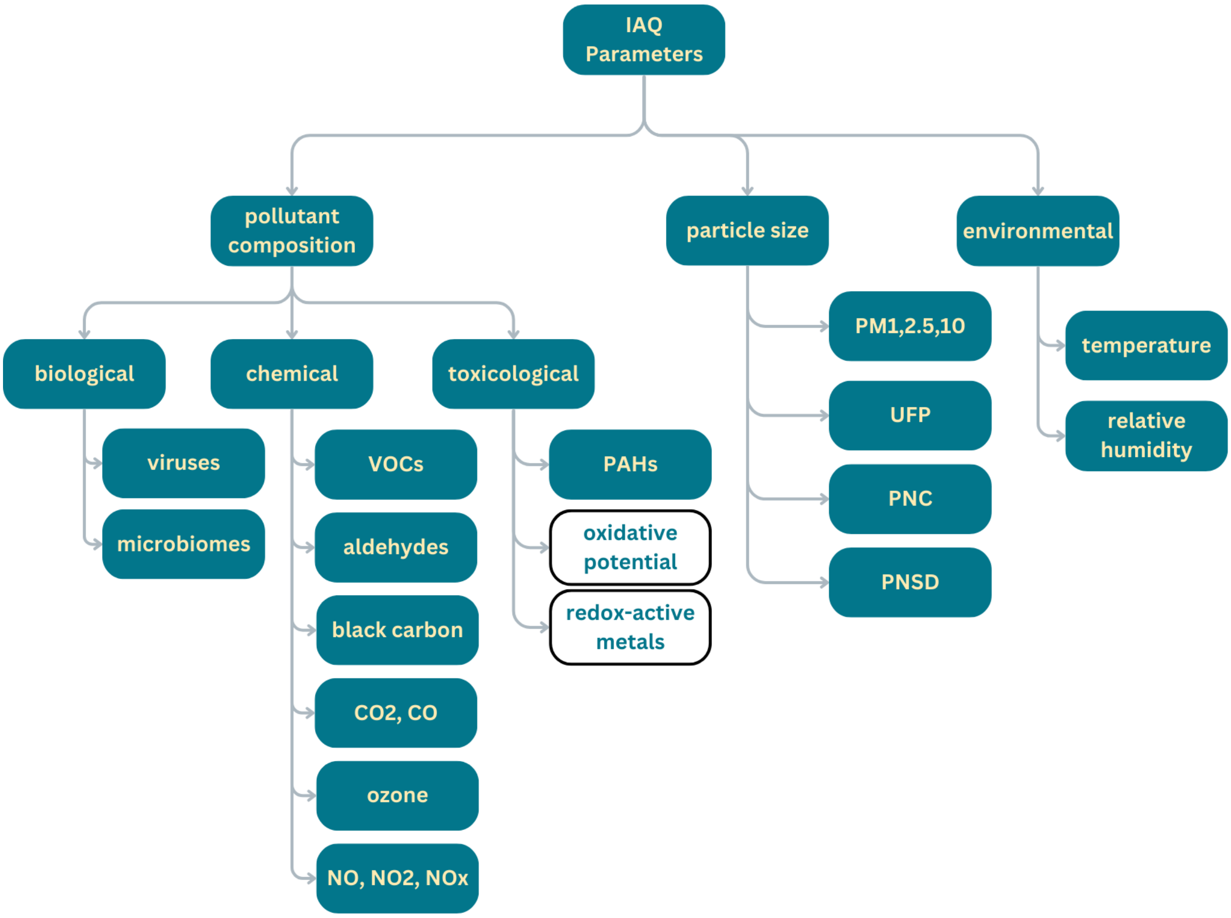


Figure 2 List of IAQ parameters experts recommended to monitor based on the expert opinion survey. Most of the parameters were included in EDIAQI except the ones in white boxes. This list did not include radon and microplastics.

The expert profiles list, sample of the survey, and the feedback obtained (with some redactions) are available in the Annex. This activity contributed to crafting the list of recommended parameters that was used to create the data glossary needed for the chapter on Semantic Interoperability in the deliverable D4.3. Additional parameters (toxicological, biological, etc.) will be provided to complete the second and final version of the same deliverable (D4.7) as part of T3.1.b Interoperability solutions with WP5.

### 1.3.1 Physico-chemical parameters

**Priority Parameters**

- $PM_{2.5}$ and $PM_{10}$

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$PM_{2.5}$ (particularly $PM_1$) particles can penetrate deep into the lungs and even enter down to the pulmonary alveoli. $PM_{10}$ and $PM_{2.5}$ exposure at high levels have been associated with respiratory and cardiovascular problems. WHO (2021) states, e.g., a threshold of an annual mean of 5 µg/m³ for $PM_{2.5}$ and 15 µg/m³ for $PM_{10}$. Since these parameters are currently regulated and widely monitored outdoors and used for health studies, having them measured in our pilots and campaigns will allow for better comparability to other studies.

- NOx – nitric oxide (NO) and nitrogen dioxide ($NO_2$)

NO and $NO_2$ are two principal nitrogen oxides that are associated with combustion sources. In indoor environments, they can penetrate from outdoor sources (such as vehicle emissions), tobacco smoke, and combustion appliances which burn wood, oil, kerosene, and coal such as stoves, heaters, and fireplaces. Indoor exposure to levels double that of the current ambient limit (200 µg/m3 in 1 hour) can have effects to the pulmonary functions of asthmatics

- CO and $CO_2$

CO is a toxic gas that is also produced by incomplete combustion of carbonaceous fuels. Similar to NOx, combustion activities indoors and penetration from outside sources are the main sources of CO indoors. CO can have varying effects on the human body based on the time of exposure and concentration, such that the WHO has developed guidelines for both acute and chronic exposures (i.e., 30 mg/m$^3$ for 1 hour; 10 mg/m$^3$ for maximum daily 8-hour mean; 4 10 mg/m$^3$ for 1 day).

$CO_2$ occurs naturally in the atmosphere but can also be a by-product of human combustion. In occupied indoor spaces, $CO_2$ can be higher than outside due to the several metabolic processes in humans without proper ventilation. High levels of $CO_2$ indoors can induce headaches, nausea, dizziness, difficulty breathing, sweating, exhaustion, vomiting, and an increase in heart rate – even loss of consciousness. During the pandemic, $CO_2$ has become a metric for ventilation to decrease the likelihood of transmission of diseases and viruses. CO2 concentration of 400-1000 ppm is considered acceptable

Additional Parameters

- Volatile organic compounds (VOCs)

VOCs are organic chemical compounds that easily evaporate into the atmosphere at room temperatures, hence they exist in gaseous or vapour form. Outdoors, they may originate

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from oil and gas fields and diesel exhaust. Indoors, they come from common household products (paints, varnishes, wax, aerosol sprays, repellents, cleaning and disinfecting products, hobby supplies, building materials and furnishings, office supplies, etc.). Hence, VOCs have been observed to be consistently higher indoors than outdoors. With the plethora organic chemicals, some of them can have both short- and long-term effects on human health.

- Black carbon (BC)

BC is an important fraction of the PM, formed by compounds resistant to a combustion up to 350 °C. Basically, it has a graphitic structure and the compounds (the composition is still unknown) are directly emitted during incomplete combustion (primary pollutant). In urban areas, BC mostly originates from road traffic and are currently being heavily argued to be regulated because of their adverse health effects. These particles are known carriers of toxic and carcinogenic compounds in the atmosphere. Because of their small size and insolubility, they can penetrate deep into the respiratory system with the toxic compounds intact enough to cause damage. BC is not a regulated metric yet but is planned for 2025 by the EU.

- Ultrafine particles (UFPs)

UFPs are defined as particles smaller than 100 nm (aerodynamic diameter). They are small and have negligible weight but abundant in number, and therefore, should not be characterized in the same way as $PM_{2.5}$ and $PM_{10}$. In indoor spaces, without any aerosol combustion sources, the main contributor of UFPs is outdoor pollution (combustion sources such as traffic). However, recent studies observed high concentrations of UFP from indoor activities such as the burning of candles (Zhao et al., 2021; Zhao et al., 2020; Manigrasso et al., 2017) and heating (Manigrasso et al., 2018). UFPs are an emerging pollutant because of increasing evidence of their adverse health effects to human as they can reach the alveoli and even into the bloodstream.  Additionally, the smaller the particles, the higher the toxicity because of the high surface area, which provides a more extensive interface to transmit toxic materials into the body (Manigrasso et al., 2019).

- Microplastics

Microplastics, particles of plastic typically smaller than 5 mm, are generated through the degradation of larger plastic items or deliberate manufacturing at a reduced scale. The increasing presence of microplastics as contaminants in indoor air has raised concerns due to their pervasive distribution in household goods, furnishings, and consumer merchandise. Inhaling microplastics indoors presents potential health hazards, as these particles may harbour hazardous chemicals or pathogens that can impact respiratory tract and overall well-being (Carrieraa et al., 2023). The comprehensive understanding of the long-term health implications of inhaling microplastics remains incomplete, underscoring the necessity for research to evaluate risks and establish safe exposure thresholds. Microplastics in indoor air can originate from the deterioration of plastics found in construction materials, furniture, and common household objects, dispersing particles within indoor spaces.

- Radon

The average activity concentration of $^{222}Rn$ in the air should be measured in indoor environment. The potential effects on human health of radon lie in its solid decay products rather than the radon gas itself. Whether or not they are attached to atmospheric aerosols, radon decay products can be inhaled and deposited in the bronchopulmonary tree to varying depths according to their size. According to EU Council Directive 2013/59/EURATOM the reference levels for the annual average activity concentration in indoor air shall not be higher than 300 Bq $m^{-3}$. Higher radon concentrations are expected in basements and ground floor; however, it is possible that due to air circulation within the dwelling radon can be accumulated in upper floors.

### 1.3.2 Toxicological and Biological Parameters

- Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are a large group of organic compounds containing two or more aromatic rings. In the air, PAHs with two or three aromatic rings are present in the gaseous phase, while PAHs with four or more aromatic rings are found mostly bound to particles. They are products of incomplete combustion or pyrolysis of organic substances, and therefore can originate from different industrial processes, traffic, biomass burning and other human activities. PAHs also arise as a consequence of natural processes such as carbonisation. In indoor air their sources are residential activities such as smoking, cooking, candle burning, heating and gas-fired appliances. They are widespread in the environment. According the International Agency for Research on Cancer (IARC), benzo(a)pyrene (BaP) is classified in group 1 (carcinogenic to humans), dibenzo(a,h)anthracene (DahA) in group 2A (probably carcinogenic), benzo(a)anthracene (BaA), chrysene (Chry), benzo(j)fluoranthene

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(BjF), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), and indeno(1,2,3-cd)pyrene (IP) are classified to group 2B (possibly carcinogenic), while benzo(ghi)perylene (BghiP), fluoranthene (Flu) and pyrene (Pyr) are classified in group 3 (not classifiable as to its carcinogenicity to humans).

- Biological pathogens

Indoor microorganisms can have severe effects on human health by e.g., exacerbating asthma symptoms or acting as allergens. Especially when they become airborne or are inhaled they can trigger reactions in susceptible individuals. Indoor dust is the main reservoir of microbial taxa in the domestic environment. Monitoring the indoor microbiome in (bed) dust allows identifying the presence and abundance of microorganisms and common associations with diseases. Higher microbial diversity in the environment has been found to be inversely associated with asthma. For example, children who grow up in the environments with a wide range of microbial exposures, like farming environments or households with a lot of members, are more likely to be protected from childhood asthma and atopy than urban children and single children.

### 1.3.3 Environmental Parameters

**Environmental Conditions**

- Relative humidity (RH)

Indoor air humidity has both negative and positive effects. For humans, dry air (15 %) can cause discomfort (dry skin and eyes leading to irritation). More seriously, dry air could also decrease the effectiveness of self-clearing mechanism of the respiratory tract. Moist air may not always be better. Moist air condensing on surfaces promotes microbial growth – moulds, which can be harmful to susceptible occupants and trigger allergic reactions. From a technical point of view, RH is an important parameter to monitor as some pollutant measuring devices are sensitive to either low or high humidity.

- Temperature

Temperature is an important factor for the level of comfort in indoor spaces. More importantly, there is evidence that high indoor temperatures affect respiratory health, diabetes management, and core schizophrenia and dementia symptoms. Similar to RH, some instruments for measuring air pollution can be affected by temperature.

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**Building Conditions**

- Layout

The configuration of the indoor space is an important factor in the fluid dynamics of a room and hence, in the movement of pollutants. In each location where measurements are conducted, the layout of the room relative to the placement of the sensors must be known including dimensions of the room, presence of furniture, walls and partitions, etc.

- Ventilation

The presence, or lack thereof, of the ventilation system must be noted. Different indoor spaces can be ventilated in a variety of ways across Europe. The rate at which the room is ventilated should also be known. If the room is ventilated mechanically, these activities and their duration may be noted as well in addition to the $CO_2$ readings which is a proxy for ventilation.

- Possible sources

All possible sources of air pollutants (in and out) must be recorded for each room where measurements are conducted. This could include proximity to traffic or other outdoor emissions, fireplaces, heaters, cooking appliances, smokers, pets, and so on.

- Occupancy

Most sources of pollutants in indoor environments can be attributed to human activities. Therefore, for some pilots and campaigns, knowing the number occupancy of the room can help in understanding and interpreting the measurements of air pollutants obtained from the sensors and other instruments.

**Indoor and Outdoor Activities**

- Time activity patterns

As mentioned above, human activities contribute largely to pollutant concentrations in indoor environments. To identify sources of pollutants, the relevant activities of the occupants must be recorded as well. Granted that activities can vary; it is recommended for each pilot and campaign to curate a general list of activities that is applicable to all occupants of a certain category. For instance, if a pilot is investigating multiple units of several indoor categories (schools, households, offices, entertainment etc.), there should be a general list for schools that can be used by all schools in the same pilot/campaign can use. Naturally, this list can be different from that of households, offices, and other categories.

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This is to ensure comparability of the results and better interpretation of the data afterwards.

## 1.4 Deliverable objectives

This deliverable serves multiple objectives within the project. The first version (v1.0) served as scientific guidance for the pilots and campaigns on the target parameters and sampling/monitoring procedures. The objective of the final version (v2.0) is to report on the how the pilots and campaigns were set-up starting from the selection of stakeholders and measurement sites to measurement technologies and involvement of the stakeholders. This version includes the documentation of a DEM for involving stakeholders (the design of the QR code experiment). This is followed by the lessons learned from pilots and campaigns which are collected to draw the guidelines for characterisation of indoor air and visualisation for different stakeholders.

## 1.5 Updated version

As the pilots and campaigns continue beyond M18, additional information and insights coming from them are still pending. Results from measurements of other emerging pollutants covered in EDIAQI (UFP, BC, radon, sampled VOCs, PAHs, microplastics, microbiome and fungi) will be analysed (T3.1c and T3.1d) in order to derive correlations between these and the pollutants measured by the sensor. These correlations will then be forwarded to the KNOW data platform (WP4) for data integration a DEM representing health effects will be delivered in the updated version of this deliverable once microbiome and sequencing tasks have concluded.

# 2 Measurement Setup: Approaches for IAP observation

This chapter reports on the different approaches of setting up the Ferrara, Estonia, and Zagreb pilots and the Vilnius campaign beginning with identifying the stakeholders (T3.2.1) to the measurement activities (T3.1).

## 2.1 Stakeholder Profile for Zagreb pilot and pilot city labs: Vilnius, Ferrara, Estonia

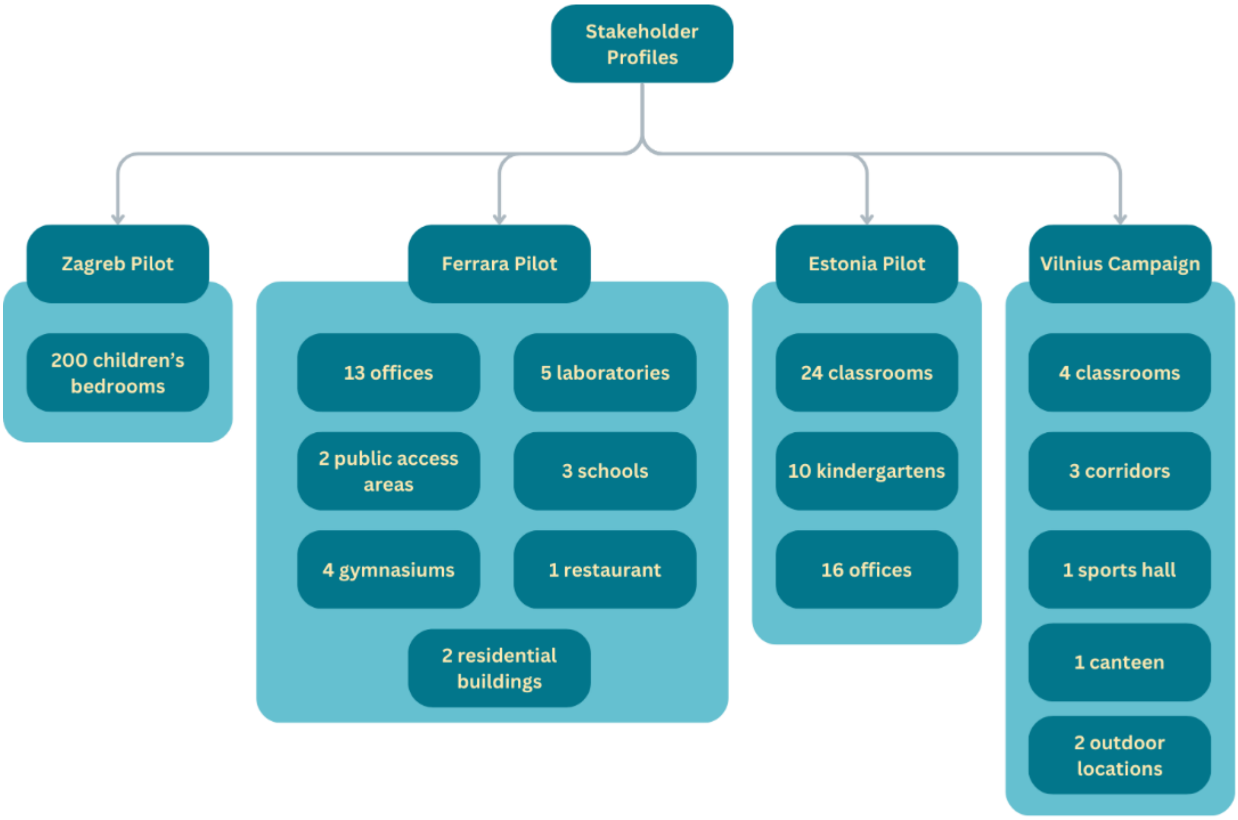


Figure 3 Stakeholder profiles for the Zagreb, Ferrara, Estonia pilots and Vilnius campaign

Each of the pilots and the Vilnius campaign were created for specific science questions, all geared towards the main objective of EDIAQI. In the Zagreb pilot, the main stakeholders are the school-aged children from the SCH asthma cohort whose bedrooms are being monitored for several IAP including biological and toxicological parameters and radon. The Ferrara, Estonia pilots, and Vilnius campaigns are the pilot city labs which are physical-digital platforms connecting stakeholders (physical) and indoor air pollution data (digital) through a platform where real-time sensor data is visualised, and stakeholders input their feedback (more in Chapter 3). The Ferrara pilot has the most diverse types of stakeholders followed by the Estonia pilot, which runs in two cities. For these two pilots, the pollutants measured are focused on sensor parameters with additional sampling for VOCs. The Vilnius campaign

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is focused on influence of outdoor air into classrooms. Additionally, emerging pollutants UFP, PNSD, and BC are measured in both outdoor and indoor spaces in Vilnius. These three pilot city labs are part of the T3.2 experiments on dweller's perspectives described in Chapter 3.

## 2.2 Setup of IAP measurements using different approaches

### 2.2.1 Ferrara pilot

Ferrara pilot has multiple objectives that can be summarised as mapping different categories of buildings to provide approaches for proper indoor air management, increasing public awareness of possible sources and exposures to pollutants, regardless of whether they are emerging or not, and the influence of characteristic pollutants we find in the ambient air.

To achieve our objectives, the following actions were taken. Firstly, a preliminary study was carried out mainly considering the city hotspots (the presence or absence of major road axes, industries, and agricultural fields). Additionally, results from previous projects were leveraged for its already existing smart monitoring stations for ambient air quality and odours installed in Ferrara by the partner Lab Service Analytica (LAS) which produce open data of TVOCs, $PM_{2.5}$, $PM_{10}$, CO, $NO_2$, $O_3$, T and RH with hourly frequency throughout the Ferrara area.


Figure 4 Map of ambient air monitoring points (red) and selected pilot buildings participating in the Ferrara pilot.

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From here, the pilot buildings were selected and a formal agreement for each was made after defining and agreeing on the monitoring plan using the LAS LCS devices and the Radiello® samplers (Figure 4). The Ferrara pilot has the most diverse stakeholders where LCS devices were installed in various building types: schools, offices, entertainment and residential. In total, 36 LCS devices were installed across these buildings. In addition to the LCS devices, passive sampling using the Radiello® is being conducted in these rooms for 7 days, both indoor and outdoor when possible and also for different seasons (winter, spring, summer, autumn). This will provide data for 17 types of VOCs and aldehydes. Finally, passive sampling for microplastics is also on-going in the Ferrara pilot both in the standard method and also developing a new method at the same time. The Ferrara pilot is further supported by the acquisition of outdoor air pollution data from the regular air monitoring stations operated by local government.

The activities to involve stakeholders began with the forming and sharing of the monitoring plan with the owners/operators of the facilities through illustrative and in-depth meetings. To reach a wider audience, a workshop was held about the EDIAQI project as part of the Ferrara Municipality's Air Festival on 5th of October, 2023.

This project has received funding from the European Union's
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Figure 5 DEM of the QR code poster used in the Ferrara pilot city lab for involving stakeholders.

The Ferrara pilot is also one of the pilot city labs performing the perception versus sensor measurement experiment through QR code scanning (Chapter 3). The QR codes (Figure 5) were placed on door and bulletin boards of rooms where the IAQ monitoring devices are installed. By leveraging IAP values and residents' subjective perceptions of the air quality situation, QR code experiments serve as an interactive and user-friendly tool, Ferrara can effectively mobilise different stakeholders to collaborate on air quality monitoring efforts. This collaborative approach not only generates valuable data, but also promotes community awareness, empowerment, and collective action to improve air quality and public health.

### 2.2.2 Estonian pilot

The Estonian pilot involved IAP measurements in 50 buildings, including educational (schools, kindergartens, universities) and office buildings. A total of 100 IAP LCS devices from Thinnect (2 devices per building) measuring temperature, RH, $CO_2$, $PM_{2.5}$, $NO_2$, $O_3$, and TVOC were installed in the buildings.

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The selection of buildings was done in collaboration with local authorities and commercial building owners, while considering the technical condition of the buildings:

City of Tallinn:

- Tallinn Property Department – office buildings of the City of Tallinn
- Tallinn Education Department – schools and kindergartens of the City of Tallinn

City of Tartu:

- Department of Municipal Property – schools and kindergartens of the City of Tartu

Commercial building owners:

- Private sector office buildings

The objective was to have a diverse range of buildings with varying states and technical systems, including those that have been renovated, those that have not, those with mechanical ventilation systems and those without.

The rooms for IAP measurements were selected, building by building, according to the following criteria:

- Already existing temperature, relative humidity and $CO_2$ sensors installed and integrated with the building management systems (BMS) for comparison.
- Mechanical ventilation airflow rates measured by rooms for subsequent analysis.
- Known complaints regarding indoor environment quality (IEQ).
- Potential to gather the perceived IEQ data with QR codes.
- Preferences of building owner/operator.

The initial outcomes of the IEQ data collection through QR codes in university auditoriums revealed that more people responded when the QR codes were placed on the tables, as opposed to the setup where the QR codes were positioned on the wall next to the door.

### 2.2.3 Vilnius campaign

The main objective of the Vilnius Campaign is to investigate how outdoor air pollution from vehicle fleets affects IAQ, particularly in schools. In addition to parameters measured by the LCS devices, several emerging pollutants are also investigated in this campaign: UFP, PNSD, BC, and microplastics. Covering a wide-range of pollutants will allow for identifying sources and investigating the exposure of schoolchildren to microparticles.

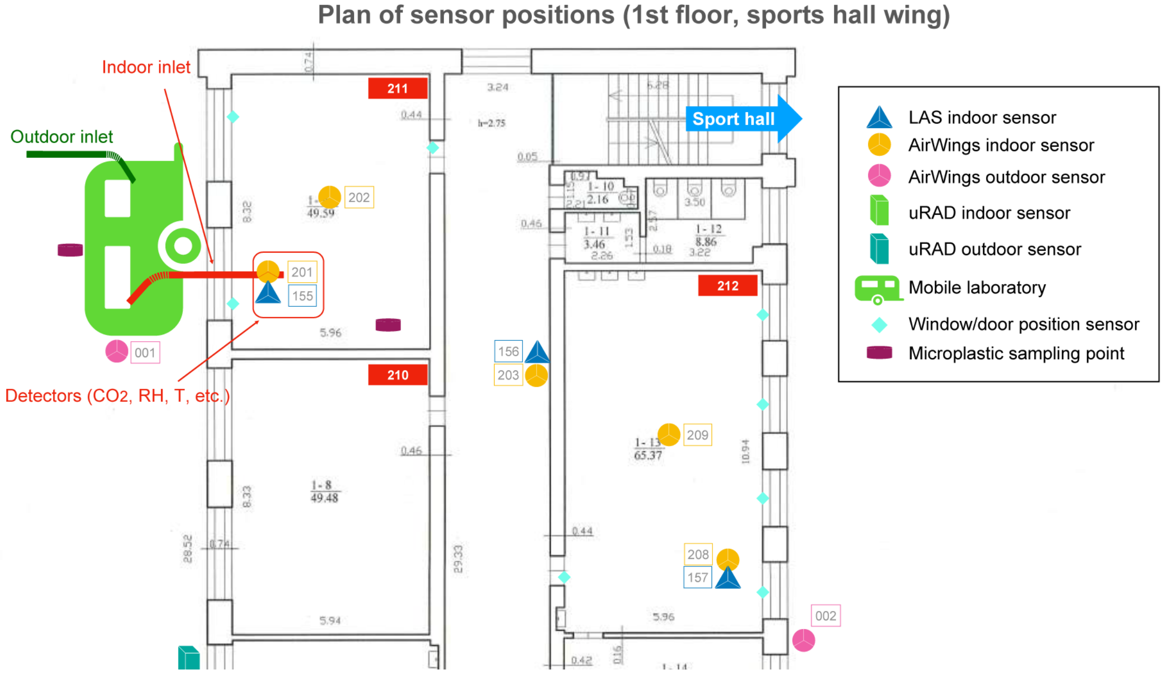


Figure 6 Location of LCS devices and state-of-the-art instrumentation in the school site of Vilnius campaign.

To identify sampling locations that represent high pollution levels and aerosol sources (particularly from traffic) a short-term pilot study for the Vilnius campaign was carried out in three school buildings. Based on the results, one school building was selected for long-term measurements.

The centre of Vilnius is situated in a valley (surrounded by hills, mostly covered by forest) and all the buildings under consideration were in this valley. The selected school is situated close to the historical Old Town of Vilnius which is located on the left bank of the Neris River.

To achieve the objective of the campaign, the WINGS sensors were selected because the indoor LCS device has an outdoor counterpart which is designed to withstand the elements. In addition, LAS and uRad sensors were also installed, and collocated with the WINGS sensors. Figure 6 shows the location of the sensors distributed in 2 classrooms and along the hallway as an example. The indoor sensors were placed in the middle of the room and adjacent to the window. The WINGS outdoor sensors were placed on the outside of the same classrooms. To better understand the dynamics inside the rooms, motion sensors were installed on all windows and doors of the two classrooms. In total, LCS devices were installed in 4 classrooms, 3 corridors, 1 sports hall, 1 canteen, and 2 outdoor sensors installed in the inner yard and outside the classroom where the mobile platform was.

In the room closest to the traffic source, emerging pollutants such as UFPs and BC, concentrations of volatile and non-volatile fine particles, and microplastics are measured in both outdoors and indoors. A mobile platform (trailer) was used to house the instruments outside the room with inlets going into the classroom to characterise the indoor air and a separate inlet system to sample from the outdoor air. Table 2 provides a list of the pollutant parameters obtained from instruments inside the mobile platform.

Table 2 List of emerging pollutants in the Vilnius campaign and instrumentation used to measure them

<table>
<tr><th>Pollutant</th><th>Instrument</th><th>Indoor</th><th>Outdoor</th><th></th></tr>
<tr><td>PNSD (10-800nm) ambient air</td><td>TROPOS Mobility particle size spectrometer (MPSS)</td><td>x</td><td>x</td><td rowspan="4">UFP (<100 nm) concentrations can be calculated from the PNSD of the MPSS.<br><br>The merged size distributions of the MPSS and OPSS can be integrated to derive $PM_1$, $PM_{2.5}$, and $PM_{10}$.</td></tr>
<tr><td>PNSD (10-800nm) of non-volatile particles</td><td>MPSS + thermodenuder</td><td>x</td><td>x</td></tr>
<tr><td>PNSD (300-10µm)</td><td>TSI Optical particle size spectrometer (OPSS)</td><td>x</td><td>x</td></tr>
<tr><td>PNSD (300-10µm)</td><td>TSI Aerodynamic particle size spectrometer</td><td>x</td><td></td></tr>
<tr><td>BC mass concentration</td><td>Aethlabs MA200</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Microplastics</td><td>Offline sampling and analysis</td><td>x</td><td>x</td><td></td></tr>
<tr><td>VOCs</td><td>Offline passive sampling</td><td>x</td><td>x</td><td>Offline analysis 17 compounds from loaded filters</td></tr>
</table>

These instruments, particularly the size spectrometers, are huge and loud and the MPSS systems also charge the particles using a radioactive source, making them unsuitable for prolonged measurement in indoor spaces which are regularly occupied by humans, especially schoolchildren. Hence, they were placed inside a trailer with controlled conditions positioned outside the classroom being monitored (Figure 7).

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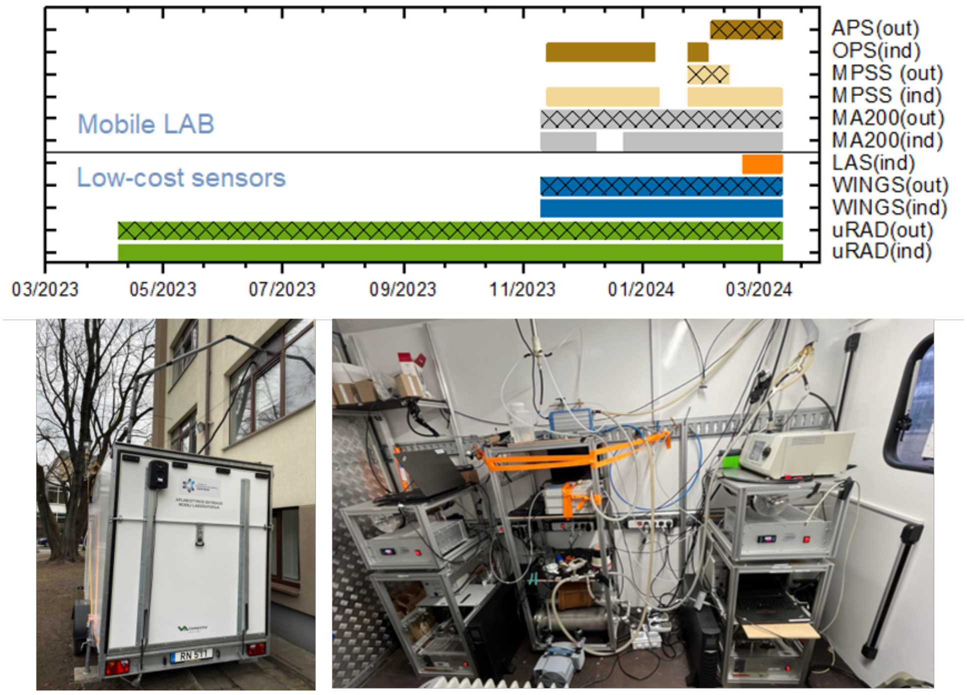


Figure 7 Measurement time-period (above) of LCS and mobile LAB (below) equipped with reference instruments in the school indoor ("ind") and outdoor ("out") environment.

In addition, workshops for school administrators, teachers, and maintenance staff, were organised about IAQ issues and mitigation strategies. Information on common indoor air pollutants, sources of pollution, health effects, and best practices for maintaining healthy indoor environments was presented. Once the data has been analysed, the next workshop is planned. This will present the school's situation and make recommendations for IAQ improvement providing a valuable opportunity for school staff, administration and students to come together, discuss findings, and collaborate on solutions for healthy and conducive learning and working environment.

### 2.2.4 Zagreb pilot

IAP measurements in Zagreb Pilot were set based on the SCH2021 cohort consisting of 200 participants, children aged 6-18 years with a physician diagnosed asthma or related respiratory diseases, as well as a control group of non-asthmatic children, matching in age and sex, from the Zagreb region. The main objective is to identify the underlying disease mechanisms driving specific asthma and allergy phenotypes, as well as certain disease outcomes and their relation to impaired indoor air quality.

Participants are being recruited at the Srebrnjak Children's Hospital (SCH) by an experienced paediatric allergy/pulmonology specialist physician, after obtaining informed consent from

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the parents. The main inclusion criterion is clinical diagnosis of asthma (according to ERS/ATS guidelines) for at least a year, being on a stable dose of anti-inflammatory treatment for at least one month with partially controlled or uncontrolled asthma according to The Global Initiative for Asthma (GINA) guidelines. Additional inclusion criteria include clinically significant allergy to indoor and outdoor allergens, with positive skin prick test and specific Immunoglobulin E levels (>0.7 kUA/L). Exclusion criteria include known inborn or perinatal pulmonary disease, pulmonary malformation, oxygen therapy after birth with a duration of more than 24 h, ventilator support or mechanical ventilation after birth, diagnosis of cystic fibrosis, primary ciliary dyskinesia, heart failure diagnosed after birth affecting pulmonary circulation, major respiratory diseases such as e.g. interstitial lung disease, acute respiratory infection at recruitment, use of systemic corticosteroids, recent asthma-related visit to emergency department (in the past three weeks) and coexistence of other serious chronic illness.  All participants undergo standard diagnostic tests and procedures as a part of their routine asthma diagnostics and biosamples (blood, exhaled breath condensate, buccal swabs) are taken.

IAP measurements are carried out in households of participants from Zagreb and surrounding places in Zagreb County, Croatia, who consent for that part of the investigation. Participants fill out a questionnaire on their habits and household characteristics.

As a first step, dust samples are collected in households (Figure 8) for two types of examinations. In each home, household members are requested to provide the contents of their vacuum cleaner bags and asked how long the content is in there. Collected dust samples are transported to the laboratory and after elimination of non-dust particles, samples are sifted twice through a 500 µm stainless steel mesh and then homogenised on a rotating mixer for 24 h. All dust samples are stored in clean glass flask in a dark place at room temperature until analysis.

For the second type of analysis, dust samples from children's bedding are collected using DUSTREAM® Collector vacuum cleaner filters that are placed on the vacuum cleaner nozzle for the analysis of bacterial and fungal composition. The samples are stored at -20 °C immediately after sampling until DNA isolation to preserve genetic material and to eliminate mites.

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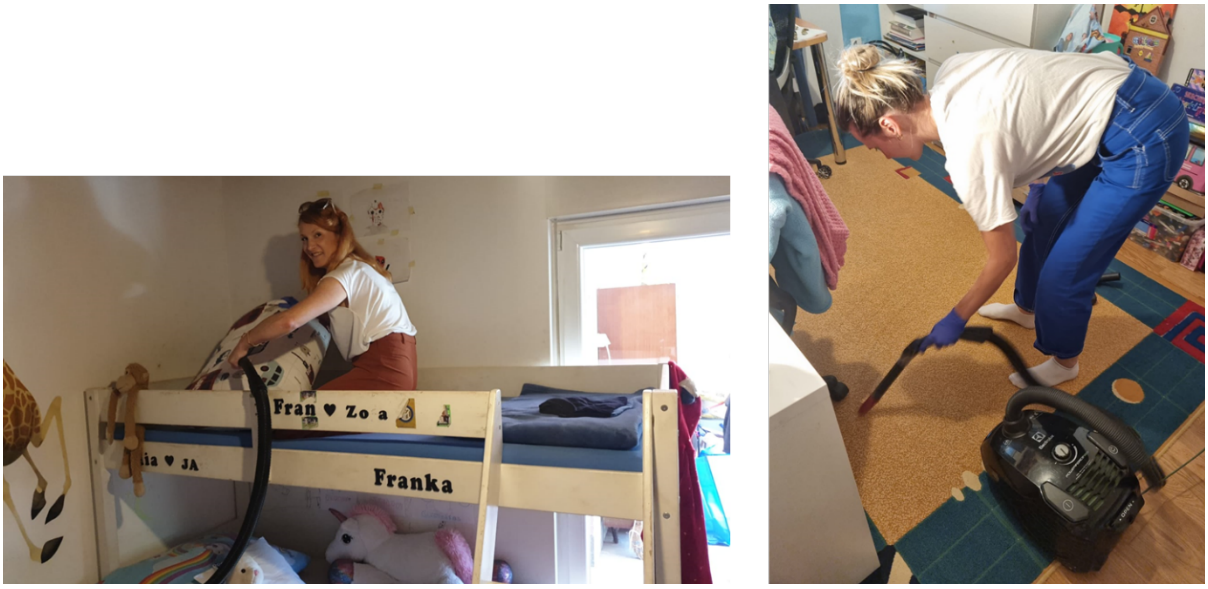


Figure 8 Exemplary photos of dust sampling from children's beddings and floor (Image source: IMROH and ANT)

The rooms are equipped with LCS devices (WINGS) and stationary active and passive samplers for different pollutants, which remain in place for a defined time period (Figure 9). Where possible, outdoor and indoor measurements with LCS are carried out in parallel, as well as collection of $PM_1$ and VOC samples for later laboratory analysis. Radon and microplastics measurements are carried out only indoors, in selected households.

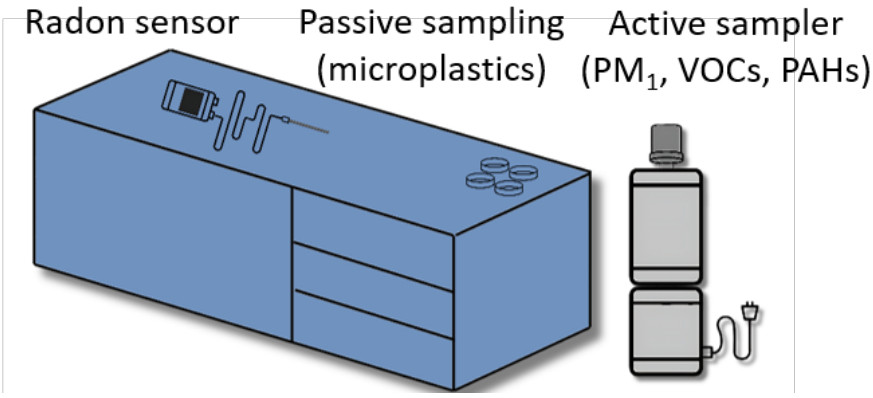


Figure 9 Illustration of radon measurements, passive sampling for microplastics, and active sampling for $PM_1$, VOCs, and PAHs in the Zagreb pilot.

Table 3 presents the list of pollutants measured in Zagreb pilot, applied sampling/measuring techniques, duration of sampling/measurements per household, and the type of measurement (indoor/outdoor).

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Table 3 List of pollutants measured in Zagreb Pilot, equipment used, duration and type of measurements

| Pollutant | Method | Duration | Type |
|---|---|---|---|
| **$CO$, $CO_2$, $NO_2$, $O_3$, TVOC, $PM_{10}$, $PM_{2.5}$, $PM_1$, air temperature, relative humidity, pressure** | LCS (WINGs) | 3 days of continuous measurements | indoor |
| **$CO$, $SO_2$, $NO_2$, $O_3$, TVOC, $PM_{10}$, $PM_{2.5}$, $PM_1$ air temperature, relative humidity, pressure** | LCS (WINGS) | 3 days of continuous measurements | outdoor |
| **$PM_1$** | Active sampling with pumps on filter | 7-day sampling | indoor, outdoor |
| **PAHs in $PM_1$** | Active sampling with pumps on filter | 7-day sampling | indoor, outdoor |
| **Radon** | Passive sampling with SSNTD (ISO 11665-4:2021) | 2-3 months | indoor |
| **Radon** | Passive sampling with activated charcoal filters (ISO 11665-4:2021) | 3-day sampling | indoor |
| **Microplastics** | Passive sampling on filters | 7-day sampling | indoor |
| **VOC** | Passive sampling with Radiello | 7-day sampling | indoor |
| **VOC** | Active sampling on adsorption tubes with pumps | 50-min sampling | indoor, outdoor |
| **PAH in dust samples** | Vacuum cleaner bags | | indoor |
| **Microbiome in dust samples** | DUSTREAM® Collector vacuum cleaner | | indoor |

In addition to mapping of biological and chemical contaminants in indoor air, the pilot also includes activities aimed at assessing the level of awareness on indoor air quality and its rise. A questionnaire has been developed and is being administered within the pilot, among the parents of asthmatic children and controls, to investigate:

1. The level of awareness of participants on health-related issues involving indoor air pollution.
2. Public sources of information about indoor air pollution and its health effects.

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3. Potential disparities in information reach and utility (related to type of environment, socioeconomic status etc).

Currently, we have replies from 64 parents. Their answers will allow for identifying knowledge gaps that need to be addressed to increase indoor air quality awareness. Recruitment has been additionally boosted using different strategies:

- Designing flyers that are being distributed in buildings, daily newspapers and across social media.
- Holding lectures on EDIAQI in schools, different events and on the radio.
- Advertising EDIAQI and the Zagreb pilot within regular lectures held by EDIAQI researchers.
- Creating special EDIAQI-related sites for easier recruitment of participants (IMROH).
- Personal contacts of researchers involved in the project.

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# 3 Information on the T3.2 Observatory

## 3.1 Set-up of physical-digital platforms

Community engagement is a cornerstone of this research endeavour, as it seeks to involve stakeholders at every stage of the experiment. Schools, kindergartens, gyms, restaurants, office building owners, homeowners, and laboratory personnel are invited to participate, via QR code scanning to submit their valuable feedback, fostering a collaborative effort to involve citizens and stakeholders in the process that will lead to the implementation of new technological and scientific monitoring solutions. By actively involving stakeholders, the study has created by mid-May minimum dataset of 300 replies for Tallinn, Vilnius and Ferrara (based on the Air Police project results, see Järvi et al. (2018)). Please, see the method distributed to the partners in 2023 in Annex 5 - T3.2 Methodology for WP3. The EDIAQI team chose a well-defined profile for Ferrara, Tallinn and Vilnius city labs, visualised in Figure 10:

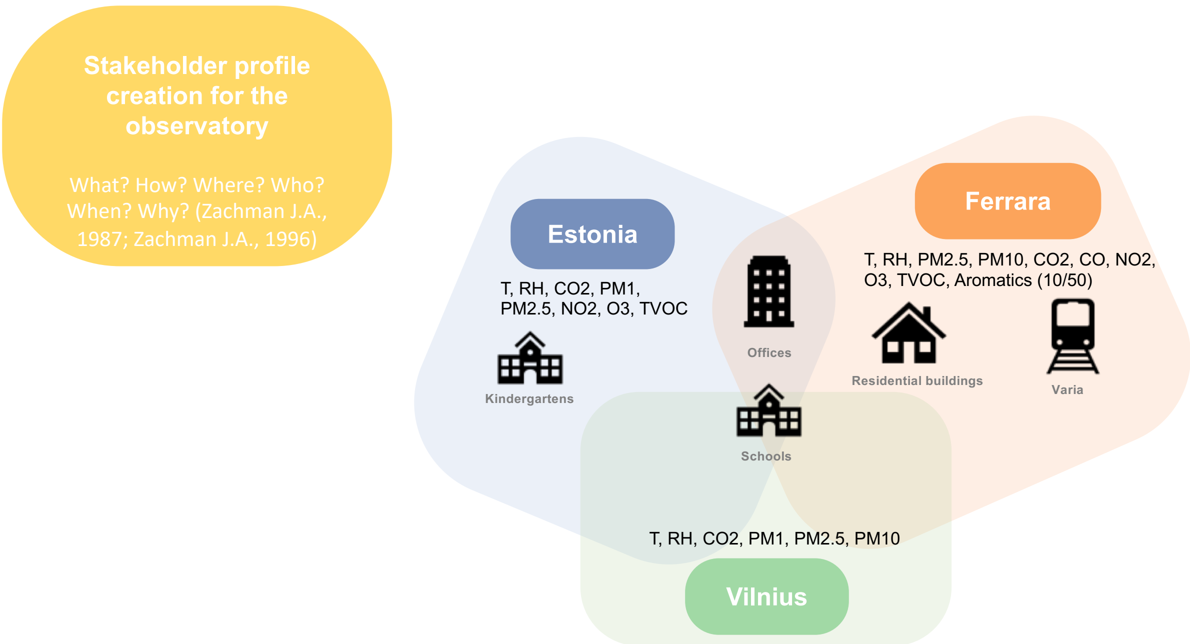


Figure 10 Where and what, for whom is measured (Zachman, 1987, 1997)? Deployment of sensor units and IoT, computing technologies with municipalities in three EU counties.

The selected dwellers and owners of schools, offices, kindergartens, private homes, gyms, labs and restaurants will act as antennae on the territory to convey EDIAQI novel indoor air pollution identification solutions in the pilot city labs. As public buildings (e.g. schools) are often managed via local municipalities, the installation of monitoring technologies and set

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up of observatories (computing technologies and visuals) were achieved via collaborations on many levels. As a result, city labs are physical-digital platforms connecting stakeholders (physical) and indoor air pollution data (digital) through a platform where real-time sensor data is visualized, and dwellers input their feedback. The experimental design at three locations within the EDIAQI project entails deploying LAS and THIN sensor technologies in real-world indoor settings while concurrently gathering feedback from occupants regarding their perceived IAQ via QR code scans. As part of this guideline, we recommend stakeholder involvement into testing monitoring solutions via QR code experiments. Including various stakeholders in IAQ systems testing through QR code feedback collection offers a highly efficient approach with several advantages. First and foremost, it ensures that the perspectives and experiences of diverse occupants, including residents, students, workers, and visitors of gyms, schools, offices, laboratories and restaurants are captured comprehensively. By allowing dwellers to scan QR codes to provide feedback on IAQ, it facilitates real-time data collection in a user-friendly manner, minimising the burden on participants and maximising response rates. Furthermore, incorporating citizens in this process fosters a sense of ownership and engagement, promoting awareness and accountability regarding IAQ issues within the community that can be later translated into work carried out in WP6. Overall, leveraging QR code feedback collection enhances the effectiveness of IAQ systems testing by harnessing the collective insights of a diverse audience, ultimately leading to more informed decision-making and targeted interventions to improve indoor air quality. Below on Figure 11 is the example of the QR code placed on doors and tables in December 2023 in Tallinn City lab.

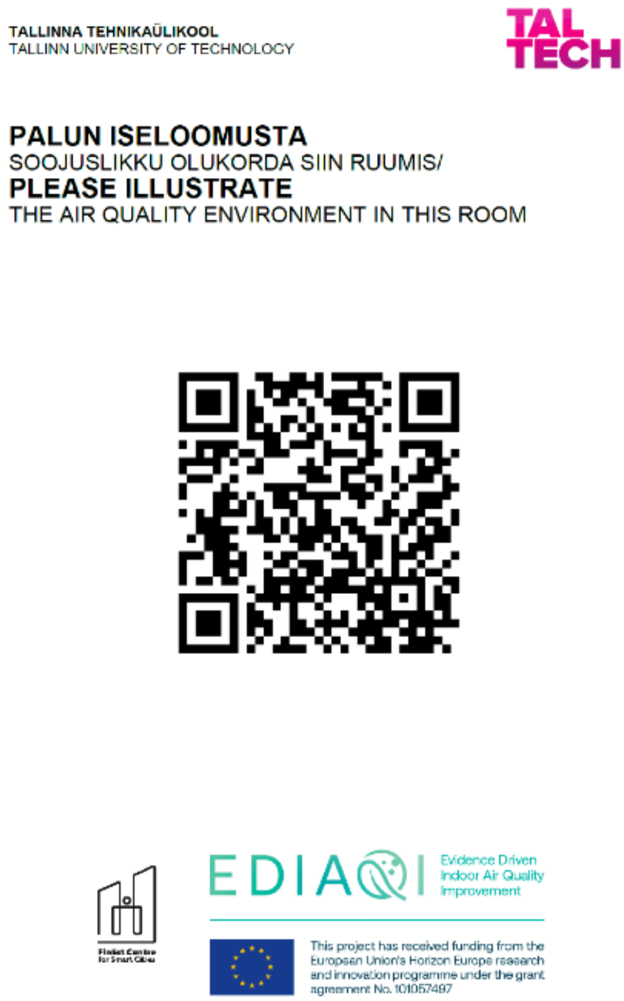


Figure 11 Example of DEM for stakeholder involvement into testing monitoring solutions via QR code experiments in Tallinn city lab

## 3.2 The IAQ information presentation

The QR code experiments for mapping the time stamped citizen feedback with the time-stamped sensor reading is supported by the T3.2 observatory. Understanding IAQ perception and its relationship with environmental factors like temperature, humidity, and IAP (e.g. PM) requires a robust technical solution for IAQ monitoring. By leveraging physical-digital platforms that connect citizens, private sector entities, and public bodies, innovative monitoring solutions have been designed and tested effectively in T3.2. Through simplified participation methods such as scanning QR codes, stakeholders can contribute their IAQ perceptions, facilitating comprehensive data collection. This approach enables the examination of how visual representations impact the alignment between perception and sensor readings. By assessing whether perceptions converge or diverge in response to visual stimuli, valuable insights can be gained into the complex design dynamics of indoor air quality visuals. Ultimately, a technical solution for IAQ monitoring is essential for enhancing our understanding of how individuals perceive indoor pollution and their sensitivity to various environmental factors, therefore when testing various visuals, the perception should move closer to actual IAQ value(s), when the visual is effective.

The system requirements are in detail explained in D3.1. In Figure 12 the logic of the T3.2 set-up is explained:

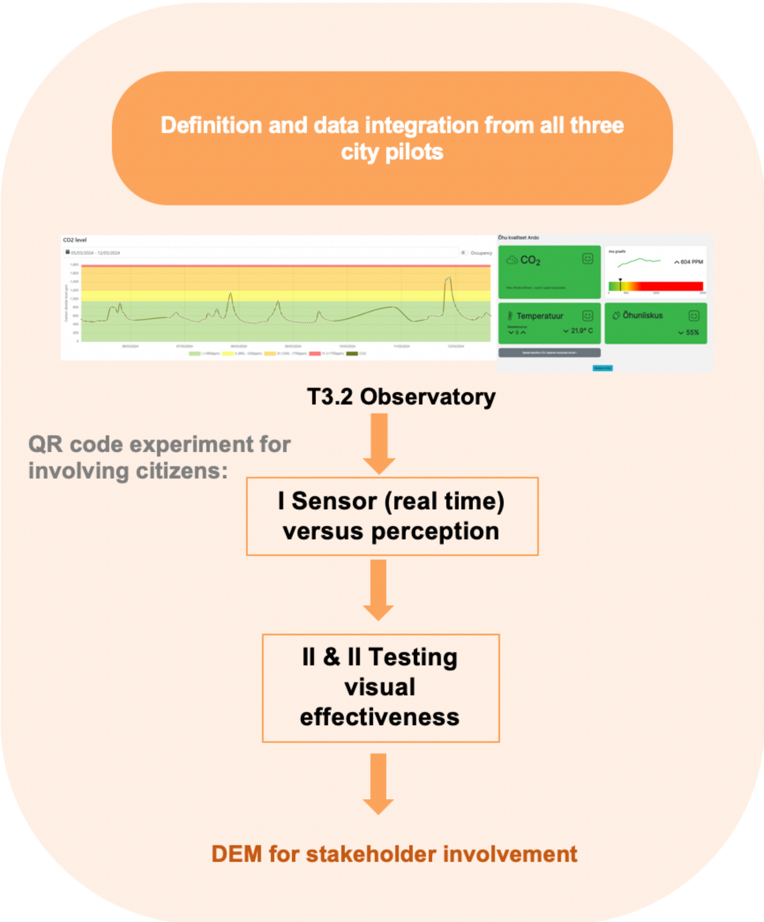


Figure 12 Illustration of T3.2 set-up

The prototype of the T3.2 is transferred as a suggestion, based on the literature review on IAQ visual representation. In WP4 T4.2 “iii) development of the tools for data collection, the platform for the analysis and visualization, the mobile application for visualisation of pollutant concentrations and the behavioural change campaigns based on gamification approach, all leveraging collaboration of citizens through co-creation” from the IT requirements document submitted as a result of T3.2 on 31st May visuals will be co-created through citizen involvement.

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## 3.3 T3.2 Observatory

Over the past two decades, IAQ information presentation has predominantly relied online charts, irrespective of the number of data sets or parameters involved. To address the data representation topic scientifically, our study introduces a well-documented scientific method grounded in the established Zachman Framework ontology, which categorises entities along six dimensions: What? How? Where? Who? When? Why? This comprehensive framework facilitates a detailed description of data visualisation features within the context of IAQ monitoring, with a particular focus on potential health impacts mitigation. Our research aimed to address three key research questions:

1. The percentage difference between perceived and measured IAQ.
2. The impact of visual representations.
3. The average time for users to perceive IAQ information.

To investigate these questions, QR code experiments were conducted in Vilnius, Ferrara, and Tallinn over 2-6-week periods. Initially, stakeholders and citizens provided perceived IAQ feedback without visual aids. Subsequently, a widget and/or visual solution incorporating IAQ visuals was implemented at Vilnius and Tallinn, and the QR code experiment was repeated. Lastly, the experiment will be conducted with extended visual exposure (results will be published in a separate paper). Comparative analysis across the three stages and locations will provide insights into the effectiveness of visual representations in IAQ perception and the time required for users to perceive IAQ information. Through this multifaceted approach, our study advances the understanding of IAQ monitoring methodologies and informs the development of more effective strategies for IAQ management.

## 3.4 IAQ Widget

An IAQ widget was necessary to carry out the scientific work for testing the impact of visual representations (research question 2), and the average time for users to perceive IAQ information (research question 3). A literature based IAQ dashboard was issued by TROPOS and uploaded to EDIAQI GitHub account under “EDIAQI-WP3-T3.2-City-Lab-Visual” folder as a guideline and a starting point for testing systems and visuals with stakeholders. As the project evolves more visuals will emerge for testing purposes from T4.3. Figure 13 shows the IAQ visual applied in Tallinn and Vilnius in T3.2.

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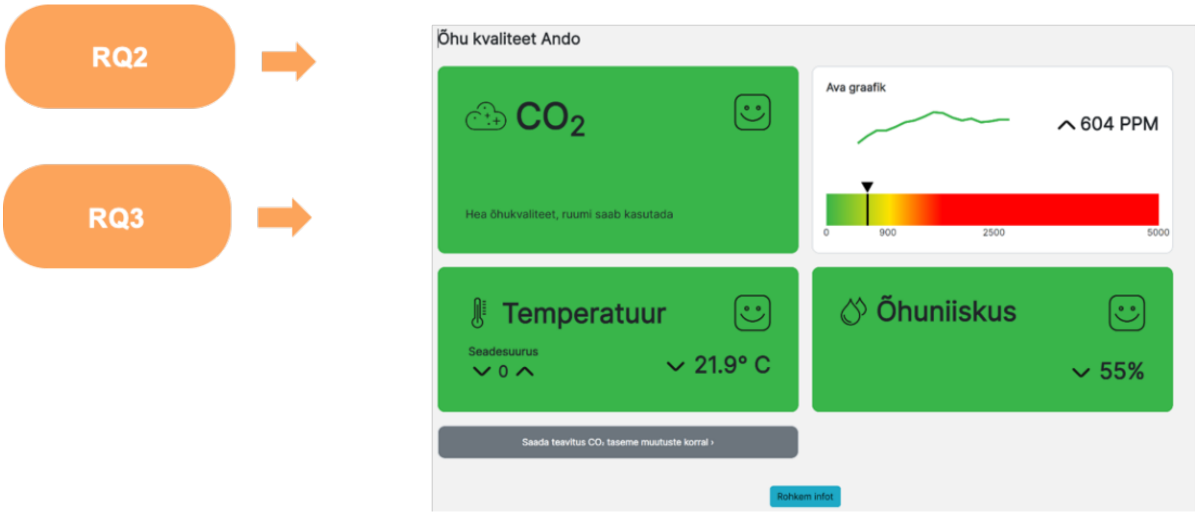


Figure 13 IAQ Widget used for the QR code experiments in Tallinn and Vilnius

## 3.5 QR code experiments at pilot city labs

The primary objective of the T3.2 experiments is to evaluate the alignment between objective IAQ measurements obtained through sensor technologies and the subjective perceptions of indoor air quality reported by dwellers. This multidisciplinary approach involves leveraging the capabilities of THIN and LAS sensor technologies, alongside active participation from citizens across diverse indoor environments via QR code scans. The fieldwork was agreed up on in the autumn of 2023 and data integration T3.2.2 was started in December 2023 (Tallinn city lab). Preliminary results will be presented in the Elsevier book "New Perspectives in Indoor Air Quality: Health, Sources and Monitoring" in chapter 12. Future technology Trends.

IAQ is a critical determinant of health and well-being, particularly in settings such as schools, kindergartens, gyms, restaurants, office buildings, homes, and laboratories. Despite its significance, there often is a disparity between objective IAQ measurements and the subjective IAQ perception among occupants. To bridge this gap and foster a deeper understanding of indoor air quality, the T3.2 study proposes engaging various dwellers in perception experiments that integrate digital and physical settings.

The physical-digital settings at Ferrara, Tallinn and Vilnius aim to create sense of ownership and awareness regarding IAQ issues within the community that can later be transferred to WP6. An example of the QR code survey active since December 2023 in Tallinn is shown in Figure 14.

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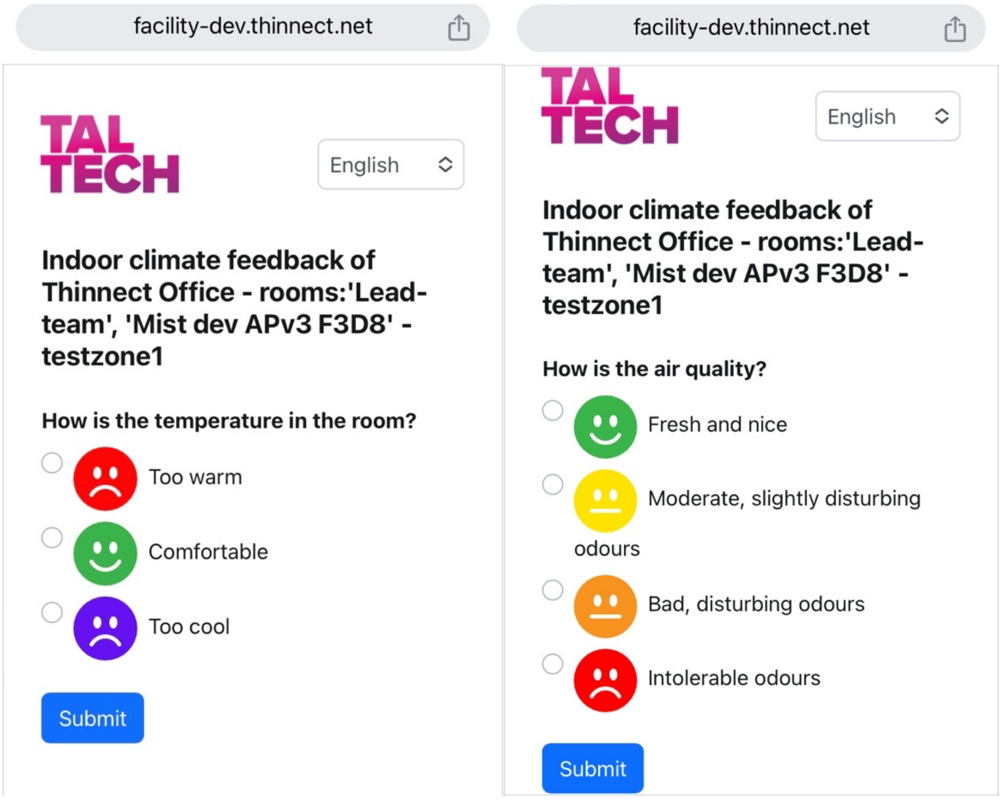


Figure 14 Example of what the dwellers see when they scan the QR code.

In T3.2, citizens are encouraged to provide subjective assessments of air quality based on their sensory experiences. These subjective perceptions are then compared with objective IAQ measurements obtained from sensor data. QR data collection from Tallinn was successfully launched in December 2023 as stated in the Grant Agreement, T3.2.2. The initial results are displayed in the graph below (Figure 15):

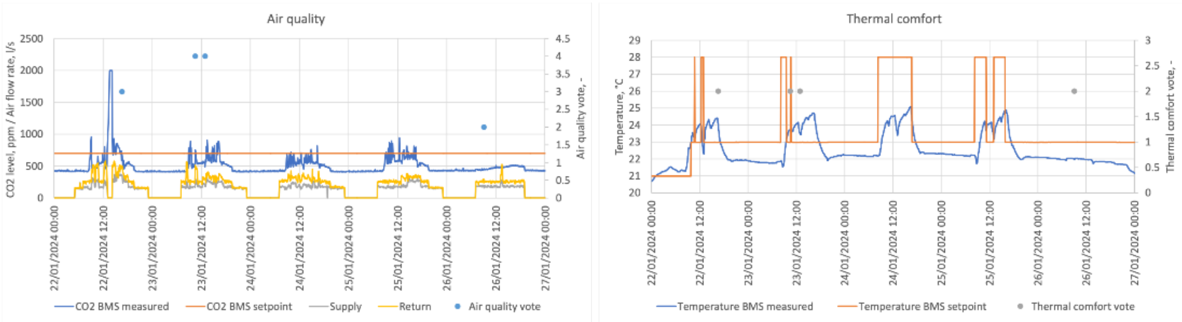


Figure 15 Exemplary results of the QR code experiments in Tallinn.

A key aspect of the T3.2 research is the integration of digital and physical settings to create dynamic experimental environments. Leveraging digital data collection technologies via T3.2 platform, enables real-time monitoring of IAQ parameters, providing valuable insights into temporal variations and spatial distributions of indoor air pollutants. Concurrently, dwellers

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physical interactions with scanning the QR code facilitate direct engagement and dialogue, fostering a deeper understanding of indoor air quality perception.

The results of these perception experiments hold significant implications for both research and practical applications. By comparing objective IAQ measurements with subjective perceptions, this study aims to identify discrepancies and potential sources of misunderstanding regarding indoor air quality. Secondly, when comparing IAQ perception with the time-stamped sensor readings the EDIAQI team can successfully test and develop further, IAQ systems and visuals in the infrastructure working package, WP4, with various stakeholders. Insights gleaned from these experiments can inform the development of more effective IAQ monitoring strategies, tailored interventions, and educational initiatives in WP6 aimed at promoting healthier indoor environments.

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# 4 Guidelines for indoor pollutant monitoring stations

This chapter summarises the lessons learned from the pilot city labs into a set of guidelines on how to monitor indoor air pollutants from measurement setups to data visualisation.

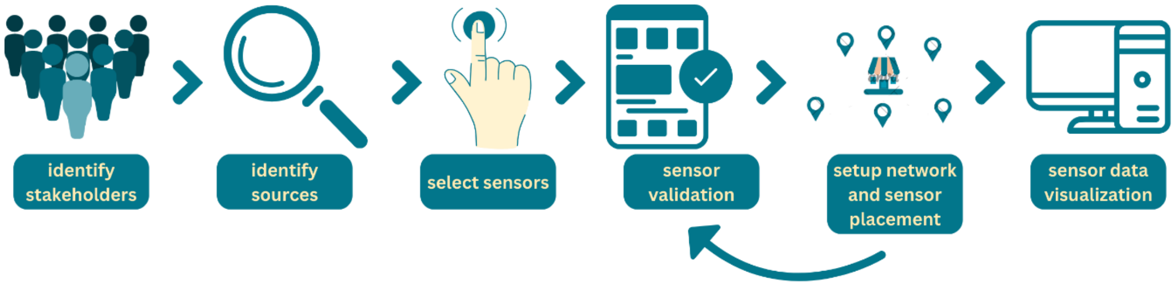


Figure 16 Schematic diagram of the general steps to take when setting up indoor air pollution monitoring station using commercially available low-cost sensors.

## 4.1 Guidelines on IAQ measurements and setup

### 4.1.1 The indoor monitoring station design

The following subsections provide guidelines for setting up indoor air monitoring, as outlined in Figure 16. Guidelines for measuring emerging indoor air pollutants are detailed in Chapter 3.3.

In setting up indoor air monitoring station(s), it is important to start by determining the primary pollutants relevant to stakeholders. Start with reviewing IAQ data from previous measurement campaigns or use expert estimations on possible IAP for the specific type of building(s). Secondly, it is important to identify your stakeholders asking the following questions:

- Who are the dwellers of the indoor space being monitored?
- Who are the users of the data? Are they the same as the dwellers?
- What is the level of participation of the dwellers?
- What is (are) the indoor air concern(s) of the main stakeholder (dweller and/or user)?

Thirdly, it is important to understand the sources of concern(s) for the main stakeholder. This will help in identifying which pollutants to monitor. For instance, if the stakeholder is a school administrator who is concerned about outdoor air pollution coming into the classrooms, then one must select both indoor and outdoor sensors that can measure finer particles ($PM_{2.5}$ or $PM_1$) and gases such as NOx which are prevalent in outdoor

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environments. If the concern of the stakeholder is indoor comfort, then one must choose sensors which can measure $CO_2$, T, and RH.

### 4.1.2 The sensors

In this subsection, the following guidelines involving sensors are described starting from choosing the type of sensor based on indoor air concerns, how to validate sensors, to setting up a sensor network and placing the sensors in indoor spaces.

#### 4.1.2.1 Target parameters

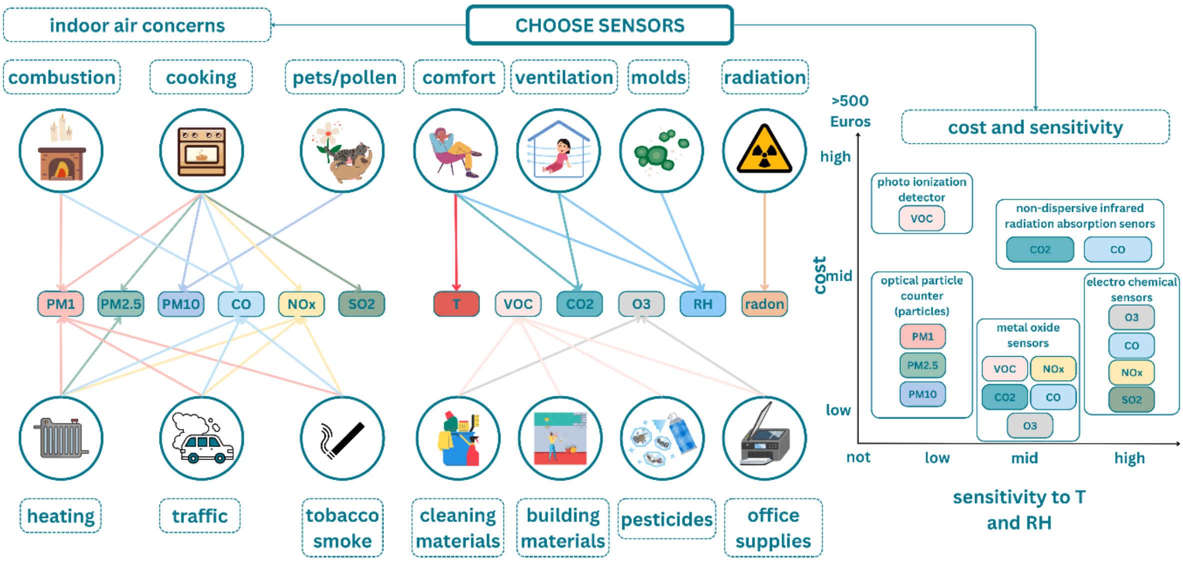


Figure 17 Guide on how to choose sensors

The look-up schematic (Figure 17Figure 16) presents a guideline to any stakeholder on which pollutant must be monitored depending on their main IAP concern. The IAQ concerns (including outdoor sources entering indoor spaces) listed are the most common while the pollutants listed are those that can be measured using LCS. Other pollutant parameters may be better tracers for a specific IAP source such as BC or UFPs, but currently do not have a low-cost monitoring alternative. Since, IAP sources produce more than one type of pollutant (particulates and gases), having multiple sensors capable of detecting several pollutants could help in narrowing down the sources. Additionally, for stakeholders needing a higher level of detail, the schematic includes the types of sensors available for each pollutant.

#### 4.1.2.2 Choosing sensors

Choosing the sensors for IAQ monitoring should meet the stakeholders' needs. In any case, there are common technical and logistical factors must be considered when selecting sensors for varying purposes.

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A. Technical factors

1. Measurement parameters

More often than not, the commercially available sensors are integrated sensors – a device containing several sensors detecting different kinds of pollutant and parameters. The device should contain pollutant sensors that will help the stakeholder monitor and mitigate the IAQ of concern. An outdoor LCS device measuring the same pollutants and parameters should also be installed. From a technical point of view, we recommend devices which include T and RH sensors. This can help the data users identify if the sensors are showing signs of sensitivity to environmental conditions and decide if the relevant data should be flagged, corrected, or excluded.

2. Performance and lifespan

LCS devices are accepted as instruments with a quality that is less than that of reference ones but can provide complimentary measurements. Nevertheless, albeit unofficial, the scientific consensus is that LCS devices can be used as “indicative measurements” (Núria Castell, 2021) of air pollution allowing for an uncertainty of 50 %, 25 %, and 30 % for PMx, $SO_2$, $NO_2$, NOx, and CO, and $O_3$, respectively, based on the current Ambient Air Quality Directive (AAQD, European Council, 2008). When choosing a device, information about the accuracy or how the sensors performed against known reference instruments must be provided and the results explicitly indicated. Likewise, the precision or the variability between devices must be provided.  How these performance metrics are calculated is described in D3.1 Chapter 2.

Due to the low-cost nature of the sensors, degradation happens quickly in the sensors’ lifetime (1-2 years, Ródenas García et al. (2022)). This can be due to the deterioration of the electronics, dust collection, consistent high pollutant concentrations, which influence the performance of the sensors over time. Therefore, when choosing sensors, the expected lifespan of the sensors must be given together with recommendations on how to prevent quick deterioration of the components of the sensors and/or alert users if maintenance is necessary. If possible, the age of the sensors should always be indicated in the user interface of the data visualisation platform provided. Ideally, the sensor age is recalculated based on internal diagnostics (age, pollutant levels, etc.).

3. Maintenance and calibration

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The LCS devices should require simple and minimal maintenance (charging, re-establishing wireless connection for data transmission through rebooting or resetting, etc.). Manual calibration should not be done by the user (unless the purpose of the monitoring requires high level data processing of the advanced user). The system should include a flagging or alert system for when the sensors must be recalibrated. The user must then be provided information on how to send the devices back to the manufacturer for sensor calibration.

4. Ease of use

First and foremost, the LCS device must come with a user-friendly manual where instructions are provided as texts and images and in the most relevant language. The sensors should be plug and play, and instructions on how they should be installed/placed provided clearly. Secondly, the user interface included (app or web widget) should be intuitive from installation or registration to daily use.

5. Data accessibility, visualisation and user communication

Like most things these days, there is usually a mobile application or at the very least, a web-based dashboard provided with the device. When choosing the sensors, the user must consider several things about the data. First and foremost, data transmission and privacy. More often than not, the devices connect wirelessly over the internet and transmit the data to the cloud/server of the sensor provider. The user must be aware of which kinds of data beyond air quality they are agreeing to be transmitted (addresses, user details, etc.) as well as the level of access of other users. The sensor provider must be explicitly transparent about data use and privacy. Secondly is data frequency – or how fast the sensors are measuring and how often is it transmitting the data to be visualised. As is best, the higher the time resolution, the better. A highly active indoor space can have fast-changing levels of pollutant concentrations and conditions (T and RH) and having a high time resolution of measurements can lead to more accurate attribution of pollution levels to sources/sinks. Thirdly, known thresholds of pollutant concentrations should be included in the visualisation either through the graphics or through alert systems to better inform the user of the current air quality status and mitigate it. Fourthly, the visualisation should be suitable for the type of user. For instance, a regular user who is only concerned about whether the IAQ is bad or not could be shown indicators either through colours of LEDs or warning emojis in the app. For more advanced user interested in trends related to activities, a line graph showing the time series of the pollutant concentration should be shown. Finally, user communication through

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an interface must be intuitive for both sides. Any malfunctions in the device must be flagged and communicated to the user either through the device if it has a screen or any indicators, or through the app or web interface. The manual should contain a table of any error indicators, what they mean, and what the user should do. On the other side, if user participation is included, the information the user put in must come from a controlled list of options for simpler user experience and easier data interpretation afterwards.

B. Logistical factors

1. Cost

LCS devices may contain pollutant sensors that are <100 Euros, but equipped with communication devices, housing, cloud, app, or web interface, the whole monitoring system could cost between 500 Euros to 5,000 Euros. Depending on the goals, the user must find a balance between cost, needs, and data quality. If the goal is to comply with certain building regulations for occupational safety, we recommend going for more reliable types of sensors with a robust system setup. The same goes for monitoring indoor air exposure of vulnerable groups (hospital rooms, care homes for the elderly, students, etc.)

2. Installation requirements

We recommend LCS devices that are easy to install (free-standing or wall-mounted, depending on the configuration of the sensors inside the device) and avoid ones that must be installed on the ceiling. Battery operated ones are preferable so that they can be placed appropriately in a room without worrying about cables and distance to power sockets. It must be rechargeable via USB and can operate through long periods in between charging. For devices which must be powered, the cable length must be enough to allow the user freedom for proper placement of the device.

3. For coupled outdoor monitoring: weather proofing

If the user wants to couple the indoor LCS device with an outdoor one, the user must make sure that the outdoor sensor is built against the elements – robust and completely waterproof. The part that is open to the air to reach the sensor must also be protected from accumulation of dust and must be regularly checked for debris which can block the flow of air. A metallic housing works best, although it will inhibit data transmission.

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#### 4.1.2.3 Validating sensors

These guidelines for high-level users of the data from either a single sensor or a network of low-cost sensors (scientists, environment agencies, etc.).

There are two primary methods used for the evaluation (and calibration) of the LCS according to the U.S EPA: (1) "base" testing wherein sensors are collocated with the regulatory-grade instruments and (2) "enhanced" testing wherein sensors tested in a laboratory using samples of known concentrations and properties in controlled chambers (Duvall, 2021).

These recommendations are followed by EDIAQI and adapted to the scientific questions of the project.

Three rounds of intercomparison experiments are recommended to evaluate and track the performance of the sensors throughout the project, which will allow for better calculation of the calibration factors necessary for high quality data.

**First Round**

Prior to deployment, the sensors must be evaluated in two scenarios (when possible and if necessary) with the following guidelines:

1. Laboratory testing

When possible, it is recommended to send the sensors to facilities such as a controlled chamber capable of testing the sensors. Ideally, sensors companies have already done this prior. The sensors should be tested based on the following parameters:

- Unit-to-unit variability.
- Intercomparability against reference instruments (or research-grade instruments).
- Detection of varying aerosol types, composition, and size distribution.
- Ability to detect varying concentration levels.
- Sensitivity to relative humidity and temperature.

Considerations:

- Collocation of at least 3 sensors simultaneously.
- The duration of the collocation with reference instruments depends on time resolution:
    - 24-hour data = around 30 days (e.g. for gravimetric analysis of PM mass, which is the reference, data is usually daily averages).

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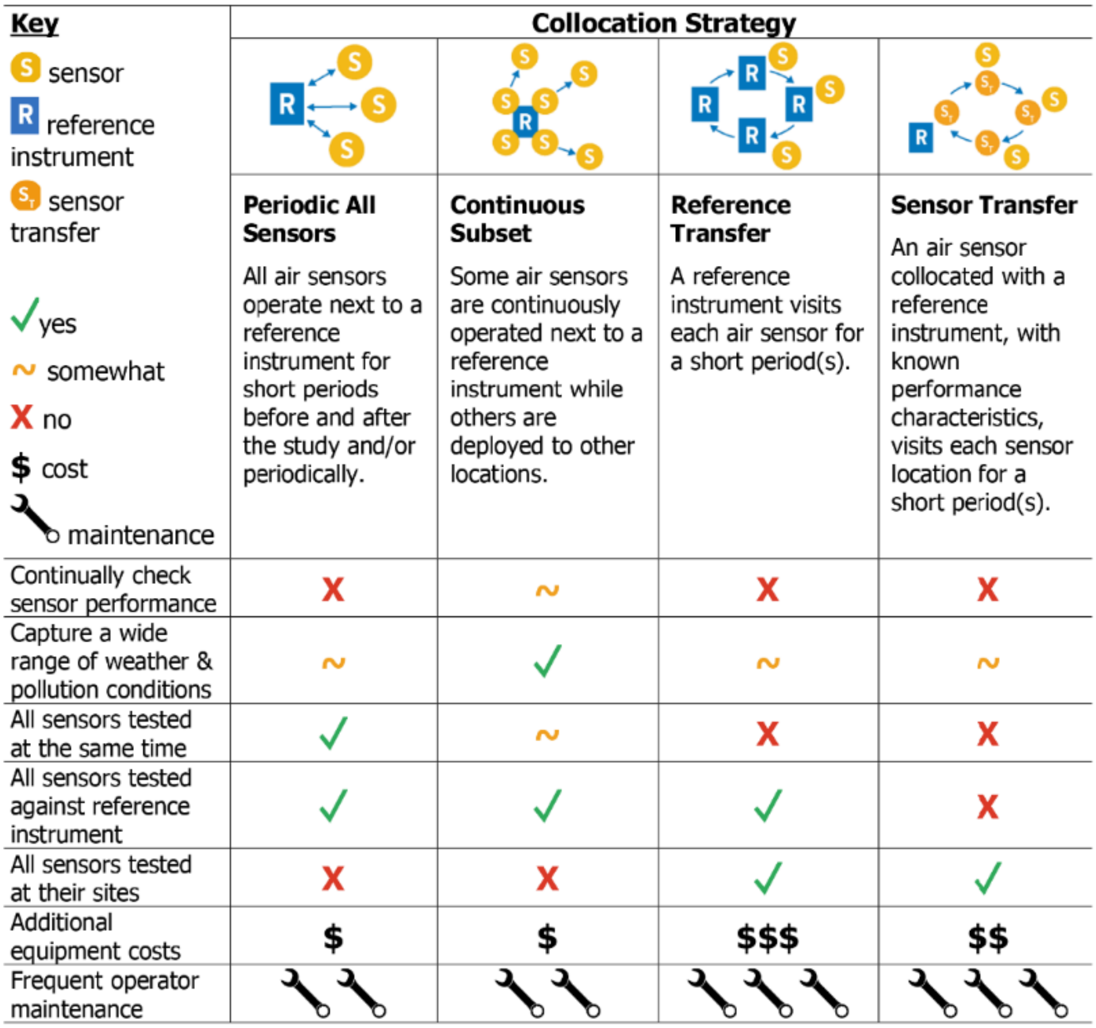
    - 1-hour data = around 14 days.
    - 5-minute data = around 7 days.
- There should be > 75% data completeness threshold.
- The concentration should reach higher levels at least 1 day (e.g. for $PM_{2.5}$: > 25 $\mu g/m^3$ (Zimmerman, 2022).
- There should be a minimum of 20 pairs of time-matched values between LCS and reference data points or 3 consecutive hours of stable data.

2. Field testing

According to the U.S. EPA Enhanced Air Sensor Guidebook (Duvall, 2022), there are four collocation strategies with reference instruments summarized in Figure 18.



| Key: S sensor; R reference instrument; $S_T$ sensor transfer; ✓ yes; ~ somewhat; X no; $ cost; 🔧 maintenance | Collocation Strategy | | | |
|---|---|---|---|---|
| | **Periodic All Sensors** All air sensors operate next to a reference instrument for short periods before and after the study and/or periodically. | **Continuous Subset** Some air sensors are continuously operated next to a reference instrument while others are deployed to other locations. | **Reference Transfer** A reference instrument visits each air sensor for a short period(s). | **Sensor Transfer** An air sensor collocated with a reference instrument, with known performance characteristics, visits each sensor location for a short period(s). |
| Continually check sensor performance | X | ~ | X | X |
| Capture a wide range of weather & pollution conditions | ~ | ✓ | ~ | ~ |
| All sensors tested at the same time | ✓ | ~ | X | X |
| All sensors tested against reference instrument | ✓ | ✓ | ✓ | X |
| All sensors tested at their sites | X | X | ✓ | ✓ |
| Additional equipment costs | $ | $ | $$$ | $$ |
| Frequent operator maintenance | 🔧🔧 | 🔧🔧 | 🔧🔧🔧 | 🔧🔧🔧 |

Figure 18 – Figure 3-9 taken from the U.S. EPA Enhanced Air Sensor Guidebook (2022)

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Any of these strategies may be used according to the capacities of the sensor users/stakeholders. Whichever strategy is employed, all the considerations mentioned above are also applicable together with the additional considerations:

- This should be done in a location most representative of the targeted study area.
- Locate the LCS as close as possible to the appropriate reference instruments.
- For outdoor, the period of collocation should allow for characterisation of the LCS response to full (or at most) range of meteorological conditions.
- Place the sensors at least 1 meter from each other.
- The sensors should be within 1-meter vertical distance from the inlet of the reference instrument.
- Monitor meteorological conditions during collocation (T, RH, wind speed and direction).
- For field testing without reference instruments, place the LCS at a height of 1-2 meters which is considered a "breathing zone".

**Second Round**

This round will occur in the middle of the pilots and campaigns – around 6 months into the measurements. The purpose of this is the following:

- Impact of sensor age on sensor performance.
- Characterisation of the actual sensors used based on the parameters of the first round.
- More statistically significant unit-to-unit variability.
- Intercomparison of all units against reference instrumentation in the laboratory and in the field.
- Determination of calibration factors for the sensors.

Pilot and campaign partners perform their own field unit-to-unit intercomparison by placing all sensors in one location with a uniform pollutant profile over a period with a wide range of concentrations possible (Friday – Saturday or Sunday to Monday).

Advantages:

- Shorter disruption of the measurements (no time wasted on shipping) which means lesser burden to the subjects.
- Lesser risk of damaging sensors during transport.

- Sensors are characterised based on the specific pollutant profile of the study area.

Disadvantages:

- Lack of intercomparison against reference instruments for some pilots and campaigns.
- No full characterisation of sensors.

**Third Round**

This round will be done at the end of the pilots and campaigns. We recommend the following:

1. Pilots and campaigns to perform a final unit-to-unit intercomparison in the field in the same manner as recommended in the first two rounds.
2. All sensors should be sent to TROPOS and IMROH for final round of tests based on the same parameters in First and Second rounds.

The main outputs of this round are final calibration factors to be recommended to the pilots and campaigns.

**IMPORTANT**: If some sensors are found with issues, please contact the sensor providers right away. All sensor providers must be immediately reachable during the pilots and campaigns.

#### 4.1.2.4 Network set-up and sensor placement

**Measurement network of LCS**

The design of the measurement network and the strategic placement of measurement points rely heavily on scientific goals. Here, "measurement network" can refer to two different spatial scales: one that covers a large spatial coverage (a city), or one that is focused on different points in a smaller area such as a building or a closed compound (a campus, office compound, etc.).

Generally, the recommendations can be categorised based on two targets: the locations and the occupants.

- Location-centred

Location-centred measurement networks refer to those with scientific goals focused on covering different indoor spaces (schools, government offices, residential areas, entertainment, public transport, etc.). Most commonly, the following external factors will be analysed to determine how they affect IAQ across these spaces:

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- proximity to outdoor sources and sinks;
- a variety of outdoor sources;
- meteorology;
- orientation/building layout.

Therefore, recommendations for this category include strategic selection of buildings and the actual placing of the sensors within the subjects' indoor space.

- Occupant-centred

Occupant-centred measurement networks refer to those with scientific goals focused on pre-determined human subject such as those participating in epidemiological studies. Here, the locations of the sensors across the city/study area do not are given by the households of the subjects. Therefore, recommendations are focused on the actual placing of the sensors within the subjects' indoor space.

The following recommendations are general to cover both targets.

#### 4.1.2.5 Selecting locations for measurement network

**Scientific considerations**

1. Representativeness

The measurement network should be designed to get the highest level of representativeness. Representativeness means that the measurements collected will reflect the actual situation of the study area/population. The chosen buildings (classrooms, office spaces, etc.) should represent what is typical in the study area in terms of age of buildings, materials used, etc. On a small scale, sensors should be placed away from irrelevant and/or hyperlocal sources and sinks which can influence the data such as smoking areas, grilling areas, ventilation exhausts, trees and bushes, air filters, etc. However, if the target is source apportionment like determining the contribution of traffic to indoor spaces, then the outdoor sensor should be placed downwind of the trafficked area without obstructions. For comparison of the indoor counterpart, the LCS must be installed in rooms with windows and doors facing the flow of the targeted outdoor source and as well as those that do not for comparison. For human exposure studies in indoor spaces, LCS should be installed in spaces occupied by a wide range of population groups (socioeconomic conditions, etc.) with several representatives of each. In the case of studies focused on a specific group (children or elderly), the LCS should be deployed in areas where most of the population gathers, or at locations with a wide range of population characteristics (children living in urban vs rural areas). For exposure of school children, the WHO recommends the sampling in at least 3 classrooms and selecting them based on how representative they are of the school building, how often are they used during school hours, their location on different floors, their orientation with respect to outdoor sources (traffic) and how long have they have been in use (if the goal is to avoid emissions from new building materials, the classroom should not have been used less than 6 months).

2. Measurement period and duration

When the LCS will be deployed also depends highly on the science question. For instance, if the target is to evaluate the effect of mitigation efforts, then the LCS will have to be deployed before and operate until after the event. Likewise, the measurement period could also depend on the season which will impact the measurements significantly, particularly sensors and pollutants with high sensitivities to meteorological factors such as humidity and temperature. Another example is investigating the exposure to school children. It is recommended to deploy the LCS prior to the beginning of classes (or during school breaks) to get a baseline of the pollution level indoors without occupants and afterwards.

3. Proximity to monitoring networks and reference instruments

When possible, it is highly recommended to have 1 or more sensors as close as possible to an existing monitoring station with reference instruments.

**Logistical considerations**

1. Capacity – As much as the number of sensors deployed depends on the scientific goals, it is also important to consider the capacity of the user(s). When designing a network of LCS, the amount of work needed for installation, maintenance, troubleshooting, and data evaluation must be considered prior to deployment.
2. Power – LCS must be deployed at locations with stable power supply, ideally without the need for an extension (can interfere with measurements). The power cable should also be covered by a power strip to prevent accidental unplugging of the device.
3. Communications – One of the main advantages of LCS is that the data are readily available through the Internet of Things (IoT). Therefore, connectivity is of utmost importance. The best option is through Wi-Fi connectivity. This provides a continuous and stable connection to the internet, allowing for a steady stream of data. Wi-Fi is also the best option for indoor LCS, especially those located in parts of the indoor space with

limited access to cellular network via sim card (such as basements). Outdoor LCS on the other hand may be equipped with a sim card but monitoring of data usage and uploading of more credits should be done automatically and remotely.

4. Accessibility – Albeit built for unsupervised operation, LCS may need care from time to time. Therefore, the sensors must be placed where they can be easily accessed by users (household occupants or researchers) for minimal disturbance of dwellers during troubleshooting.
5. Security – The LCS must be placed in areas which are tamper resistant and safe to install, inspect, and access.

#### 4.1.2.6 Selecting measuring points within and around an indoor space

**Scientific considerations**

1. Placement

Indoor sensors:

- Vertical placement – LCS must be placed at a height within the breathing zone (1-2 m). However, this can vary depending on the target population. For instance, when considering school children, the breathing zone can mean the average height when students are seated. For children's sleeping rooms, the height can be even lower, considering a typical bed height and lying position.
- Horizontal placement – the LCS must be out in the open. Granted that the centre of the room may not be suitable in all scenarios, at the very least, the LCS must be where people spend their time and not be hidden behind furniture or walls. There should be free airflow to the sensor, ideally 180 – 270 degrees of unobstructed flow.
- Proximity to sources and sinks – the LCS must be kept away from hyperlocal sources which could overestimate the exposure (directly above cooking devices, altars, chalkboards, etc.) or sinks which could underestimate the exposure (air filters, etc.). LCS must also be placed away from heaters, ventilation, air conditioning systems, which could rapidly change RH and T and influence sensors.

Outdoor sensor(s):

- Vertical placement – the outdoor LCS must be placed at a height within the breathing zone (1-2 m).

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- Horizontal placement – the outdoor LCS must be out in the open with free airflow to the sensor, ideally 180 – 270 degrees of unobstructed flow.
- Proximity to sources and sinks – the outdoor LCS must be kept away from hyperlocal sources which could overestimate the exposure (smoking areas, bus stops, grilling, unless these are targeted sources) or sinks which could underestimate the exposure (vegetative barriers). The flow of the targeted emission source (traffic) to the LCS should not be obstructed by other structures.

2. Identification of sources (indoor and outdoor)

The possible sources and sinks of the area where sensors will be placed must be thoroughly identified and recorded during the measurement period. This will contribute significantly to the subsequent interpretation of the data. This could also include cleaning routines and cleaning products used.

### 4.1.3 The emerging pollutants

#### 4.1.3.1 UFPs and BC

UFPs and BC are two important emerging pollutants that are currently being pushed by the scientific community to be included in the list of regulated air pollutants for outdoor ambient air because of their health effects and because they originate from combustion sources. Several studies (Zhao et al., 2021; Zhao et al., 2020; Manigrasso et al., 2018; Manigrasso et al., 2017) have shown that these two pollutants are also prevalent in indoor spaces, particularly during household activities that involve combustion – incense and candle burning and cooking activities. Zhao et al. (2020) presented methods of measuring UFPs and BC in indoor settings which involved an MPSS measuring particles from 10–800 nm and a microAethalometer AE51 for BC. The setup with the MPSS allows for the high-quality data of UFPs but uses a radioactive material to charge the nanoparticles, allowing them to be sized correctly. The system is also big, loud (with pumps), and expensive making it unsuitable for prolonged indoor air measurements. On the other hand, the BC monitor AE51 is a robust, portable, mid-cost instrument that has been extensively characterised in the field (Alas et al., 2020) and is widely used for personal exposure studies including indoor spaces. For future studies, the AE51 (or the newer models such as MA200 (Good et al., 2017)) is still a highly recommendable device for monitoring BC mass concentrations in indoor spaces. They are small, quiet, and can measure at really high time resolution (every

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second) – capturing the highly variable nature of indoor spaces. As for online measurements of UFP, we recommend using a naneos Partector which is a relatively new, mid-cost and portable UFP monitor device in the field and has also been evaluated but mostly for outdoor applications (Bezantakos et al., 2024).

#### 4.1.3.2 Radon

When measuring indoor radon activity concentration, the architectural characteristics of the building (crawl space, basement, multiple storeys, earthen floor, building materials, etc.) and the room characteristics should be considered. The detector should be placed at a height of approximately 1–1.5 m on the furniture (e.g., wardrobe, bookshelf, rack, etc.), and 20 cm of free space should be left around the detector. If a single-owned dwelling has multiple floors, it is recommended to set multiple detectors on different floors.

#### 4.1.3.3 Microplastics

The presence of microplastics in indoor environments is an emerging concern due to their potential adverse health effects, particularly through inhalation. Research on the toxicity of microplastics and their impact on human health is still evolving. However, several key points should be considered. Microplastics can act as a carrier for pathogenic and antibiotic-resistant microorganisms by sorbing persistent organic pollutants and/or toxic metals from environmental matrices.

#### 4.1.3.4 Microbiomes

Indoor dust microbiome includes different fungi and bacteria (mostly gram-positive bacteria). Molecular methods such as next generation sequencing is used for identifying and tracking the bacterial and fungal diversity in dust samples. For that purpose, 16S ribosomal RNA gene (16S rRNA gene) (V3-V4 region) and internal transcribed spacer (ITS) amplicon (ITS2 region) are commonly analysed.

### 4.2 Guidelines on stakeholder participation and data visualisation

In this subchapter, we offer recommendations/guidelines on how best to engage local actors and how to communicate IAQ data to them through appropriate visualisation of IAQ data. This guideline outlines recommendations for engaging stakeholders, feedback collection, data visualisation, and data communication with users as illustrated in Figure 19 based on best practices according to literature review and preliminary lessons learned from the QR code experiments in EDIAQI.

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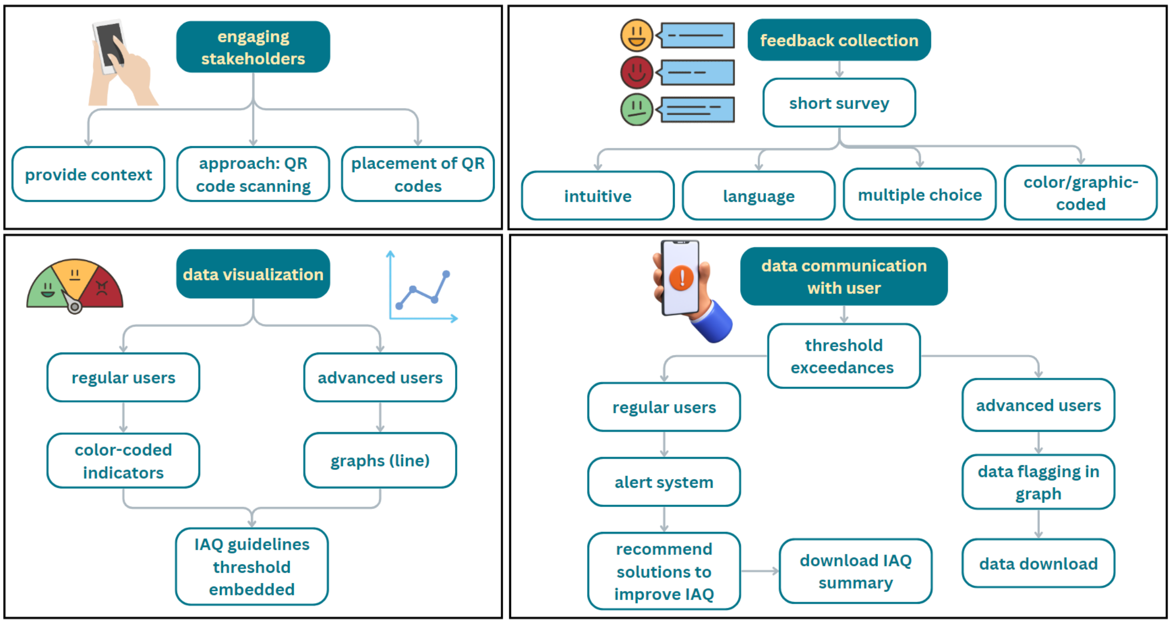


Figure 19 Overview of the guidelines/recommendations on engaging and communicating with stakeholder on IAQ

### 4.2.1 Engaging stakeholders

Stakeholder participation is an essential aspect in understanding IAQ. When monitoring IAQ, knowing how the indoor space dwellers (stakeholders) behave indoors and which activities they perform provide invaluable information when analysing the dynamics of IAQ, determining how dwellers perceive IAQ, and raising awareness. Prior to any IAQ monitoring, we recommend laying a strong foundation to ensure maximum stakeholder participation through provision of the context/introduction of the monitoring and other activities. This can be done through public seminars and/or infographics displayed in and around the indoor space being monitored. For the actual stakeholder engagement, the use of QR codes is recommended and has been proven to result in a higher response rate than the normal pen-and-paper method (Fishbein et al., 2019; Pérez-Sanagustín et al., 2016). Within EDIAQI, particularly in schools in the Estonia pilot, we learned that placing the QR codes as stickers on the desks of the students/participants resulted in a better response rate than having as posters on the doors of the rooms.

### 4.2.2 Feedback collection

When collecting feedback, short surveys are better than longer ones because the lesser the work/activity, the more willing people participate. We recommend having the survey as short as possible (max 2 questions) with predetermined answers given as choices in the

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preferred language of the participants (usually local language). To make it as intuitive as possible, we recommend including graphical or color-coded descriptions of the choices.

#### 4.2.3 Data visualisation

The way the IAQ data is visualised (in an app or web interface) can vary depending on the stakeholder. Based on the review carried out by TROPOS, we recommend for regular users, those who wish to have minimal but intuitive information, colour-coded graphics or indicators would suffice. This means that known thresholds of different pollutants are binned into colours to inform the user if the limits have been exceeded. For more advanced users who require more details, particularly in tracing the sources of IAP, a simple graphical line chart would be effective, particularly if the advanced user is also recording time-activity patterns. Similarly, we also recommend embedding the pollutant limits/thresholds in the line graph either by indicating the limits as a static horizontal line and/or varying the line colour based on ranges of pollutant concentrations.

#### 4.2.4 Data communication with user

Communicating with the user is an essential part of IAQ monitoring as it happens during the entire life cycle of the IAQ monitoring from providing static information about the indoor space being monitored through an app to informing the user of worsening air quality. Here, we cover the part when threshold exceedances. Similar to data visualisation, communication should also be customized based on the user. For regular user, when thresholds are exceeded, they should be alerted either visually or aurally. We recommend following this up with suggested actions to improve IAQ. For instance, if the limit of the $CO_2$ level has been reached and the user has been alerted or notified, increasing ventilation through opening of window or turning on of ventilation systems can be recommended. We also suggest regularly providing the user a summary (for a specific or several time intervals) of IAQ. For more advanced users, on top of the alert system, the threshold exceedances should be flagged in the data (time stamped in the data downloaded) and in the graphical visualisation.

In conclusion, monitoring IAQ goes beyond the technical and scientific aspects of IAP and should include understanding the stakeholders through appropriate engagement activities, data visualisation and communication. Finally, we also recommend further improving the recommendations and guidelines presented here to be more inclusive, for example, by having auditory options for visually challenged stakeholders.

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# Annexes

## Annex 1 – Indoor Air Guide Values from UBA, 2023

In 2023, the German Committee on Indoor Air Guide Values (AIR) has set guide values for indoor air pollutants. These values are either health-based or risk-related. The tables shown in this annex are publicly available and downloadable from:

German Committee on Indoor Air Guide Values (AIR)

**AIR Guide Values I and II for indoor air pollutants**

Version: 2023.01 (March 31, 2023)

**Indoor air guide values derived by the German Committee on Indoor Air Guide Values (AIR)**

| Name | CAS No. | Year[2] | GV II | GV I | Unit | Remarks[3] |
|---|---|---|---|---|---|---|
| **Aldehydes** | | | | | | |
| Formaldehyde | 50-00-0 | 2016 | - | 0.10 | mg/m³ | |
| Acetaldehyde | 75-07-0 | 2013 | 1.0 | 0.10 | mg/m³ | |
| 2-Furaldehyde | 98-01-1 | 2011 | 0.10 | 0.010 | mg/m³ | |
| Benzaldehyde | 100-52-7 | 2010 | 0.20 | 0.020 | mg/m³ | V |
| ∑ $C_4$-$C_{11}$ Aldehydes [1] | various [1] | 2009 | 2.0 | 0.10 | mg/m³ | G |
| **Aliphatic hydrocarbons** | | | | | | |
| ∑ $C_9$-$C_{14}$-Alkanes / Isoalkanes [1] | various [1] | 2005 | 2.0 | 0.20 | mg/m³ | G |
| **Alcohols** | | | | | | |
| 1-Propanol | 71-23-8 | 2022 | 46 | 14 | mg/m³ | |
| Methanol | 67-56-1 | 2022 | 40 | 13 | mg/m³ | 60 min |
| 2-Propanol | 67-63-0 | 2021 | 45 | 22 | mg/m³ | |
| Propan-1,2-diol | 57-55-6 | 2017 | 0.60 | 0.060 | mg/m³ | |
| 1-Butanol | 71-36-3 | 2014 | 2.0 | 0.70 | mg/m³ | |
| 2-Ethylhexanol | 104-76-7 | 2013 | 1.0 | 0.10 | mg/m³ | V, S |
| Benzyl alcohol | 100-51-6 | 2010 | 4.0 | 0.40 | mg/m³ | |
| **Aromatic hydrocarbons** | | | | | | |
| ∑ $C_7$-$C_8$ Alkyl benzenes | various [1] | 2016 | 1 [1] | 1 [1] | - | G, R |
| Toluene | 108-88-3 | 2016 | 3.0 | 0.30 | mg/m³ | |
| ∑ Xylenes | various [1] | 2015 | 0.80 | 0.10 | mg/m³ | G |
| ∑ Naphthalene and naphthalene-like subst. | various [1] | 2013 | 30 | 10 | µg/m³ | G |
| Ethylbenzene | 100-41-4 | 2012 | 2.0 | 0.20 | mg/m³ | |
| ∑ $C_9$-$C_{15}$ Alkyl benzenes | various [1] | 2012 | 1.0 | 0.10 | mg/m³ | G |
| ∑ Cresols | various [1] | 2012 | 50 | 5.0 | µg/m³ | G |

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| | | | | | | |
|---|---|---|---|---|---|---|
| Phenol | 108-95-2 | 2011 | 0.20 | 0.020 | mg/m³ | |
| Styrene | 100-42-5 | 1998 | 0.30 | 0.030 | mg/m³ | |
| **Carboxylic acids** | | | | | | |
| Methanoic acid | 64-18-6 | 2023 | 1.0 | 0.51 | mg/m³ | |
| Ethanoic acid | 64-19-7 | 2023 | 3.7 | 1.3 | mg/m³ | |
| Propionic acid | 79-09-4 | 2023 | 1.6 | 0.78 | mg/m³ | |
| **Esters** | | | | | | |
| Methyl methacrylate | 80-62-6 | 2021 | 2.1 | 1.1 | mg/m³ | |
| Ethyl acetate | 141-78-6 | 2014 | 6.0 | 0.60 | mg/m³ | |
| Tris(2-chloroethyl) phosphate (TCEP) | 115-96-8 | 2002 | 50 | 5.0 | µg/m³ | |
| **Glycols / Glycol ethers / Glycol esters** | | | | | | |
| 2-Phenoxyethanol | 122-99-6 | 2018 | 0.10 | 0.030 | mg/m³ | |
| Ethylene glycol monomethyl ether (EGME) | 109-86-4 | 2013 | 0.20 | 0.020 | mg/m³ | |
| Diethylene glycol methyl ether (DEGME) | 111-77-3 | 2013 | 6.0 | 2.0 | mg/m³ | V |
| Diethylene glycol dimethyl ether (DEGDME) | 111-96-6 | 2013 | 0.30 | 0.030 | mg/m³ | |
| Ethylene glycol monoethyl ether (EGEE) | 110-80-5 | 2013 | 1.0 | 0.10 | mg/m³ | |
| Ethylene glycol monoethyl ether acetate (EGEEA) | 111-15-9 | 2013 | 2.0 | 0.20 | mg/m³ | V |
| Diethylene glycol monoethyl ether (DEGEE) | 111-90-0 | 2013 | 2.0 | 0.70 | mg/m³ | V |
| Ethylene glycol butyl ether (EGBE) | 111-76-2 | 2013 | 1.0 | 0.10 | mg/m³ | |
| Ethylene glycol butyl ether acetate (EGBEA) | 112-07-2 | 2013 | 2.0 | 0.20 | mg/m³ | V |
| Diethylene glycol butyl ether (DEGBE) | 112-34-5 | 2013 | 1.0 | 0.40 | mg/m³ | V |
| Ethylene glycol hexyl ether (EGHE) | 112-25-4 | 2013 | 1.0 | 0.10 | mg/m³ | |
| Propylene glycol methyl ether (2PG1ME) | 107-98-2 | 2013 | 10 | 1.0 | mg/m³ | |
| Dipropylene glycol monomethyl ether (D2PGME) | 34590-94-8 | 2013 | 7.0 | 2.0 | mg/m³ | V, S |
| Propylene glycol monoethyl ether (2PG1EE) | 1569-02-4 | 2013 | 3.0 | 0.30 | mg/m³ | |
| Propylene glycol 1-tert-butyl ether (2PG1tBE) | 57018-52-7 | 2013 | 3.0 | 0.30 | mg/m³ | |
| Default-value: Glycol ether [1] | various [1] | 2013 | 0.050 | 0.0050 | ppm | V, [4] |
| ∑ Glycol ethers | various [1] | 2013 | 1 [1] | 1 [1] | - | R |
| **Halogenated hydrocarbons** | | | | | | |
| Tetrachloroethene | 127-18-4 | 2017 | 1.0 | 0.10 | mg/m³ | |
| 2-Chloropropane | 75-29-6 | 2015 | 8.0 | 0.80 | mg/m³ | |
| Polychlorinated biphenyls (PCB) [1] | various [1] | 2007 | [1] | [1] | mg/m³ | G |
| Dichloromethane | 75-09-2 | 1997 | 2.0 | 0.20 | mg/m³ | 24 h |
| Pentachlorophenol (PCP) | 87-86-5 | 1997 | 1.0 | 0.10 | µg/m³ | |
| **Ketones** | | | | | | |
| Acetophenone | 98-86-2 | 2022 | 220 | 66 | µg/m³ | |
| Acetone | 67-64-1 | 2021 | 160 | 53 | mg/m³ | |

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| | | | | | | |
|---|---|---|---|---|---|---|
| Methyl isobutyl ketone | 108-10-1 | 2013 | 1.0 | 0.10 | mg/m³ | |
| **Terpenes** | | | | | | |
| ∑ Monocyclic monoterpenes (limonene)[1] | 5989-27-5 | 2010 | 10 | 1.0 | mg/m³ | S, L |
| ∑ Bicyclic terpenes (α-pinene, ß-Pinen, 3-Caren) [1] | various [1] | 2003 | 2.0 | 0.20 | mg/m³ | L |
| **Others** | | | | | | |
| Benzothiazole | 95-16-9 | 2020 | - | 15 | µg/m³ | V |
| Nitrogen dioxide | 10102-44-0 | 2018 | 0.25 | 0.080 | mg/m³ | 60 min |
| 2-Butanone oxime | 96-29-7 | 2015 | 60 | 20 | µg/m³ | |
| 1-Methyl-2-pyrrolidone | 872-50-4 | 2014 | 1.0 | 0.10 | mg/m³ | |
| ∑ Cyclic dimethylsiloxanes $D_3$-$D_6$ | various [1] | 2011 | 4.0 | 0.40 | mg/m³ | G |
| ∑ Diisocyanates [1] | various [1] | 2000 | [1] | [1] | mg/m³ | G |
| Mercury (as metallic vapour) | 7439-97-6 | 1999 | 0.35 | 0.035 | µg/m³ | |

Source: German Environment Agency (UBA)

The values in the current corresponding publications are valid.

Values correspond to the AIR rounding rules for indoor air guide values, March 2020.

[1] See corresponding publication

[2] Year of publication in Bundesgesundheitsblatt

[3] Remarks: G (details on substance spectrum see in the respective publications); L (guiding substance); R (∑Ri = Ci/RWi);
S (value referes to stereoisomers mixtures as for single stereoisomers); V (preliminary); times given for averaging periods deviate from the usual long-term value

[4] Conversion factors for ppm in mg/m³ or µg/m³ see corresponding publication

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**Hygienic guide values from the German Committee on Indoor Air Guide Values**
**Status: July 2022**

**Hygienic guide values for carbon monoxide (2021)[1)]**

| | 15 minutes | 1 hour | 8 hours | 24 hours |
|---|---|---|---|---|
| Hygienic guide values [mg/m$^3$] | 100 | 35 | 10 | 4 |

1) The German Committee on Indoor Air Guide Values accepts the hygienic guide values for CO from the World Health Organization (WHO, 2021) derived in the WHO Guidelines for Indoor Air Quality.

Source: German Environment Agency

**Hygienic guide values for carbon dioxide (2008)**

| $CO_2$-concentration (ppm) | Hygienic assessment | Recommendation |
|---|---|---|
| ‹ 1000 | hygienically safe | no action |
| 1000–2000 | hygienically noticeable | Ventilation (outdoor air flow rates or rather increasing air change) proof of ventilation habits and improvement |
| › 2000 | hygienically unacceptable | Proof for options of ventilation, proof for further measures |

Source: German Environment Agency

**Hygienic guide values for particulate matter in indoor air (2021)[1)]**

| concentration [µg $PM_{2,5}$/m$^3$] | Hygienic assessment |
|---|---|
| 15 µg/m$^3$ | The 24-hour mean value applies only for clean indoor spaces with absence of relevant indoor air sources of dust |

1) The German Committee on Indoor Air Guide Values accepts the hygienic guide values for CO from the World Health Organization (WHO, 2021) derived in the WHO Guidelines for Indoor Air Quality.

Source: German Environment Agency

**Hygienic guide values for TVOC in indoor air (2007)**

| Stage | concentration level [mg TVOC/m$^3$] | Hygienic assessment |
|---|---|---|
| 1 | ≤0,3 mg/m$^3$ | hygienically safe |
| 2 | 0,3 - 1 mg/m$^3$ | hygienically still safe, if indoor air guide values are not exceeded for single substances or substance groups |
| 3 | 1 - 3 mg/m$^3$ | hygienically noticeable |
| 4 | 3 - 10 mg/m$^3$ | hygienically alarming |
| 5 | ›10 mg/m$^3$ | hygienically unacceptable |

Source: German Environment Agency

**Risk-related or preliminary guide values**[1, 2]

| Substance | risk-related or preliminary guide value [µg/m³] | Year of derivation |
|---|---|---|
| **Vinyl chloride** | 2,3 | 2021 |
| **Benzo[*a*]pyrene** | 0,0008 (v) | 2021 |
| **Benzene** | 4,5 (v) | 2020 |
| **1,2-dichloroethane** | 1,0 (v) | 2018 |
| **Trichloroethylene** | 20 | 2015 |

[1)] According to the amendment of the basic scheme for carcinogenic substances in indoor air.
[2)] Values correspond to the AIR rounding rules for indoor air guide values, March 2020.
(v) preliminary

Source: German Environment Agency

Odour guide values (OGV) from the German Committee on Indoor Air Guide Values (AIR), August 2023.

| Name | CAS No. | Year | ODT | $K_W$ | OGV | Unit | Annotation[1] |
|---|---|---|---|---|---|---|---|
| **Acetone** | 67-64-1 | 2023 | 24,69 | 2,51 | **250** | mg/m³ | A, GV |
| **Acetophenone** | 98-86-2 | 2023 | 2,9 | 2,83 | **22** | µg/m³ | A, GV |
| **Benzothiazole** | 95-16-9 | 2023 | 3,4 | 1,95 | **66** | µg/m³ | A, GV |
| **2-Butanone oxime** | 96-29-7 | 2023 | 0,27 | 3,27 | **1,6** | mg/m³ | M, GV |
| **Butyric acid** | 107-92-6 | 2023 | 1,1 | 2,27 | **14** | µg/m³ | M |
| **Caprolactam** | 105-60-2 | 2023 | 0,32 | 3,04 | **2,0** | mg/m³ | A |
| **Acetic acid** | 64-19-7 | 2023 | 21 | 1,95 | **400** | µg/m³ | M, GV |
| **2-Ethylhexanol (Racemate – 1:1 (R)- or (S)-2-Ethylhexanol)** | 104-76-7 | 2023 | 0,098 | 2,23 | **1,3** | mg/m³ | A, GV |
| **Hexanoic acid** | 142-61-1 | 2023 | 0,016 | 2,56 | **0,15** | mg/m³ | M |
| **Hexanal** | 66-25-1 | 2023 | 3,2 | 2,74 | **26** | µg/m³ | A, GV |
| **m-cresol** | 108-39-4 | 2023 | 0,3 | 2,28 | **3,2** | µg/m³ | A, GV |
| **p-cresol** | 106-44-5 | 2023 | 0,4 | 2,10 | **5,6** | µg/m³ | A, GV |
| **Naphthalene** | 91-20-3 | 2023 | 1,0 | 2,86 | **7,3** | µg/m³ | A, GV |
| **1-Methylnaphthalene** | 90-12-0 | 2023 | 1,9 | 2,72 | **15** | µg/m³ | A, GV |
| **2-Methylnaphthalene** | 91-57-6 | 2023 | 1,6 | 3,31 | **8,9** | µg/m³ | A, GV |
| **1,4-Dimethylnaphthalene** | 571-58-4 | 2023 | 4,2 | 2,54 | **41** | µg/m³ | A, GV |
| **Nonanal** | 124-19-6 | 2023 | 2,2 | 2,99 | **15** | µg/m³ | A, GV |
| **Phenol** | 108-95-2 | 2023 | 14,2 | 3,40 | **77** | µg/m³ | A, GV |
| **2-Phenoxyethanol** | 122-99-6 | 2023 | 4,2 | 2,42 | **45** | mg/m³ | A, GV |
| **2,4,6-Trichloroanisole** | 87-40-1 | 2023 | - | - | **-** | µg/m³ | M, OGV will be revised |

Values correspond to the AIR rounding rules for indoor air guide values, March 2020 (German Committe on Indoor Air Guide Values (AIR), 2020).

[1]Annotation:
**A** – The $ODT_{50}$ was determined analytically, the values can be found in Table 128 in (UBA research project, 2020). If no value is given in the column „optionale Geruchsschwelle (analytisch)", the analytical concentration in the primary bag was divided by the mean odorant concentration (can be found in the respective substance specific chapters in (UBA research project, 2020)). Example acetone: 13899/563 = 24,69.
**M** – The $ODT_{50}$ was determined mathematically, the values can be found in table 128 in (UBA research project, 2020).
**GV** – Health-based indoor air guide values derived from the AIR are also available for this substance.

UBA research project (2020), Determination of odour detection thresholds for indoor pollutants (in German), final report, Environment & Health 04/2023, online: https://www.umweltbundesamt.de/publikationen/bestimmung-von-geruchswahrnehmungsschwellen-fuer

## Annex 2 – Stakeholder profiles: Experts

| Expert | Research Field |
|---|---|
| **Lidia Morawska** | air quality research, article on the Medical Journal of Australia about the need for improving indoor air |
| **Anette Peters** | health impacts of exposure to ambient particulate matter |
| **Tamara Schikowski** | environmental epidemiology particularly the effects of exposure to harmful pollutants of women and the elderly |
| **Gaelle Uzu** | oxidative potential of air pollutants and its health effects, particularly in pregnant women |
| **Colette Heald** | prediction of air quality extremes in a future climate |
| **Jos Lelieveld** | environmental science, air pollution and health effects |
| **Ulrich Pöschl** | atmospheric chemistry, interactions of aerosol and their effects on public health |
| **Shu Tao** | urban and environmental science and negative effects on public health |
| **Wolfram Birmili** | indoor and outdoor air quality monitoring and policy-making |
| **Catherine Noakes** | ventilation, indoor air quality and infection control in the built environment |
| **Juha Pekkanen** | indoor air exposures; microbes on respiratory health |
| **Ying Xu** | relationships among sources, indoor environments, and human health for indoor pollutants, especially semi-volatile organic compounds; president of international society of indoor air quality and climate |
| **Tunga Salthammer** | VVOC/VOC/SVOC emission studies on indoor materials using test chambers and cells, indoor chemistry, airborne particles, and settled dust. |
| **Giorgio Buonanno** | indoor air exposures, metrology of airborne particle measures and airborne transmission of respiratory pathogens. |

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## Annex 3 – Survey form for expert opinion on indoor air quality

### Questionnaire for identifying relevant air quality paraments for better health

Disclosure Agreement:

- ☐ Anonymous: I agree that my responses will be made publicly available EXCEPT MY IDENTITY.
- ☐ Named: I agree that my responses will be made publicly available INCLUDING MY IDENTITY.

1. What does the particle science state-of-the-art consider to be the most dangerous air quality parameters to date for children, elderly and pregnant women? Please list the parameters in the order of relevance with short justification.

2. What chemical and physical parameters should and could be measured in every indoor environment by 2050?

3. Where will the next scientific breakthrough be concerning air quality microparticles?

4. What are the biggest differences between Europe and the USA if it comes to legislation and definition of indoor and outdoor air pollution limits, what can the EU learn from the USA and vice versa?

5. How will climate change affect indoor and outdoor air quality state-of-the-art? What parameters should the scientific community start observing more closely as soon as possible?

TROPOS

Leibniz-Institut für Troposphärenforschung

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## Annex 4 – Collected feedback from experts

### 1. Expert opinion 1: Dr. Gaelle Uzu

**Questionnaire for identifying relevant air quality paraments for better health**

Thank you for agreeing to participate in this survey.

You have the option to make your answers anonymous. However, we highly regard it if you agree that your answers be publicly published on our project website.

Please
find 20 minutes to shortly write down your answers to the five questions below.

Please get back to us
latest by the end of April.

Name: *

Gaëlle Uzu

Work on air pollution *

- ○ air pollution measurement and monitoring
- ○ air pollution modelling
- ○ health effects of air pollution (epidemiology)

Institution: *

Institute for Environmental Geosciences (IGE, https://www.ige-grenoble.fr/?lang=en)

Disclosure Agreement *

- ☐ Anonymous: I agree that my responses will be made publicly available EXCEPT MY IDENTITY.
- ☑ Named: I agree that my responses will be made publicly available INCLUDING MY IDENTITY.

1. What does the particle science state-of-the-art consider to be the most dangerous air quality parameters to date for children, elderly and pregnant women? Please list the parameters with short justification. *

Atmospheric oxidants for lungs : ozone, NOx and diverse compounds of the PM (some redox-active metals like copper or manganese, quinones, nitro-PAHs, Brown carbon etc etc)

+ emerging atmospheric components that can be metabolized ( dionin-like effect) such as pesticides, flame retardents

in Indoor air, many additional harmful components are emitted by perfume, detergents etc

2. What chemical and physical parameters should and could be measured in every indoor environment by 2050? *

Most important: Learn to people to ventilate every day, every indoor environment
CO2 level for ventilation status
PM10-2.5 concentrations
and for then for PM compounds like metals or BC, or oxidative potential, it will depend of the price of technologies

3. Where will the next scientific breakthrough be concerning air quality microparticles? *

To regulate oxidative potential of PM as an health-relevant exposure metric

4. What are the biggest differences between Europe and the USA if it comes to legislation and definition of indoor and outdoor air pollution limits, what can the EU learn from the USA and vice versa? *

EU could learn from USA pollution limits for PM10, 2.5 and NOx
USA could learn from EU by regulating more metals as we do in EC and EU intends to set up a follow-up for oxidative potential(OP)

5. How will climate change affect indoor and outdoor air quality state-of-the-art? What parameters should the scientific community start observing more closely as soon as possible? *

Climate change will dramatically affects all type of emissions
outdoor : increase of biogenic VOC and increase of ozone. Increase of wildfires => increase of brown carbon emissions that carry out may EPFRs that emit more ROS in vivo (increase OP)
indoor: increase of indoor temperature will increase emissions of VOC, PFAS from domestic products

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## 2. Expert opinion 2: Anonymous

### Questionnaire for identifying relevant air quality paraments for better health

Thank you for agreeing to participate in this survey.

You have the option to make your answers anonymous. However, we highly regard it if you agree that your answers be publicly published on our project website.

Please
find 20 minutes to shortly write down your answers to the five questions below.

Please get back to us
latest by the end of April.

Name: *

[redacted]

Work on air pollution *

- ◯ air pollution measurement and monitoring
- ◯ air pollution modelling
- ◯ health effects of air pollution (epidemiology)

Institution: *

University of Massachusetts Amherst (USA)

Disclosure Agreement *

- ☑ Anonymous: I agree that my responses will be made publicly available EXCEPT MY IDENTITY.
- ☐ Named: I agree that my responses will be made publicly available INCLUDING MY IDENTITY.

1. What does the particle science state-of-the-art consider to be the most dangerous air quality parameters to date for children, elderly and pregnant women? Please list the parameters with short justification. *

particle size and composition. bulk metrics of particles, such as mass, are imperfect predictors of toxicity, and sometimes results in cases where exposure response functions to particle mass are inconsistent. Reliance on this alone likely results in exposure misclassification, as it is likely that specific chemical or physical features are likely driving a significant fraction of health impact.

2. What chemical and physical parameters should and could be measured in every indoor environment by 2050? *

particle size, and perhaps acellular proxy measurements of toxicity (such as oxidation potential or reactive oxygen species)

3. Where will the next scientific breakthrough be concerning air quality microparticles? *

I don't know what a 'microparticle' is. But the breakthroughs will occur when interdisciplinary researchers collaborate, rather than the typical approach where epidemiology relies solely on regulatory (and somewhat unsophisticated) measurements, or atmospheric scientists who don't work in the health arena. These two disciplines must converge to elicit these breakthroughs.

4. What are the biggest differences between Europe and the USA if it comes to legislation and definition of indoor and outdoor air pollution limits, what can the EU learn from the USA and vice versa? *

USA process is more politicized, and relies on older and more established metrics for assessing clean air. EU standards are similar, but include novel compliance standards as a result different emission profiles (e.g. increased use of diesel fuel for transportation). This is not to say EU is particularly innovative, but they have at least taken the first step at addressing/quantifying source-specific pollutants, which the US rarely performs.

5. How will climate change affect indoor and outdoor air quality state-of-the-art? What parameters should the scientific community start observing more closely as soon as possible? *

Not entirely sure, but my assumption is we will see more extreme values across many measured values. At the same time, climate change is likely to drive individuals indoors more than outdoors (some exceptions to this, of course). As a result, indoor exposure will probably play an increasing determinative role in air pollution exposure - more time indoors = more exposure indoors.

For outdoor measurements, one has to assume urban heat islands are an important topic that needs further study. Further, we must reduce exposure misclassification - it would be useful to deploy low cost sensing devices for air pollutants in major cities, with a central focus on the global south where measurements are lacking, but also in the global north to quantify concentrations in spatial areas not captured by regulatory monitors. In the indoor context, it would be wise to start building exposure profile libraries of typical parameters of pollution found in major indoor environments - industrial and non-industrial workplaces, schools, different housing stock, etc - so we can better understand these exposures.



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## 3. Expert opinion 3: Anonymous

### Questionnaire for identifying relevant air quality paraments for better health

Thank you for agreeing to participate in this survey.

You have the option to make your answers anonymous. However, we highly regard it if you agree that your answers be publicly published on our project website.

Please
find 20 minutes to shortly write down your answers to the five questions below.

Please get back to us
latest by the end of April.

Name: *

[redacted]

Work on air pollution *

- (x) air pollution measurement and monitoring
- ( ) air pollution modelling
- ( ) health effects of air pollution (epidemiology)

Institution: *

Max Planck Institute for Chemistry

Disclosure Agreement *

- [x] Anonymous: I agree that my responses will be made publicly available EXCEPT MY IDENTITY.
- [ ] Named: I agree that my responses will be made publicly available INCLUDING MY IDENTITY.

1. What does the particle science state-of-the-art consider to be the most dangerous air quality parameters to date for children, elderly and pregnant women? Please list the parameters with short justification. *

Fine particulate matter (PM2.5); enhanced differential toxicity of ultrafine particles (UFP, <100 nm) and combustion aerosols and certain chemical components likely but still unclear (soot, PAHs and derivatives, transition metals, secondary organic aerosols). Ozone, nitrogen oxides, and certain volatile organic compounds (VOC, e.g., formaldehyde) are also hazardous pollutants.

2. What chemical and physical parameters should and could be measured in every indoor environment by 2050? *

CO2 as an indicator for ventilation efficiency. If possible, also PM2.5, UFP and VOC. Not sure if continuous measurements are really needed in every indoor environment - benefit/cost ratio remains to be checked, not only financially but also with regard to the use or potential waste of energy and resources.

3. Where will the next scientific breakthrough be concerning air quality microparticles? *

Clarification of effective differential toxicities and dose-response-relations in real life (not just in biological/chemical assays or cell cultures).

4. What are the biggest differences between Europe and the USA if it comes to legislation and definition of indoor and outdoor air pollution limits, what can the EU learn from the USA and vice versa? *

EU should adopt more ambitious air quality targets as practiced in US (e.g., PM2.5 target/limit values)

5. How will climate change affect indoor and outdoor air quality state-of-the-art? What parameters should the scientific community start observing more closely as soon as possible? *

Climate change (global warming) has the potential to increase certain air quality problems (e.g., secondary formation of PM2.5, ozone and other reactive species, changes in atmospheric self cleaning by oxidation, precipitation/washout etc.). More comprehensive monitoring of PM2.5, aerosol size distributions, and reactive species in outdoor and indoor environments (as far as practicable with reasonable cost/benefit ratio - see above). More targeted experimental and model studies for mechanistic understanding of aerosol health effects and differential toxicities.



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4. Expert opinion 4: Dr. Lydia Morawska

## Questionnaire for identifying relevant air quality paraments for better health

Disclosure Agreement:

☐ Anonymous: I agree that my responses will be made publicly available EXCEPT MY IDENTITY.

☒ Named: I agree that my responses will be made publicly available INCLUDING MY IDENTITY.

1. What does the particle science state-of-the-art consider to be the most dangerous air quality parameters to date for children, elderly and pregnant women? Please list the parameters in the order of relevance with short justification.

   - PM2.5 with established epidemiology, which allowed new WHO AQGs to be established in 2021 (https://apps.who.int/iris/handle/10665/345329) and, according to GBD, is the sixth key risk facing people https://vizhub.healthdata.org/gbd-compare/.
   - UFP (which is PNC – particle number concentration), for which, according to WHO AQG 2021: "The evidence is insufficient to derive quantitative AQ guideline levels, but pointing to their health relevance."
   - The above are both outdoor and indoor hazards, but a specific hazard of indoor environments are virus laden (pathogen laden) particles emitted from human respiratory activities.

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2. What chemical and physical parameters should and could be measured in every indoor environment by 2050?
   - PM2.5, using optical sensors, which are sufficiently reliable now, and the data should be used by building management systems to act accordingly, depending if the source is inside or outside.
   - CO2, which is a proxy for ventilation and infection transmission.

3. Where will the next scientific breakthrough be concerning air quality microparticles?

   By "microparticles", I understand UPF or PNC. The breakthrough will be in terms of epidemiology/toxicology that will enable to replace the current WHO Good Practice "typical values" for UFP (https://apps.who.int/iris/handle/10665/345329) with numerical guideline values.

4. What are the biggest differences between Europe and the USA if it comes to legislation and definition of indoor and outdoor air pollution limits, what can the EU learn from the USA and vice versa?

   I am not the best person to address this question as I reside in Australia.

5. How will climate change affect indoor and outdoor air quality state-of-the-art? What parameters should the scientific community start observing more closely as soon as possible?

   With the climate warming there will be more wildfires, which will affect both, outdoor and indoor air quality, as discussed in our paper: https://doi.org/10.1016/j.atmosenv.2021.118550. Building ventilation systems will have to improve, to lower the risk of infections due the presence of human emitted respiratory particles, while doing this in a way that buildings do not consume more energy

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## Annex 5 - T3.2 Methodology for WP3

QR code experiments as physical-digital platforms that connect citizens, private sector, and public bodies with the aim of creating simplified conditions for designing and testing innovative indoor air quality monitoring solutions. We follow the method of Air Police project (Järvi et al., 2018) and have a 10-step method for the T3.2.

1. Participant Selection:
    - Select a diverse sample of dwellers (age 12-99, all genders) from various indoor environments (homes, gyms, schools, day cares, offices, public spaces).
    - Ensure fair representation across different City Labs and demographic factors.
2. QR Code Implementation:
    - Thinnect and DEDA launch a QR code system linked to an online platform for real-time data collection that can map dweller IAQ perception with sensor measured IAQ parameters simultaneously (time-stamped).
    - LAS, FTMC and TalTech integrate sensors to measure key IAQ indicators (e.g., temperature, humidity, $CO_2$ levels, particulate matter).
    - Place QR codes strategically in selected dwellings (stickers on tables, make sure EU Grant number and EDIAQI project logo is present).
3. Perception Survey (phase I):
    - Create a pre-tested survey to gather participants' subjective perceptions of IAQ.
    - Participants scan QR codes and provide feedback on the designated online platform (T3.2 Observatory).


Figure A 1 Example of the Ferrara City Lab QR code experiment

5. Actual IAQ Measurement:
   - Collect real-time IAQ data through integrated sensors.
   - Analyze data for temperature, humidity, $CO_2$ levels, and particulate matter concentrations (for T3.2 $CO_2$ is enough, try to also cover $PM_{2.5}$, if possible, check with your PI for City Lab specific requirements) versus dweller perception, submitted via QR code.
   - Visualize the difference between the reported and perceived indoor air quality levels and the sensor measurement values (e.g. $PM_{2.5}$) in R using the *tidyverse* package (Wickham et al., 2019):

```r
# Load necessary libraries
library(tidyverse)

# Tallinn City Lab data
data <- data.frame(
  timestamp = seq(as.POSIXct("2022-01-01 00:00:00"), by = "hour", length.out = 24),
  reported_air_quality = c(2, 3, 1, 3, 2, 1, 3, 4, 3, 2, 1, 2, 3, 2, 1, 2, 3, 4, 3, 2, 1, 2, 3, 4),
  pm25_measurement = runif(24, 5, 50) # PM2.5 values
)

# Create a bar chart
ggplot(data, aes(x = timestamp)) +
  geom_col(aes(y = pm25_measurement, fill = "PM2.5 Measurement"), width = 0.5) +
  geom_line(aes(y = reported_air_quality * 10, group = 1, color = "Reported Air Quality")) +
  scale_fill_manual(values = c("PM2.5 Measurement" = "blue")) +
  scale_color_manual(values = c("Reported Air Quality" = "red")) +
  labs(x = "Timestamp", y = "Value", title = "Reported Indoor Air Quality vs. PM2.5 Measurement") +
  theme_minimal() +
  theme(legend.position = "top")
```

Figure A 2 Sample code in R to check for differences between perceived (reported via QR code IAQ values) and actual sensor measurements. This code is available in the EDIAQI public repository (GitHub) as part of the D3.1 toolkit.

This code generates a bar chart with a line plot overlay where the via QR code reported indoor air quality levels are represented by the red line and the $PM_{2.5}$ sensor measurement values are represented by the blue bars. Adjust the *data* dataframe according to your actual data.

6. Visual Testing (phase II and III):

- Check the "Review on IAQ Systems & Visuals" distributed by TROPOS in October 2023:

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| Spalte1 | ref | date | parameters | visual |
|---|---|---|---|---|
| 1 | Zampolli et al. | 2004 | $NO_x$, CO, VOCs and RH | no real time visuals |
| 2 | Pillai et al. | 2010 | VOCs, CO, hydrogen | LED display units of measure |
| 3 | Kim & Paulos | 2010 | VOC, PM | Line chart on iPod |
| 4 | Bhattacharya et al. | 2012 | RH, temperature, gaseous | mote GUI showing live IAQ data /LED DUSTTRAK DRX 8533 Monitor screen |
| 5 | Saad et al. | 2013 | RH, temperature, PM and | a self-developed program displaying units of measure (log) |
| 6 | Cheng et al. | 2014 | $PM_{2.5}$ levels | AirCloud APIs/Visualization web app to view time-series data. |
| 7 | Kim et al. | 2014 | $CO_2$, VOCs, $SO_2$, $NO_x$, CO, F | line chart |
| 8 | Abraham & Li | 2014 | CO, VOC and $CO_2$, $O_3$, RH, t | line charts |
| 9 | Yu & Lin | 2015 | $CO_2$, RH, temperature | GPS location, line charts,trend of CO2 concentration as line chart |
| 10 | Kang & Hwang | 2016 | VOC, $PM_{10}$, CO, temperatu | time series, line chart, alert list |
| 11 | Pitarma et al. | 2016 | Luminosity, $CO_2$, CO, RH ar | alert list, line chart |
| 12 | Wu et al. | 2017 | PM | Whole field-of-view differential hologram image |
| 13 | Alhmiedat & Samara | 2017 | $CO_2$, benzene, $NO_x$ and am | line charts |
| 14 | Ahn et al. | 2017 | VOC, light quantity, RH, te | line charts |
| 15 | Moreno-Rangel et al. | 2018 | $PM_{2.5}$, $CO_2$, VOCs, RH and temperature | |
| 16 | Idrees et al. | 2018 | RH, temperature, $O_3$, $SO_2$, | Line chart with 2 (even 3) different Y axes, different level of time, bar charts |
| 17 | Sivasankari et al. | 2018 | RH, temperature, $NO_2$, CO | Graph can be plotted for every half-an-hour (thing speak platform) |
| 18 | Benammar et al. | 2018 | RH, ambient temperature, | line chart |
| 19 | Tiele et al. | 2018 | Sound levels, illuminance, | OLED display, line charts back-end |
| 20 | Dawit Uta Urku et al. | 2018 | PM2,5, CO2, RH, temperat | visual via mobile app (log in, index, traffic light) |
| 21 | Arroyo et al. | 2019 | Toluene, ethylbenzene, benzene, and xylene | |
| 22 | Ali et al. | 2019 | temperature, relative hum | Grafana—Timeseries visualization |
| 23 | Goncalo et al | 2019 | RH, temp, CO2, PM2,5 | AirPlusMobile - both numeric and chart form, real-time notifications |
| 24 | Marques | 2020 | temperature, humidity, CO2, light, and PM2.5 | |
| 25 | Pies et al. | 2020 | CO2, temparture, RH, atm | Grafana—Timeseries visualization |
| 26 | Mumtaz et al. | 2021 | RH, temperature, NH3, CO | Alert list, line chart |

Figure A 3 Overview of the IAQ projects in the last two decades circulated for T3.2.2 and described briefly in D3.1 Chapter 4.1.

- Apply visuals representing IAQ conditions that are aligned with the TROPOS issued review (presented above on Fig A 3), alternatively use TROPOS issued EDIAQI dashboard from EDIAQI GitHub account (e.g., line-charts, thresholds, colour codes). A good example given below, applied in Tallinn City Lab since December 2023:

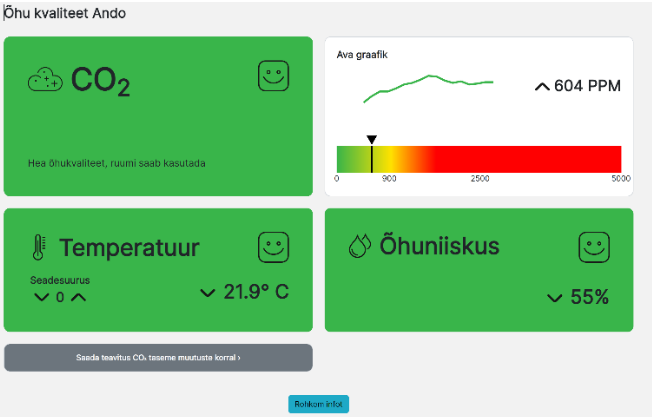


Figure A 4 Example of the Tallinn City Lab visuals aligned with the overview of IAQ project review of visual representation.

- Introduce visuals alongside QR codes in a controlled manner; first showcasing the widget for 3 seconds, and in phase II for 8 seconds.

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- Collect participants' perceptions of IAQ based on visuals and compare with actual IAQ data to answer to following RQ:
    - RQ1: How big is the difference (%) between perceived and measured IAQ?
    - RQ2: Is there a difference between the perceived IAQ and sensor data, if visuals are included to the experiment?
    - RQ3: What is the average time needed for a user to perceive IAQ information?

7. Data Analysis:
    - Conduct statistical analysis to compare participants' perceived IAQ with actual IAQ measurements at three locations, among various dweller, stakeholder groups.
    - Examine the impact of different visuals on dwellers' IAQ perceptions.
    - Consider correlations between demographic factors and perception accuracy.
8. Ethical Considerations
    - Obtain informed consent from participants.
    - Ensure data anonymity and confidentiality.
    - Comply with ethical guidelines and EDIAQI ethics plan.
9. Time Frame:
    - Implement the phase I over a specified time period (e.g., 3 weeks) to capture weekly weather variations. Each phase should result in minimum 300 replies (the more the better).
    - Phase I should be finalized at all three City Labs by end of May. Work will continue on T3.2 throughout 2024.
10. Reporting and Dissemination
    - Prepare a comprehensive report detailing findings, insights, and recommendations for the monthly WP3 meetings.
    - Disseminate results through publishing in scientific journals.

By employing this research design, we aim to bridge the gap between dwellers' subjective IAQ perceptions and the objective reality, while also exploring the influence of visuals on their perception accuracy.

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Deliverable D3.2

# Guidelines for Pilot City Labs to set-up indoor pollutant monitoring stations

Work Package

SCIENCE

Version: Final

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