Evidence Driven Indoor Air Quality Improvement (EDIAQI): An innovative and interdisciplinary approach to improving indoor air quality

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Abstract

Indoor air pollution is a recognized emerging threat, claiming millions of lives annually. People are constantly exposed to outdoor and indoor air pollution; the latest research shows that people in developed countries spend up to 90% of their time indoors and almost 70% at home. Although impaired IAQ represents a significant health risk, it affects people differently, and specific populations are more vulnerable: children, the elderly, and people with respiratory illnesses are more sensitive to these environmental risks than the general public. Despite rather extensive research on IAQ, the majority of current understanding about the subject, which includes pollution sources, indoor-outdoor relationships, and ventilation/filtration, is still quite limited, mainly because air quality monitoring in the EU Is primarily focused on outdoor air quality and regulatory requirements are lacking for indoor environments. Therefore, the EDIAQI project aims to improve guidelines and awareness for advancing the IAQ in Europe and beyond by allowing user-friendly access to information about indoor air pollution exposures, sources, and related risk factors. The solution proposed with EDIAQI consists of conducting a characterization of sources and routes of exposure and dispersion of chemical, biological, and emerging indoor air pollution in multiple cities in the EU. The project will deploy cost-effective/user-friendly monitoring solutions that will create new knowledge on sources, exposure routes, and indoor multipollutant body burdens. The EDIAQI project brings together 18 organizations from 11 different European countries that provide interdisciplinary skills and expertise in various fields, including environmental science and technology, medicine, and toxicology, as well as policy design and public engagement.

Keywords: indoor air quality, machine learning, cohorts, asthma, toxicology

Introduction

Humans are constantly exposed to outdoor and indoor air pollution (IAP), which is progressively becoming an important issue as we spend more and more time indoors. Research shows that people in developed countries spend up to 90% of their time indoors [1]. Recently, we witnessed a dramatic increase in the time spent indoors during the global pandemic of COVID-19, and while isolation might prevent viruses from spreading, poor indoor air quality (IAQ) may have other severe health outcomes. A systematic review and meta-analysis noted that in 2017, household air pollution was associated with 1.8 million deaths and more than 60 million disability-adjusted life years globally [2]. Most of the burden related to household air pollution is seen in low and middle-income countries. In Europe alone, exposure to particulate matter (PM) reduces each person's life expectancy by an average of almost a year, mainly due to the increased risk of cardiovascular and respiratory diseases, neurological disorders, and lung cancer [3]. Although impaired IAQ represents a major health risk, it affects people differently, and certain populations are more vulnerable. Children, the elderly, and people with respiratory illnesses are more sensitive to these environmental risks than the general public [4]. For example, children living near highways with high loads of heavy-duty vehicles have a twofold higher risk of respiratory problems than those who live near less congested streets [5]. IAQ is determined by various factors and processes, such as outdoor pollution levels, pollution transport between indoors-outdoors, internal emission, chemical reactions of gasses on particles and surfaces, dynamic processes (e.g., resuspension, deposition, evaporation, growth, coagulation, etc.), and ventilation/indoor air filtration [6–8]. Outdoor pollution can be transported into the indoor environment through building cracks, shells, etc., and doors/windows [7]. Indoor air chemistry is yet another process that significantly contributes to IAQ. Despite rather extensive research on IAQ, pollution sources, indoor-outdoor relationships, and ventilation/filtration are still limited on temporal and spatial scales. Only a few studies have focused on ultrafine, black carbon, submicron particles, and chemical pollutants. Moreover, it is known that the ventilation rates and deposition velocities are highly variable (up to 30% on average) between the different residential buildings and experimental periods (e.g., summer versus winter). Differences in the ventilation habits of the inhabitants, varying material surfaces, meteorological conditions, etc., render stationary and static IAQ investigations rather limited in usable output [9]. There is a lack of knowledge of representative residential particle, gas, and allergen exposure levels, risk assessment, and IAQ legislations in the long-term and multiple indoor environments in Europe. Analysis of the existing guidelines for IAQ in EU Member States revealed significantly different reference values of indoor pollutants across Europe. Such differences can create social segregation and different lifestyle conditions [10]. Most countries' legislative regulations to control airborne pollution still refer to PM, such as PM_{10} and $PM_{2.5}$ (aerodynamic particle diameter <10 and <2.5 µm, respectively) fractions only. However, scientific evidence shows that more attention should be focused on the chemical composition of smaller particle fractions such as PM_1. Some toxicological studies suggest that PM_1 particle fraction is more hazardous than $PM_{2.5}$ in terms of cytotoxic effects and inflammation [11]. Furthermore, scientific-based evidence on indoor and outdoor air suggests that the use of PM_{10}-bound benzo(a)pyrene, as the only marker of exposure to carcinogenic polycyclic aromatic hydrocarbons (PAHs), must be supplemented by including other health-relevant PAHs gas phase PAHs (e.g., naphthalene) and smaller PM fractions [12].

Health effects

The health effects of most airborne pollutants such as gases, PAHs, volatile organic compounds (VOCs), PM, and biological pollutants such as microbial spores, mold, allergens- seasonal such as pollen, and perennial, e.g., house dust mites, are usually associated with prolonged exposure. However, acute toxic effects of impaired IAQ, such as those in the case of carbon monoxide (CO) poisoning, also represent a significant health issue. Poor IAQ is associated with a range of health effects, such as chronic neurological, cardiovascular, and respiratory conditions, sick building syndrome (SBS), malignancies (lung cancer) [13], and even vocal cord dysfunction [14, 15]. Moreover, children exposed to indoor air pollution (prenatal and early life influences) are more likely to have low birth weight. They are more prone to anemia, acute respiratory infections, and premature mortality [16]. Different indoor air pollutants may also act synergistically and cause adverse health effects [17]. The mechanisms underlying the health effects of impaired IAQ include oxidant stress, DNA damage, differential gene expression patterns, and epigenetic modifications (such as DNA methylation) [14]. Several studies have demonstrated that outdoor air pollution affects asthma susceptibility and severity [18, 19] and chronic obstructive pulmonary disease (COPD) [20], but emerging evidence links indoor air pollution with asthma and its outcomes [21]. Studies have shown that increases in the level of indoor coarse PM are associated with a higher number of severe asthma attacks, asthma symptoms, increases in medication use, and emergency department visits [22]. Similarly, exposure to NO_2 from gas appliances was found to increase the risk of asthma exacerbations [23]. Children are an especially vulnerable population in the context of indoor air pollution, and evidence [24] shows that there are dose-response effects in the level of exposure to both coarse and fine PM and asthma symptoms: for every 10 $\mu g/m^3$ increase in $PM_{2.5}$–PM_{10} concentration, a 6% increase in the number of days involving asthma symptoms such as wheeze, cough or chest tightness was observed. Additionally, for every 10 $\mu g/m^3$ increase in indoor $PM_{2.5}$, a 7% increase in the number of days involving severe wheezing and a 4% increase in the number of days requiring rescue medication use was observed. Coarse and fine PM affect asthma pathophysiology separately but likely also synergistically. Fine PM (<PM2.5) reaches further into the airways, perhaps even into the alveoli, thus affecting gas exchange, and coarse PM depositions in the proximal airways may cause inflammation and airway hyperreactivity. Moreover, increased indoor NO_2 levels were associated with asthma symptoms (severe wheezing, cough, and nocturnal awakenings due to asthma symptoms, chest tightness, etc.). Exposure to tobacco smoke and second-hand smoke in children is a well-established and independent risk factor for the development of asthma. It significantly increases the risk of severe asthma exacerbations requiring hospitalization [25]. Evidence shows that exposure to tobacco smoke aggravates asthma severity by shifting the balance of regulatory T/T helper 17 (Treg/Th17) cells and cytokine secretion towards a Th17 profile [26], characteristic of severe and corticosteroid-resistant asthma. Additionally, exposure to biological agents, such as molds, has been associated with poorer asthma control [27]. House dust mites are a ubiquitous indoor air pollutant and common triggers [28, 29]. Many asthma prevention and management strategies are based on environmental control and the elimination of house dust mites from rooms patients spend most of their time in [30]. Moreover, house dust mites have high allergenicity, and sensitization to house dust mites increases the risk for asthma development [31]. Sensitization to house dust mites has also been associated with poorer asthma outcomes [32]. Two recent studies investigated the effect of short- and long-term exposure to (ambient) NO_2 and $PM_{2.5}$ species on different metabolic pathways. Both studies found that several metabolic pathways were affected, and all had in common that these pathways are crucial in inflammation, oxidative

stress, immunity, and nucleic acid damage and repair [33, 34]. However, not all findings show clear association. In a high-risk asthma cohort, COPSAC2000, long-term exposure to indoor air pollution ($PM_{2.5}$, NO_x, formaldehyde, and black smoke) and its effect on wheezing symptoms were investigated in Denmark. The study [35] found no associations between indoor air pollution concentrations and the number of wheezy episodes or any wheezing. In conclusion, most children were exposed to low concentrations of the particles, and previous studies showing short-term associations between higher concentrations and wheezing could not be translated to associations of cumulative low-dose exposure to air pollution. The main contributors to $PM_{2.5}$ were smoking, heavy traffic, and winter. For black smoke, the main contributor is smoking [36]. The indoor microbiome, and especially fungi and bacteria therein, might also play important roles in disease development [37–39]. Special attention must also be dedicated to better understanding exposure to other and novel compounds that are not reported in the regulations but are considered hazardous to human health. For example, exposure to ultrafine particles and black carbon has particularly negative health effects due to their small size (ability to penetrate the air-blood barrier in the respiratory tract) and chemical composition. Determining the size distribution of particle-bound carcinogen compounds, black carbon and ultrafine particles deposition dose, and physical-chemical characteristics of some newly emerging pollutants, such as microplastics and plasticizers [40, 41], would allow estimating respiratory tract deposition dose of pollutants for much more accurate health risk assessment. One of the key questions is how to monitor health effects with regard to IAQ. The first results, from a detailed literature overview, revealed generally higher levels of DNA strand breaks and chromosomal damage due to indoor air pollutants compared to matched control or unexposed groups [42], as well as the importance of the comet [43] and micronucleus [44] assays as sensitive tools for the evaluation of DNA and genome damaging potential of different indoor air pollutants. Besides, to evidence the role of the comet assay in air pollution monitoring, the qualitative analysis on exposure to air pollution indicates the genotoxic effects of the variety of air pollutants and increased levels of DNA strand breaks in subjects exposed to such substances compared with the non-exposed population stressing that by reducing air pollution levels to the WHO-recommended concentrations, an average person might improve their life expectancy, and the comet assay might be a useful tool in detecting the most vulnerable population [45]. Additionally, so far, data indicate that the level of genome damage evaluated by the micronucleus assay differs between the countries, and this could be attributed to lifestyle differences, geographical location, weather conditions, and pollution levels across Europe since some cities and areas have heavy industrial activity coupled with increased traffic and higher levels of both outdoor and indoor air pollution that could affect the frequencies of those parameters in various cells [46]. All the abovementioned underscores that research in this particular direction is warranted since little is still known about the level of indoor air pollution in households or public buildings and its impact on genetic material and its relation to possible health outcomes.

Project aim and objective

The Horizon Europe EDIAQI project has several objectives and tasks as outlined in the project proposal and listed below:

1) Validating user-friendly IAQ monitoring solutions such as low-cost sensors
2) Creating a Europe-wide knowledge base for risk factors associated with a spectrum of indoor air pollutants
3) Providing standardized guidelines to improve IAQ

4) To ensure FAIR data access to relevant stakeholders (e.g., public authorities, consumer protection entities, and patient associations), including both physical-chemical and microbiological properties, as well as characterization of main sources of indoor air pollutants for relevant and representative indoor environments
5) To support policy-makers in revising IAQ standards and regulatory measures for IAQ control and monitoring
6) To support the Zero-Pollution Action Plan of the European Green Deal that is backed up by science-based evidence

In the framework of the project EDIAQI, multiple indoor exposure scenarios to standard and beyond the state-of-the-art air pollutants will be investigated. The study domain is residential (houses and public offices) and recreational sites (i.e., cinemas, theatres, restaurants), hospitals, and schools across Europe. IAQ will be quantified by deploying the latest aerosol instrumentation alongside the latest innovative and technologically advanced low-cost sensors. Sensorics and data collection will be aligned using standardization and interoperability protocols. The project's data platform will be used for real-time building performance audits, which will be developed, including digital twins, to simulate indoor events. Continuous monitoring of ventilation and IAQ in buildings will collect big data, which will be used for performance analytics. The project has a large focus on epidemiology and toxicology. Asthma and allergies have been the focus of this project. With estimations that one in every five children will develop asthma during childhood [47], researching IAQ showed to be a relevant topic. Within the scope of the project, the role of impaired IAQ in asthma pathophysiology and specific disease subtypes (phenotypes) will be investigated. Common clinical traits, including disease severity and the level of asthma control, as well as traits corresponding to discrete disease endotypes (such as gene expression profiles and epigenetic modifications), will be assessed in association with IAQ. Toxicological studies of the adverse effects of chemicals on living organisms play a key role in understanding the potential harm caused by impaired IAQ. In the project, we will first investigate the toxicity of individual pollutants to assess their mechanisms of action. They will be selected based on chemical analysis data in households. In the next step, the combined effects of several pollutants will be examined in binary and more complex mixtures to assess their impact on human health, which represents a real situation as in our daily lives, we are exposed to multiple chemicals at once that may have combined (additive, synergistic, antagonistic, or potentiating) effects. Developing effective strategies to mitigate indoor air pollution requires a comprehensive understanding of toxicological principles, enabling the implementation of measures to improve indoor air quality and protect human well-being.

Methods and concepts

In the following section, we explain the steps for this project as given by our plans in the project grant agreement.

Assessment of chemical and particle exposure indoors

The sampling approaches are relevant to investigate IAQ better. Generally, VOC sampling in indoor air is carried out using sorbent tubes. For passive sampling, samplers such as Radiello are widely used samplers [48]. The Radiello samplers are able to provide correct results about VOCs for a weekly sampling. The Radiello sampler is made of a stainless-steel net coaxial cylindrical cartridge. It is filled with 40-60 mesh adsorbent phase (Carbograph 4). The Radiello is placed on a cellulose acetate plane. Therefore, during the sampling, the VOC particles pass through the cylindrical membrane towards the cartridge. Hence, VOCs are adsorbed by the adsorbent phase. VOCs are then extracted from the adsorbent phase with carbon disulfide and analyzed by gas chromatographic analysis, particularly employing gas chromatography equipped with mass spectrometry (GC-MS) [49]. Another approach for VOC sample collection is active sampling on sorbent tubes using pumps with low flow rates (usually about a few mL/min), with later direct analysis by thermal desorption coupled with gas chromatography/mass spectrometry (TD-GC/MS). Conditioned sampling tubes packed with a combination of porous polymer, graphitized carbon black, and carbonized molecular sieves (Markes, Llantrisant, United Kingdom) are suitable collecting media for indoor VOCs. TD-GC/MS is an analytical technique that enables VOC analysis without previous sample preparation, which reduces the possibility of analyte loss, enables low detection limits, and also, considering that organic solvents are not used for sample preparation, it is more acceptable from the aspect of environmental protection and occupational health. However, the limitation of TD is that there is no possibility of dilution after sampling, so longer exposure results in samples that are out of the measuring range. Sampling periods of about 50 min were found to be optimal for active VOC sampling followed by TD-GC/MS. However, attention should be paid to ensure that the sampling period is representative of the overall IAQ. For indoor PM sampling, reference samplers, which are often in use for the collection of PM in ambient air (airflow 55 m3/day), are not appropriate for indoor environments due to the size and noise they produce. Silent samplers with smaller dimensions are preferable (e.g., Sven-Leckel, AirMetrics), with a flow rate between 3 and 5 L/min. They consist of a sampling head with size-selective impactor inlets (different depending on the particulate matter size, PM_{10}, $PM_{2.5}$, PM_1) and a filter holder loaded with Teflon or quartz filters, for the determination of inorganic and organic species, respectively. The collection of PM on filters enables their later chemical characterization in the laboratory. Weekly PM samples are collected on quartz filters to determine PAHs. PAHs are extracted from filters in an ultrasonic bath with a solvent mixture of toluene and cyclohexane. After extraction, extracts are centrifugated and evaporated to dryness in a mild stream of nitrogen, re-dissolved in acetonitrile, and analyzed by high-performance liquid chromatography (HPLC) with a fluorescence detector [50]. However, if the measurements aim to determine the mass concentrations of airborne PM but not their chemical composition, then it is possible to use an instrument such as DustTrak, which allows sampling and directly measuring PM in real-time, namely PM_{10}, PM_4, $PM_{2.5}$, and PM_1 based on light-scattering laser photometry. On the other hand, particles with granulometric size below 1 µm are analyzed by condensation particle counters, which can be portable or not. In this case, it is possible to investigate the different granulometric sizes, which are very important for evaluating human exposure. Finally, it is important to investigate a new class of emerging contaminants, which are microplastics. It should be underlined that the agreement on the definition of such a term is still an important issue. Frias and Nash [51] tried to summarize the different definitions reported in a previous paper. They proposed such a statement: “Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water”. The attention to microplastics is mainly based on the still current uncertainty of the potential long-term effects that these could have on the human organism. Analyzing the literature, it emerges that, in accordance with the percentages of synthetic polymers produced, the microplastics identified most frequently in the environment, specifically indoor environments, are composed of polyethylene (PE) and polypropylene (PP). From an analytical point of view, the lack of a defined protocol is a limitation. In any case, a Raman analysis is considered the best analytical approach for reaching the maximum information possible [52].

Non-destructive vibrational spectroscopic methods, such as Raman and Fourier-transform infrared spectroscopy (FT-IR) spectroscopy, are the most common techniques for the identification and quantification of microplastics. Some authors have noted that FTIR provides only preliminary information, which depends on the size of the microplastics. Nowadays, μ-Raman and μ-FTIR analysis are considered the best analytical approaches for reaching the maximum information possible [52]. Also, recent studies have included the Laser Direct Infrared Chemical Imaging System (LDIR) [53]. An automated workflow system in these methods allows the analysis of the size and composition of collected particles, including microplastics. In automated mode, particles in the range from 10 μm to 500 μm can be determined. Further importance also depends on the fact that microplastics can have a carrier role, i.e., be able to transport other contaminants adsorbed on their surface. In this way, the determination of Polycyclic Aromatic Hydrocarbons (PAHs) could be important considering their cancerogenic effects. For this determination, a protocol based on Dispersive Liquid-Liquid Microextraction (DLLME) coupled with vortex and ultrasound steps manages to separate PAHs from the matrix; finally, a GC-MS analysis allows us to determine such dangerous compounds. Figure 1 presents a general measurement setup for the sampling in this project.

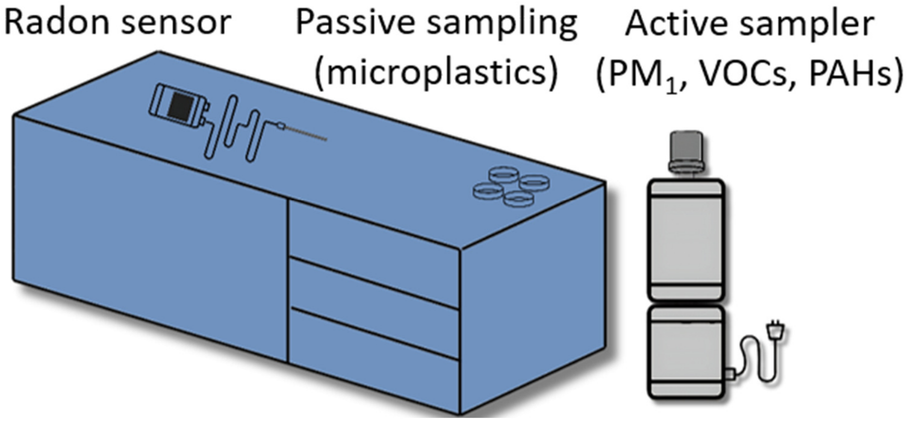

Figure 1. Illustration of radon measurements, passive sampling for microplastics, and active sampling for PM_1, VOCs, and PAHs in the Zagreb pilot.

Assessment of Radon indoors

In EDIAQI, the average activity concentration of ^{222}Rn (Radon) will be measured as well. The potential effects of radon on human health lie in its solid decay products rather than the radon gas itself, which can be inhaled and deposited in the bronchopulmonary tree to varying depths [54, 55]. Higher radon concentrations are expected in basements and ground floors; however, it is possible that due to air circulation within the dwelling, radon can be accumulated in upper floors. The integrated measurement of the average radon activity concentration using solid-state nuclear track detectors (SSNTD)[56] is based on the following elements: a) passive sampling 30 – 90 days, during which the alpha particles, including those produced by the disintegration of radon and its short-lived decay products, transfer their energy by ionizing or exciting the atoms in the polymer; this energy that is transferred to the medium leaves areas of damage called “latent tracks”; b) transport of the exposed sensors to the laboratory for the appropriate chemical processing, for example the transformation of the “latent tracks” into “etched tracks” counted with a suitable system; the number of these “etched tracks” per surface unit area is linked to the exposure of the radon by the calibration factor previously defined for sensors from the same manufacturing batch of SSNTD processed chemically, and counted under the same conditions; and c) determination of the average activity concentration from the radon exposure value, the sampling duration and consideration of the background noise. Additionally, a good screening method for indoor radon determination is a 3-day measurement with activated charcoal filters. The principle is that radon is adsorbed on activated charcoal encapsulated in a container. The ^{222}Rn activity concentration is determined by high-resolution gamma-ray spectrometry of its decay products (^{214}Bi and ^{214}Pb) after their equilibrium is reached. Both methods are standardized (ISO 11665-4:2021).

Indoor microbiome

Microorganisms can occur in complex communities that often include hundreds or thousands of different species. Living microorganisms that are present in a defined environment, along with their molecular building blocks, metabolites, and other non-living elements, are commonly referred to as the microbiome [57]. Microbiome research has gained considerable momentum over the last ten years, mostly due to advances in high-throughput sequencing techniques. The human gut microbiome was shown to be an important factor in health and disease [58]. This also applies to the microbiome of the human respiratory tract [59]. Humans are mostly exposed to microorganisms present in food, natural environments, and indoor environments. It is hypothesized that microbiomes present in indoor environments are interconnected with the human microbiome [60, 61]. More specifically, the first links between indoor microbiomes and respiratory diseases were established [39, 62]. EDIAQI will collect and analyze dust samples to retrieve microbiome data from children's beddings (16S rRNA gene fragment and ITS metagenomic sequencing on the Illumina MiSeq platform). Figure 2 shows the microbiome extraction pipeline.

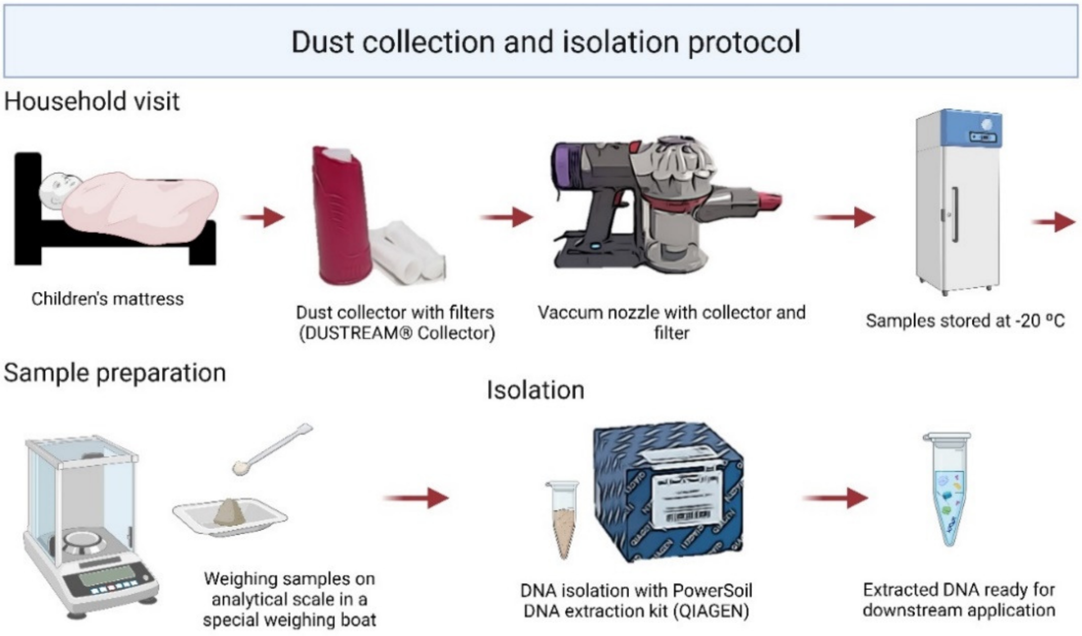

Figure 2. Illustration of the dust collection and isolation protocol in the Zagreb pilot.

Found bacterial families in samples will be associated with the health of the subjects, with a special focus on asthma and allergies. Based on the results, differences in the relative abundance of bacterial families and fungi in house dust samples of allergic and non-allergic subjects will be compared and related to IAQ data, as well as with the type of housing, urban vs. rural environment, indoor pets, siblings, etc. [63]. This part of the project is based on the assumption that house dust is the main reservoir of microbial taxa in the domestic environment and that the amount and diversity of the microbiome in dust affect health, especially since dust-born microbes and their products suspend into the air and produce a significant indoor exposure by breathing [64]. Previous studies indicate that higher microbial diversity in the environment has been found to be inversely associated with asthma. For example, children who grow up in 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 [37]. It has been suggested that the protective effect of a farming lifestyle and living in a rural environment comes from extensive microbial exposure in early life [62]. The most prominent environmental factors affecting the house dust microbiome in general are living conditions, level of urbanization, seasonality, and pets.

Technological challenges

Data management, security, and interoperability

Interoperability is an important aspect of EDIAQI, ensuring that data can be shared within the project and with third parties [65]. The interoperability is ensured using standards for data representation and interfaces, as well as including open-source components in the developed software solutions for EDIAQI. The data exchange needs adequate standards [66] for interoperability so that the involved parties can collect, transmit, and share the data based on a common technical approach. It is necessary to establish common semantics described by machine-readable vocabularies, ensuring the interpretability of the data throughout the data exchange and the foreseen analytics in EDIAQI. These semantics need to cover the elements of interest for indoor air quality studies, namely, the investigated buildings, the involved people and their respective risk levels, real-time measurements of the air quality parameters, and the subjective perception and complaints of people [67]. Taking well-established technical standards like the Indoor Air Quality System standard (ISO 16000) into account, a data organization scheme was designed to ensure semantic interoperability. This schema consists of three main parts: 1) Metadata providing information about the data; 2) Data, which is further divided into static and dynamic data, depending on the expected temporal resolution; and 3) Auxiliary data describing the rooms where the data has been collected. Technical interoperability is ensured by complying with standards and by building onto reference software solutions. When looking at the standard, the SensorThings API [68] is employed as a REST communication method to transmit measurement data in JSON format over HTTP(S). The SensorThings API handles the semantics to identify the measurement as well as the environment of the measurements that produced the data. Alongside the tabular data and diagrams for statistical data, visualization services are employed to create maps and visual representations from spatialized data. These standards are implemented by the selected open-source software implementation, like the FROST (FRaunhofer Opensource SensorThings-Server) for implementing the OGC SensorThings API Part1: Sensing 1.0 (with PostgreSQL / PostGIS for storing measurements and geospatial data) and geographical servers, like Geoserver, for implementing ISO19128 (WMS) and ISO19128 (WFS) standards. Semantics about pilot buildings will be achieved by exploiting existing standard data models from OGC CityGML [69] or INSPIRE Buildings data specifications[70]. The Data Platform (DP) is the central element in collecting the data generated in the EDIAQI pilots and campaigns [71]. The DP is designed along the FAIR principles [72], i.e., the DP provides search functionality so that the data and metadata can be found (Findability), are available to all interested parties, but data protection requirements also respected (Accessibility), are represented in open formats and via open interfaces (Data Interoperability) and are organized and licensed to allow future uses (Reusable). With its federated architecture, the DP caters for different levels of integration.

Low-cost measurement networks

EDIAQI will use, among other means, low-cost sensors to detect the chemical and physical characteristics of IAQ. Alongside the traditional approach of sampling on adsorbent supports, irrespective of whether they are active or not, for the subsequent characterization and quantification using analytical instruments commonly used by laboratories, we will try to study the phenomenon of indoor pollution from a different perspective. The sensors will be used for measurement for different purposes in the project campaigns and pilots: Zagreb (Croatia), Ferrara (Italy), several locations in Estonia, Vilnius (Lithuania), and Seville (Spain). The first campaign, also in order of priority, will be to carry out a comprehensive evaluation of the performance of the multi-sensor devices envisaged in the Project so as to verify the different sensitivities through real inter-comparisons [73]. A series of low-cost monitoring sensors, already commercially available but implemented experimentally, will be tested and used to measure IAQ. Manufacturers will provide wireless and easy-to-use sensors to pilot managers. The second campaign intends to focus on the physicochemical characterization of indoor pollutants and measure the impact of behavioral differences. The contribution of outdoor air and the proper management of ventilation systems (air dilution and filtration) under different scenarios will be studied. All sensors used will have to meet multimodal requirements: be able to measure the mass concentration of particles in different size classes, various gases (e.g., CO_2, CO, NH_3, NO_X), TVOC, temperature, and relative humidity (RH). Incorporating technological novelties and some of the latest developments in the field of sensors, some units installed in Ferrara will be equipped with an adjunctive detector to detect trends in aromatic compounds (e.g., detection of benzene, toluene, ethylbenzene, and xylene - BTEX) predominantly anthropogenic compared to trends in total organic volatiles. Finally, the last two campaigns will focus on how outdoor air pollution from vehicles affects indoor air quality, and not least, how raising awareness contributes to the overall improvement of people's living and working conditions. All research data related to the monitoring of environments from a chemical and physical point of view will be shared in IPCHEM.[1]: the European Commission's chemical monitoring information platform, which provides a reference access point for research, access, and recovery of data relating to chemical occurrences collected and managed in Europe. State-of-the-art scientific reference instrumentation will be used in parallel to assess low-cost sensor accuracy and provide high-quality additional information about indoor particle number size distribution (10 nm to 20 µm) [74] and reference concentrations of gases and VOCs [75]. Additionally, the contribution of outdoor air and the correct management of the ventilation systems (air dilution and filtration) in the various scenarios will be investigated. The devices can also communicate with the aforementioned data platform, where the user will be able to get all vital information regarding real-time air quality measurements on each of the measured parameters while also having an overall evaluation of the status of the station.

The application of machine learning and modeling in the project

EDIAQI will use different machine learning (ML) techniques for modeling data in indoor and ambient environments [76]. To help with a better understanding of indoor effects, EDIAQI will implement several modeling techniques, namely Digital Twins (DT) [77] and Computational

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[1] https://ipchem.jrc.ec.europa.eu/

Fluid Dynamics (CFD) [78]. These two modeling techniques are used to complement ML algorithms with virtual representations and simulations of physical indoor environments. Digital Twins will used to create a virtual representation of a physical object, system, or process [77]—in this case, a room in which we will simulate different aspects related to IAQ. This will be done by integrating data from sensors and other sources (e.g., cleaning, cooking, using air diffusers). Another feature of DT is continuous monitoring and diagnostics that can be done throughout its cycle. We plan to implement different sources of pollution inside a room and observe how the environment changes. DT was successfully installed in various industries, such as manufacturing, healthcare, urban planning, and predictive maintenance [79]. Within EDIAQI, we will implement it to monitor and understand indoor environments. The second modeling technique is CFD, which is a part of fluid mechanics used for understanding and solving different problems related to fluid flows. By employing algorithms and computational power, CFD solves interactions between fluids (liquids and gases) and solid surfaces [78]. The main objective of using CFD in EDIAQI is to understand the physical interaction between pollutants dispersed in the air and objects in the room since the placement of objects and windows plays a major role in creating the indoor environment. Nowadays, with the paradigms of hybrid modeling [80], CFD and DT have started to merge and create a setting that will be used in this project.

Indoor air epidemiology, biomonitoring and toxicology

Toxicological assessment of indoor air pollutants

The project aims to investigate the toxicological effects of indoor air through a combination of human biomonitoring, *in vitro* studies in human cell models, and *in vivo* studies in Wistar Hannover rats. Human biomonitoring will target populations, specifically children with asthma and healthy controls, using peripheral blood lymphocytes (PBLs) and exfoliated buccal cells. PBLs, obtained minimally invasively, act as indicators of early biological effects due to their exposure to indoor air pollutants like $PM_{2.5}$. Buccal cells, easily harvested and suitable for children, represent epithelial respiratory tract cells that metabolize carcinogens. Increased DNA DNA damage, and micronuclei frequency in PBLs has been linked to urban air pollutants, with a correlation established between buccal cells and PBLs [42, 45]. Besides, since exposure to indoor air can cause DNA damage and induce chromosomal damage, both the comet and micronucleus assays, that will be used in the frame of the project, represent useful tools to quantify the extent of such damage by detecting abnormalities within the cell's genome. The application of these assays in studies on indoor air pollution may contribute to understanding the genotoxic effects of pollutants at a cellular level and, in turn, shed light on the potential onset of non-communicable diseases including cancer [80, 81] consequently causing a significant financial and social burden, especially in ageing populations [82]. *In vitro* toxicological studies will assess the toxic effects of IAPs on human lung and hepatic cells. Lung epithelial A549 cells, commonly used in toxicology, will be grown in monolayer cultures. Another cell line widely used in toxicology for the detection of directly and indirectly acting genotoxic compounds is the human hepatocellular carcinoma (HepG2) cell line, which expresses the wild-type tumour suppressor P53 and retains the activity of a number of Phase I and II metabolic enzymes. Hepatic cells will be grown in monolayer (2D) cultures and in 3D conformation (spheroids). The latter provides a more physiologically relevant model for human exposure due to improved cell-cell and cell-extracellular matrix interactions in the 3D microenvironment, and higher expression of liver-specific functions including metabolic activity compared to 2D. In addition, the 3D cell model also allows for longer chronic exposure, which is limited in traditional 2D models [83]. Importantly, advanced *in vitro* 3D cell models represent an alternative to animal experiments based on the 3R principle (replace, reduce, refine). Adverse genotoxic effects in lung and liver cells will be assessed with the comet assay and cytokinesis block micronucleus (CBMN) assay detecting DNA strand-breaks and chromosomal instability, respectively. In addition, a multi-labelling approach will be applied in HepG2 cells using flow cytometric analyses to assess the formation of DNA double-strand breaks (γH2AX assay), corresponding to clastogenicity, mitotic cells (H3-positive cells) corresponding to aneugenicity, and to study the impact of indoor air pollutants on cell proliferation by detecting Ki-67 positive cells and cell cycle analysis [84]. This will be complemented by target gene expression analysis, where genes that respond to DNA damage and repair, altered cell proliferation, and metabolism will be selected [85]. *In vivo* studies will use the Wistar Hannover rat, a well-characterized strain, to evaluate selected indoor air pollutants. This model shares features with human allergic asthma. Pulmonary function testing will assess respiratory diseases, with plethysmography detecting changes in bronchoconstriction levels in non-anesthetized rats, aligning with the 3R principles. A graphical schema of the toxicological studies in EDIAQI is presented in Figure 3.

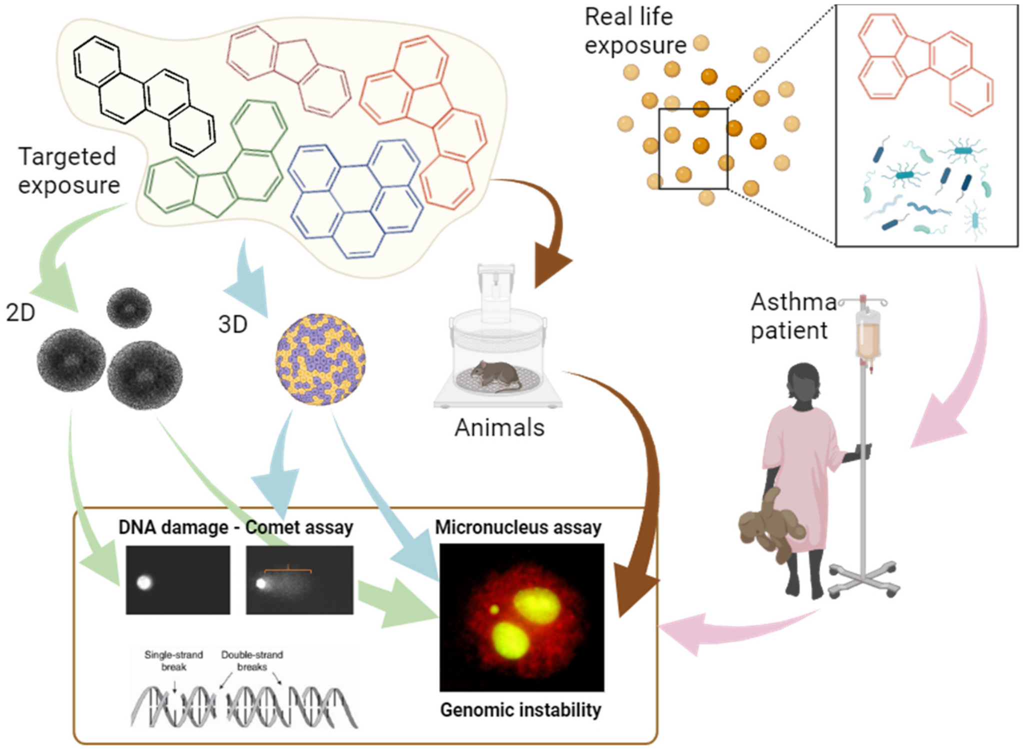

Figure 3. A schematics of the toxicologica and biomonitoring aspects of the EDIAQI project

Project cohorts

Within EDIAQI, health effects for young asthmatic and allergic children, and their connection to indoor and outdoor air pollution will be researched in three retrospective and two prospective cohorts. Building on existing data and cohorts is necessary to produce new data with the aim to make this research more comprehensive, investigate the relationship to asthma and specific asthma phenotypes/endotypes and to achieve valuable clinical tools for future applications. The retrospective cohort data will be analysed on associations and non-linear relationships by means of machine learning, while the novel cohorts will take into account further measurements and analyses including microbiome dust analysis and connection to IAQ monitoring as well as deposit measurements.

The EU FP7 ATOPICA [86] cohort involves 4016 children aged 3-15 from Croatia. It encompasses a rich dataset, including demographics, clinical, genetic, and environmental factors. This cohort provides insights into children from three diverse Croatian regions, each with unique environmental exposures and lifestyles. Key data includes medical histories, allergy tests, air quality data for all participants, and biological samples (serum, blood) for 1000 participants.

The prospective SCH2021 (EDIAQI) cohort will consist of 200 school-aged children with asthma and non-asthmatic controls within the Zagreb pilot. The dataset will include demographic data, extensive clinical data (allergy tests, personal and family medical history, biochemistry, data on asthma control and exacerbations, medication use etc.), IAQ data, transcriptomic data, biological samples (blood, buccal cells, exhaled breath condensate, induced sputum) and follow up data (for up to 2 years). A visual of the planned cohort activities is shown in Figure 4.

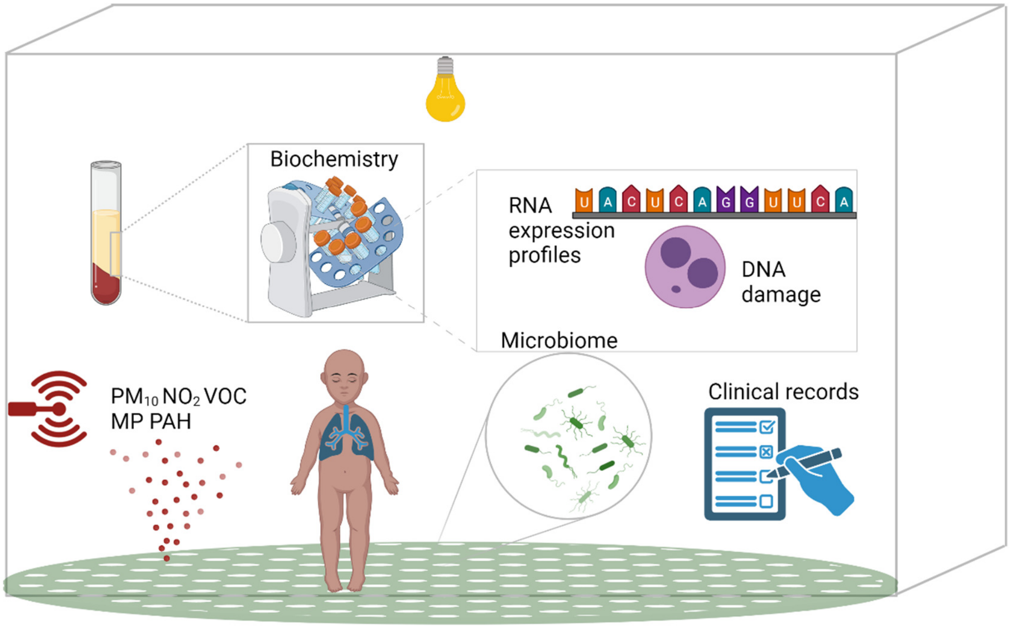

Figure 4. The SCH2021 cohort. A total of 200 children with asthma and non-asthmatic controls will be recruited to assess the health effects of impaired IAQ. Clinical parameters, including those related to asthma (asthma control, lung function, inflammation, sensititzation, etc.), dust microbiome, and gene expression patterns will be assessed in association with indoor air pollutants.

The COPSAC2000[2] cohort tracks 411 children of asthmatic mothers from infancy to adolescence with the overarching aim of understanding gene-environment interactions in common but heterogeneous childhood diseases asthma, allergy, and eczema. Indoor air

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[2] https://copsac.com/home/copsac-cohorts/copsac2000cohort/

pollution was monitored in children's homes in early childhood, and the impact on wheezing symptoms has previously been published [35].

COPSAC2010[3] is a prospective clinical mother-child cohort of 700 children from the general Danish population born around year 2010 [87]. Similar to the COPSAC2000 cohort the main focus is strong clinical follow-up and algorithm-based diagnosis of childhood asthma and related diseases, and early life measures to mitigate the risk. The children are deeply phenotyped as well as multiple layers of omics data (such as repeated measures of microbiome, and metabolome) are collected prospectively. For indoor air quality the indoor air microbiome was collected in dust samples later sequenced with 16S RNA sequencing.

The prospective COPSAC$_{\text{severe}}$ [4] is a novel Danish national cohort aiming at the recruitment of 300 Danish children with severe asthma. By collaborating with pediatric departments across Denmark, the study will distinguish severe asthma cases from difficult-to-treat cases and use multi-omics approaches for assessment. The goal is to identify specific disease mechanisms to personalize treatment and predict exacerbations. This cohort will serve as a valuable resource for our project since indoor air dust will be sampled as well. Figure 5 shows a schematic across the three COPSAC cohorts.

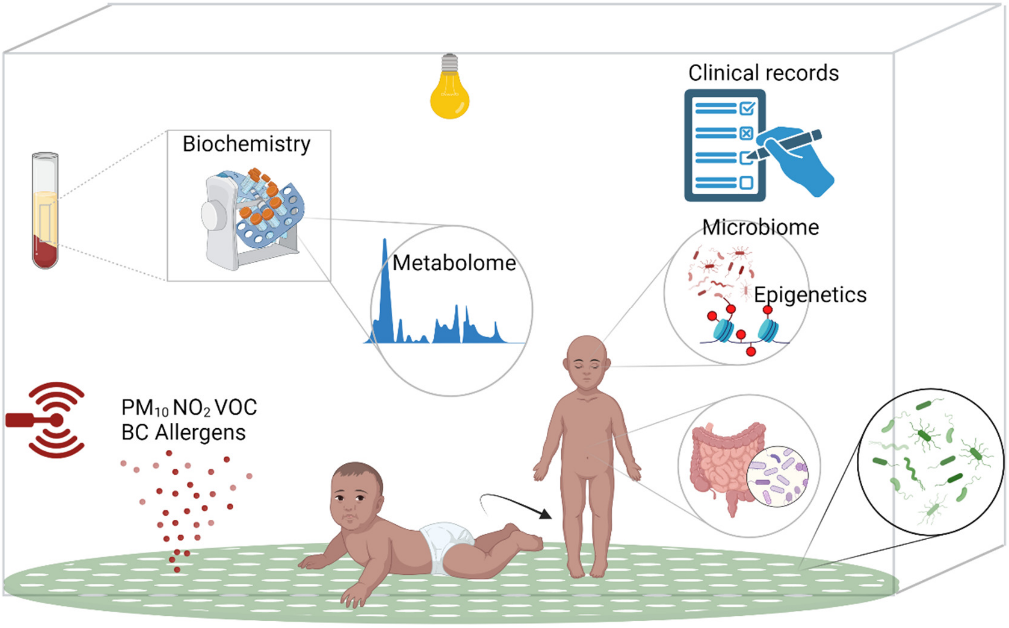

Figure 5. A joint schematic of the COPSAC cohorts with different levels of biochemical and indoor air assessments.

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[3] https://copsac.com/home/copsac-cohorts/copsac2010-cohort/

[4] https://copsac.com/home/copsac-cohorts/copsac-severe-cohort/

A pilot- and campaign-driven approach

The EDIAQI project is driven by multiple pilots and campaigns deemed as "testing grounds" for the science planned in the project. The testing grounds are depicted in Figure 6 with numbers of objects included in the project at the time of writing this work.

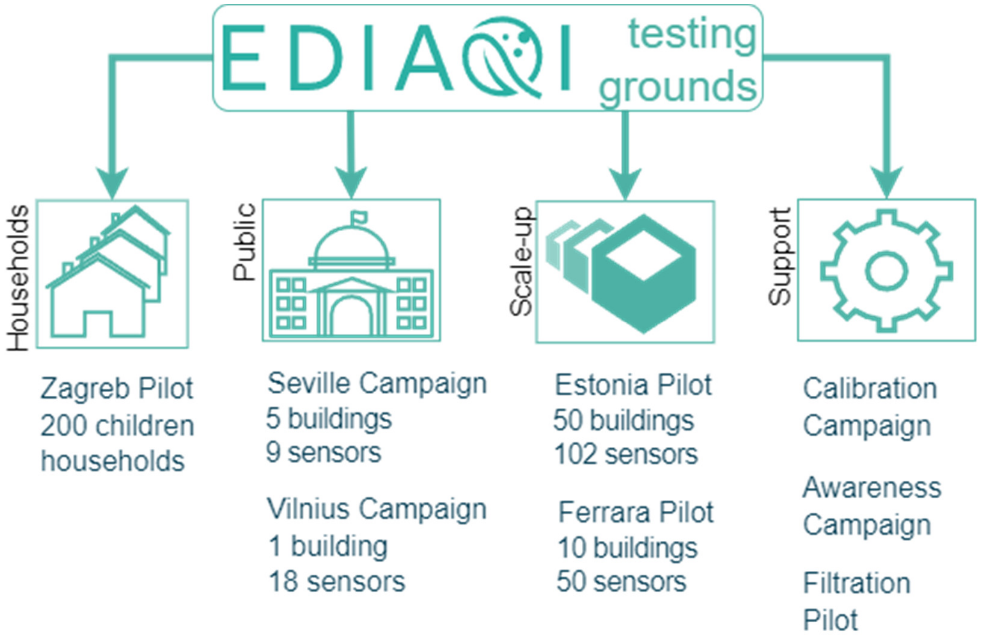


Figure 6. Stakeholder profiles and anticipated numbers of testing grounds in the project

P1 – Ferrara Pilot

The Ferrara Pilot examines indoor air quality across four building types: schools, offices, entertainment venues, and residences. Each setting has unique occupants, activities, and building characteristics. Central to this pilot is the community's active involvement. They'll participate in campaigns to share their experiences and perceptions, which we term "warm data." Alongside this, we'll deploy low-cost indoor multi-sensors and remote reference stations to gather detailed data on indoor air pollutants. Key goals include: i) Categorizing buildings to guide indoor air quality management and raise awareness about pollution sources, habits, and environmental influences; ii) Initiating campaigns targeting various occupants (like students, workers, and residents) to influence their understanding and behavior regarding indoor air quality and assess the impact of mitigation strategies; iii) Undertaking the epidemiological aspects to understand the effects of prolonged exposure to emerging pollutants.

P2 – Estonian Pilot on Big Data Analytics

The Estonian initiative aims to improve the indoor climate of educational buildings, such as kindergartens, schools, universities, and non-residential work environments like offices. The project plans to achieve this by installing IAQ monitoring sensors to help understand indoor air quality. The project integrates 50 buildings and uses Big Data for analysis, which will promote awareness and behavioral changes. The sensors and user feedback will be used to achieve the following goals: i) Enhancing IAQ knowledge, ii) Creating tools for continuous IAQ monitoring, iii) Boosting public awareness and promoting healthier indoor behaviors, and iv) Assisting facility managers in improving IAQ.

P3 – Zagreb Pilot

The pilot is built around the aforementioned SCH2021 cohort of 200 childhood subjects consisting of asthma patients and their corresponding controls. They'll complete ISAAC and other questionnaires, and their bedrooms will have pollutant traps and sensors for dust collection. This dust will be analyzed for chemical and microbial content. Air quality will be monitored over several days. Regular follow-ups at the clinic will occur every 3-6 months, while blood and other sample collection for biomarker analysis will be done at the beginning and the end of the study. The goal is to study adverse health effects (such as asthma outcomes and genomic instability) in relation to indoor pollutants. The goals include: i) Analyzing health effects and air pollution correlation; ii) Identifying airborne and bed-dust biological contaminants; iii) Assessing genomic instability in the target population's blood and buccal cells; iv) Profiling indoor-outdoor pollutants.

Table 1. 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, outdoor
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

P4 – Filtration Pilot

The pilot focuses on enhancing IAQ in public buildings using air filtration systems. Its goal is to identify pollutants effectively filtered out, guiding future technological advancements in filtration systems. The study will pinpoint optimal methods for IAQ enhancement, leading to recommendations on efficient filters, maintenance schedules, and filter replacement timings. In addition, P4 aims to gather data on office space habits and comfort needs. To achieve all of this, partners will employ a comprehensive approach, utilizing low-cost sensors to capture ambient pollution data, Computational Fluid Dynamics (CFD) [88], and mass transfer of aerosols [7], alongside Artificial Neural Network (ANN) analysis for obtaining a detailed indoor airflow field for accurate and efficient control of indoor air quality. The end goals include: i) Promoting awareness of IAQ and indoor air filtration; ii) Gathering best practices for air filtration system maintenance; iii) Pinpointing air quality risk areas in office spaces.

C1 – Evaluation of low-cost sensorics

The rise of affordable, compact environmental sensors has empowered researchers, community groups, and citizen scientists to conduct extensive and real-time indoor air quality (IAQ) monitoring. Yet, while these low-cost sensors hold immense promise, they remain in the developmental phase. There's limited knowledge about their data reliability, precision, and optimal usage guidelines. C1 aims to rigorously assess the performance of various consumer-grade sensors, examining their ability to detect elements like particulate matter, CO_2, NO_X, tVOCs, and more. This evaluation will take place in controlled lab settings and in the field using benchmark instruments. Key goals include: i) Categorizing available low-cost air quality monitors based on factors like cost, accuracy, user-friendliness, suitability for extended indoor use, and maintenance needs; ii) Understanding the variability between low-cost instruments and their responsiveness to environmental changes, such as temperature shifts; iii) Offering guidance to users about the most effective commercially available sensors for IAQ tracking.

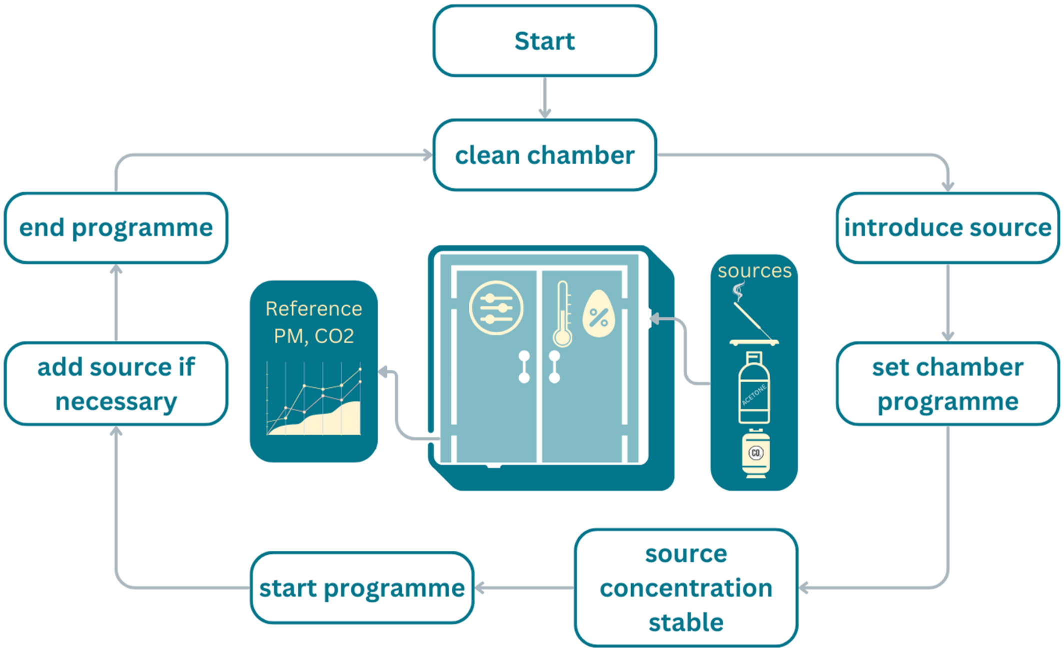


Figure 7. Schematic diagram of the chamber experiments.

C2 – Measurement campaign Sevilla

The Sevilla IAQ campaign will assess indoor air pollutants and study behavior and ventilation practices in key areas like schools, day care centers, homes, and public transport. Goals include i) Understanding health impacts on children due to indoor air pollution concerning building structures and systems; ii) Assessing the benefits and enhancements in well-being and hygiene in schools, homes, and public transport; iii) Aiding in creating preventive strategies to boost environmental quality in educational settings; iv) Elevating public awareness about indoor air pollution sources, behaviors, and factors influencing IAQ.

C3 – Measurement campaign in Vilnius

This in-depth campaign will study the impact of outdoor vehicular, biomass burning- and transport-related pollution on IAQ. The focus will be on schools in high-pollution downtown areas. Advanced aerosol measurement tools, alongside low-cost sensors, will be used to analyze various aerosol particle metrics, including ultrafine particle numbers and black carbon concentrations. The study will also determine the sources and exposure levels of these particles in children. During school hours, students will wear sensors that record PM2.5 exposure every five minutes. Furthermore, air samples will be analyzed for air-borne microplastic and black carbon levels. The main goals are: i) Understanding the daily and seasonal changes in students' exposure to aerosol particles, black carbon, and microplastics; ii) Determining how intense outdoor pollution, primarily from vehicles, impacts the IAQ of schools in polluted zones.

C4 – Awareness campaigns

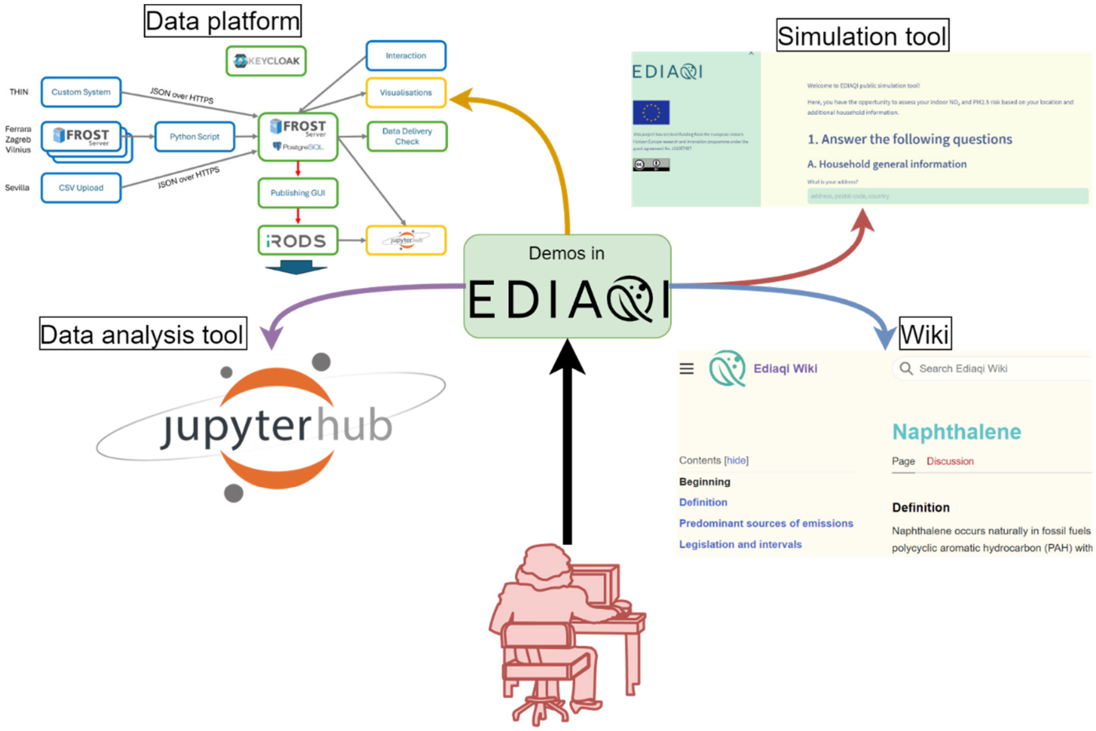
EDIAQI aims to elevate environmental consciousness to combat both indoor and outdoor air pollution. A central component of this initiative is an awareness campaign targeting children and their families participating in the project's pilot studies. To gauge participants' understanding of IAQ-related health concerns, EDIAQI will introduce a specially designed questionnaire. The responses will shed light on the public's perception of IAQ issues, revealing potential gaps or misconceptions. These insights will guide the creation of guidelines and educational materials, promoting informed actions and effective communication strategies. Ultimately, the goal is to bolster health advocacy and preventive measures across diverse socio-economic landscapes, amplifying environmental health awareness. Key objectives include: i) Assessing public understanding of health implications linked to pollution; ii) Identifying effective strategies to heighten awareness about indoor air pollution; iii) Enhancing knowledge about indoor pollution sources and mitigation techniques; iv) Addressing any uneven distribution or effectiveness of information; v) Critically reviewing the public's primary information sources on IAQ causes and management.

Project impact

The EDIAQI project will have an impact in a wide range of different areas with the overall objective of making living and working environments in European cities and regions healthier, more inclusive, safer, resilient, and sustainable. More specifically, the EDIAQI project will help to:

- **Provide a better understanding of IAQ through data**: the EDIAQI project will generate and provide access to FAIR (Findable, Accessible, Interoperable and Resusable) data on air pollutants, including chemical and biological determinants and their main sources in indoor environments and settings. This data will be obtained using 180 sensors installed in 68 buildings in cities across Europe in the pilot and measurement campaigns. It will be integrated into the project Data Platform, providing a centralised data access point, facilitating collaborative research, and enabling accurate assessments of IAQ, bridging a distinct knowledge gap that currently exists in this area.

- **Develop affordable and easy-to-understand monitoring solutions**: a variety of different user-friendly solutions are being developed and implemented in the project. Low-cost sensors are installed in the different pilots and measurement campaigns to monitor IAQ in different building typologies. Guidelines for their most effective use will also be published to help ensure that they are used properly. An IAQ simulation tool (Figure 8) as part of the EDIAQI ecosystem is under development to provide the user with an idea of the quality of air, considering the different characteristics of their indoor setting. This tool will be built on data from both the retrospective and prospective cohorts included in this project and will provide advice on what to do to improve indoor air quality. Finally, user-facing dashboards are being developed and tested to present and explain IAQ information in the most intuitive and accessible manner possible. Guidelines on how to set up these "City Labs" will be provided as one of the project results.



Welcome to EDIAQI public simulation tool!

Here, you have the opportunity to assess your indoor NO_2 and PM2.5 risk based on your location and additional household information.

1. Answer the following questions

A. Household general information

What is your address?

address, postal code, country

Naphthalene occurs naturally in fossil fuels
polycyclic aromatic hydrocarbon (PAH) with

Figure 8. The EDIAQI demo ecosystem based on the IAQ simulation tool a project wiki and a data platform for data collection and analysis.

- **Support IAQ policy and regulations through evidence:** it is essential that policymakers and regulators are aware and well-informed about environmental, socioeconomic, health, and occupational risk factors. The analysis of the data generated in the project will contribute to the development of proposals to support and improve policy and regulatory measures on IAQ. More specifically, evidence-based strategies and concrete actions to promote indoor air quality will be included in the Clean Air Act 2050 Roadmap. This roadmap will be one of the results of the project and will be designed to generate synergies with the current work being carried out under the Zero Pollution Action Plan of the European Green Deal.

- **Generate awareness on IAQ**: an awareness campaign is being rolled out which will shine a spotlight on the importance of IAQ and the simple measures that can be done to improve it. A questionnaire has been developed within the project and it is being administered in all project pilots and campaigns. The aim of the questionnaire is to investigate and critically evaluate the awareness of the participants on health-related issues involving indoor air pollution, public sources of information about the causes and controllability of indoor air pollution and its health effects, and potential disparities in information reach and utility (Garnett 2020). The novel findings on the level of awareness and general attitude of participants towards IAQ and its consequences on health will help formulate guidelines for specific actions and communication models. Based on these findings, training materials will also be created and implemented to improve knowledge and awareness of IAQ, targeting different groups ranging from school children and families to building owners. Furthermore, an IAQ Wiki[5] has been developed to provide easy-to-understand information on IAQ-related topics and concepts. The idea is that this will provide the starting point to continue generating new knowledge and research on IAQ and making it available to the public. This work on awareness will support health promotion and disease prevention in different sectors and across various socio-economic settings and increase awareness of environmental health in general.

- **Lead to increased competitiveness of the industrial sector related to IAQ**: an exploitation plan will be created with the aim of ensuring that the main exploitable results from the EDIAQI project are sustainable over time and are successfully taken up in the market. Furthermore, the data generated from the EDIAQI project will be open and available to all, helping indoor air quality sensor providers and other related industry players to improve the quality and performance of their products, leading to a more knowledgeable and competitive market in this area.

Joining forces in research on IAQ – The IDEAL Cluster

The IDEAL cluster[6] is made up of seven European research and innovation projects focussing on indoor air quality and health, funded under the Horizon Europe framework program. The projects involve more than 100 organisations throughout Europe and beyond. To achieve its objectives, the IDEAL cluster is divided into seven working groups, each serving a specific purpose:

- **Working Group 1:** Translating scientific research into policies and practices for improving IAQ and well-being.
- **Working Group 2:** Facilitating collaboration and standardisation of data analysis and management techniques across multiple projects.
- **Working Group 3:** Focusing on communication and dissemination to ensure effective outreach and impact.
- **Working Group 4:** Led by the German Institute for Standardisation, concentrating on standardisation activities related to the cluster's research projects.
- **Working Group 5:** Dedicated to sensors, raising awareness about IAQ, and enhancing sensor technologies for effective monitoring.
- **Working Group 6:** Concentrating on health outcomes, including examining the clinical effects of indoor and outdoor air quality.

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[5] EDIAQI IAQ Wiki Page
[6] IDEAL Cluster Project Website

- **Working Group 7:** Primarily dedicated to in-vitro models, aiming to contribute further information in the future.

Through the collaborative efforts and coordination of these working groups, the IDEAL cluster aims to generate impactful results, merge data from various sources, and actively contribute to the improvement of IAQ and public health. The projects that form part of the IDEAL cluster in addition to EDIAQI include:

- **InChildHealth project:** Integrating health, environmental, technical, and social sciences to assess IAQ and its impact on school children. The project employs novel approaches like cytotoxicity testing and aims to create an integrated risk assessment tool for pollutants, develop user-friendly monitoring technology, and disseminate findings to improve IAQ management in schools [89].
- **INQUIRE project:** Focused on enhancing IAQ and protecting the health of European citizens, especially children. INQUIRE monitors over 200 homes in eight countries to understand IAQ determinants through innovative sampling methods. The project combines chemical, biological, and toxicity analyses to identify sources, prioritise pollutants, and test novel technologies for improving IAQ [90].
- **K-HEALTHinAIR project:** Concentrates on assessing the effects of IAQ on health through extensive monitoring of chemical and biological pollutants in representative indoor environments across the EU. The project aims to develop affordable IAQ measurement devices and tools, providing structured knowledge for public authorities, policymakers, and citizens to influence new IAQ standards [91].
- **LEARN project:** Aims to assess IAQ in European schools and its effects on children's health and cognition. The project focuses on developing novel sensors, advanced biosensors, and effective remediation strategies to improve IAQ and children's well-being [92].
- **SynAir-G project:** Addresses the complexity of indoor air pollutants and their potential synergistic effects on human health, particularly impacting susceptible groups. The project focuses on school environments, aiming to uncover synergistic interactions between pollutants, develop novel sensors, eco-friendly air-purifying devices, and provide accessible health outcome data through gamified applications [93].
- **TwinAIR project:** Introduces technological solutions to enhance air quality across various indoor contexts. The project aims to investigate the adverse effects of indoor air pollutants on occupants' health, establish a framework for identifying health hazards, and contribute to open research data initiatives [94].

These projects collectively contribute to advancing knowledge, technologies, and strategies for improving IAQ and its impact on health, aligning with the overarching goals of the IDEAL cluster. Furthermore, these collaborative endeavours will significantly enhance the quality and efficiency of EDIAQI's outcomes, thereby maximising its potential for success and impact in influencing European policy on indoor air quality.

Contributing to Europe's Zero Pollution Action Plan

The activities in the EDIAQI project have been designed so that the outputs are alligned with the current European initiatives addressing IAQ, namely the Zero Pollution Action Plan (ZPAP) of the European Green Deal. In October of 2022, the European Commission proposed changes to the EU's ambient air quality directives as part of the European Green Deal. These directives have been implemented since the 1980s and focus on the quality of outdoor air. The main reason for these proposed changes was to allign European air quality standards with the World Health Organization (WHO) recommendations to achieve zero air pollution by 2050[7]. The revisions included regular reviews of air quality standards, enhanced legal clarity, and support for local authorities. they only pertain to outdoor air and not IAQ[8].

The **ZPAP** is a cornerstone initiative of the European Green Deal, aimed at comprehensively addressing pollution across different domains. This plan encompasses a range of key objectives, primarily directed towards water, air, and soil pollution, with the overarching vision of achieving a pollution-free environment by 2050. While the action plan is broad in scope, it explicitly highlights the importance of tackling air pollution[9]. Despite its focus on improving air quality as part of its holistic vision for pollution reduction, the plan does not currently encompass a specific, EU wide legislative framework for IAQ. EDIAQI will provide support through the provision of recommendations and actions that focus specifically on indoor air, a topic that has received a renewed interest from the European Commission, particularly in the wake of the Covid-19 pandemic. This will be achieved through the development of the Clean Air Act 2050 Roadmap, one of the outputs of the EDIAQI project. The EDIAQI team will share this roadmap with the Zero Polution Stakeholder Platform, the group of stakeholders that will help the European Commission to deliver on its promises set out in the action plan. Members of the EDIAQI project and IDEAL cluster are acively involved in this stakeholder platform.

Outlook

Indoor Air Quality remains an overlooked facet within the European Union's school curriculum, representing an opportunity for significant improvement. While various subjects are covered in the educational framework, the crucial topic of IAQ tends to be sidelined. Integrating this subject into the curriculum presents a chance to augment the comprehensiveness of education, addressing a vital aspect of health and well-being often underestimated in educational settings. Incorporating IAQ into the European Union's school curriculum can yield multifaceted benefits. Firstly, it provides students with essential knowledge about the environmental factors that directly impact their daily lives. Understanding the significance of air quality indoors empowers students to make informed choices, promoting healthier lifestyles and fostering a sense of responsibility toward their immediate surroundings. Furthermore, the children we educate today are the future of the European Union. Educating them on IAQ not only equips them with crucial knowledge but also positions them as influencers within their families and communities. Children often become educators themselves, sharing what they've learned with their parents, thereby extending the reach and impact of IAQ education beyond the classroom. This dynamic contributes not only to shaping healthier environments at home but also to cultivating a society that values and prioritizes indoor air quality for the well-being of all its members.

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[8] The European Commission, "Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions Empty: Pathway to a Healthy Planet for All: EU Action Plan: Towards Zero Pollution for Air, Water and Soil," the European Commission, 12 May 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0400&qid=1623311742827

[9] The European Commission Joint Research Centre, "Zero Pollution Report 2022", Publications Office of the European Union, 2022. Available online: https://joint-research-centre.ec.europa.eu/scientific-activities-z/zero-pollution-outlook-2022_en

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