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A new framework for indoor air chemistry measurements: towards a better understanding of indoor air pollution.

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Abstract

This paper reports on the findings from INDAIRPOLLNET (INDoor AIR POLLution NETwork), a recently completed European COST Action network. INDAIRPOLLNET ran from September 2018 to March 2023 with more than 200 indoor and outdoor air quality scientists from universities, large and small companies, and research institutes around Europe and beyond. The expertise of our interdisciplinary network members covered chemistry, biology, standardisation, household energy, particulate matter characterisation, toxicology, exposure assessment, air cleaning, building materials, building physics and engineering (including ventilation and energy), and building design. The aim of INDAIRPOLLNET was to design a framework for future indoor air chemistry field campaigns, building on our improved understanding of indoor air chemistry. The main focus of our network was to better understand the sources, transformations and fate of chemical pollutants found in the air in buildings. In this paper, we present the main findings from our network, which include a call for greater spatial and temporal coverage of measurements indoors, the need for standardised techniques for indoor measurements and the impact of occupants on indoor air quality. We also present a checklist of building parameters that should be measured in any future indoor air campaign. Finally, we present our new framework, focusing on 5 key research areas: reactivity in indoor environments; mapping organic constituents indoors; the role of the occupant in indoor air chemistry; indoor modelling studies and novel materials and technologies indoors. We hope this framework will be of use to the indoor air quality community, enabling healthier buildings for the future.

Keywords: indoor air quality, INDAIRPOLLNET, EU COST Action, indoor air chemistry

Implications and Impacts

In high income countries, we spend 80-90% of our time indoors, where we receive most of our exposure to indoor air pollution. However, compared to outdoor air quality, indoor air quality remains relatively understudied. Based on the results from the INDAIRPOLLNET network, this paper identifies some of the key research questions that need to be addressed to better understand indoor air quality. For each research question, it then provides a framework that defines which species to measure indoors, how to measure them, and in which type of building, if we are to better understand how to improve the air quality in buildings in the future.

Introduction

The World Health Organisation (WHO) recently stated that exposure to indoor and outdoor air pollution was one of the greatest risks to human health, and that improving air quality was necessary to reduce the global incidence and impact of diseases such as lung cancer, stroke and asthma [1]. Recognition of the significance of exposure to pollution indoors has grown over the last 35 years or so, given we are estimated to spend around 90% of our time indoors in high income countries [2]. Consequently, even for pollutants generated outdoors, our exposure to them and any subsequent impacts to our health, are likely to happen indoors. An increased recognition of the importance of good indoor air quality (IAQ) was also brought into sharper focus with the COVID-19 pandemic.

In recent years, buildings have become more airtight as we aim to reduce energy loss and carbon dioxide emissions, to combat climate change impacts. Consequently, ventilation rates have been reduced in buildings, which means that if indoor sources provide our main exposure routes to air pollution indoors, we are likely to be exposed to higher indoor concentrations as energy efficiency measures are put in place. In fact, lower ventilation rates have been associated with adverse health effects indoors [3,4]. However, research, advice and regulations still focus predominantly on outdoor air pollution.

There are numerous sources of air pollution in buildings. The direct sources of pollution include combustion activities such as cooking (e.g. nitrogen oxides (NO_x) when using gas, particulate matter (PM), nitrous acid (HONO), carbon monoxide (CO), and volatile organic compounds (VOCs)), cleaning (typically producing emissions of VOCs, chlorinated compounds, ammonia, or hydrogen peroxide), use of fragranced products such as air-fresheners and home improvement products (VOCs), building materials (a wide range of VOCs and semi-volatile organic compounds, SVOCs) and occupants (carbon dioxide (CO₂), VOCs, ammonia) (see Weschler and Carslaw [5] and references within).

Some indoor air pollutants can also enter buildings from outdoors. Nitrogen oxides can enter buildings in this way, and combined with the additional source of cooking on gas stoves, can produce higher concentrations of NO_x indoors than outdoors under some conditions [6]. Ozone (O₃) is another pollutant that enters buildings from outdoors. Although there are indoor sources such as photocopiers and laser printers, most derives from outdoors and indoor concentrations are typically 20-70% of the outdoor concentration [7]. The lower indoor concentration arises because ozone can undergo deposition to, and reaction with, components of indoor surfaces, and also initiate chemical processing through oxidation of VOCs [5].

Ozone preferentially reacts with VOCs containing double bonds, such as alkenes and monoterpenes. The latter species are ubiquitous components of cleaning and other fragranced products [8]. Ozonolysis reactions can form a wide range of secondary species, some of which are harmful to health, such as

formaldehyde (HCHO), a known carcinogen, and ultrafine particles. They can also form shorter lived species such as the hydroxyl (OH) radical, which goes on to drive indoor oxidation processes [5,9,10]. Understanding indoor air chemical processing helps to avoid high concentrations of harmful pollutants accumulating indoors through chemical reactions.

Indoor air chemistry understanding has advanced significantly in recent years, most notably through a large funded program in the US called the Chemistry of Indoor Environments (CIE) program. The CIE program has funded two intensive measurement campaigns: HOMEChem (House Observations of Microbial and Environmental Chemistry) and CASA (Chemical Assessment of Surface and Air). HOMEChem was held in a test house in Austin, Texas, in the summer of 2018 and explored the impact of cooking and cleaning on IAQ through a series of scripted experiments [11]. The results from this campaign have demonstrated the importance of occupant activities and surface processes on IAQ (e.g. [12-15]). The CASA campaign was held in the NIST (National Institute of Standards and Technology) Net Zero Energy Residential Test Facility in Gaithersburg in the US in the spring of 2022 and aimed to investigate the impact of chemical and environmental perturbations on IAQ with a focus on wildfire smoke. Data analysis is still at an early stage for CASA, but will no doubt yield some interesting results.

Both HOMEChem and CASA were US-led campaigns and much of the existing IAQ literature is based on North American and Asian studies. However, meteorology, house construction, ventilation methods and lifestyles, such as differences in cooking practices and the use of solvent containing products indoors, will also be subject to wide variations across populations and hence have differential effects on IAQ and pollutant exposure. Since IAQ is strongly influenced by these factors, the findings from studies cannot always be generalised across different countries. Identifying the specific needs for IAQ research in Europe was therefore a major focus of the COST (European Cooperation in Science and Technology) Action network called INDAIRPOLLNET (INDoor AIR POLLution NETwork)

COST Actions are interdisciplinary networks dedicated to scientific collaboration. They are open, collaborative and based on a 4-year work programme. Unlike many funding mechanisms, they work on a bottom-up basis with the network driven by a scientific idea. COST Actions are organised using a range of networking tools, such as scientific and management meetings, early career investigator training schools, short-term scientific missions, and dissemination activities. They are open to all science and technology fields, all institutions, and all career stages.

The overarching aim of INDAIRPOLLNET was originally *to **define a blueprint for the optimal indoor air chemical characterisation campaign**, which is relevant for the buildings we use and for the way that we use them*. This aim developed over the course of the project and the blueprint became a framework, as explained in the *Results and Discussion* section. In essence, a blueprint suggests one solution, whereas a framework permits more flexibility. There were also some additional objectives, which were to:

- significantly advance the field of indoor air pollution science,
- to train a new generation of Early Career Investigators (ECIs),
- to highlight future research areas,
- to bridge the gap between research and business to identify appropriate, and mitigation strategies that optimise IAQ.

There were 48 original proposers of the Action from 17 different countries, and we finished the program with 208 participating scientists from 37 countries, demonstrating the interest in this research area.

This paper reports the main findings from INDAIRPOLLNET, focused on understanding the sources, transformations, and fate of chemical pollutants indoors. We highlight knowledge gaps based on our overview of existing measurement and modelling studies (both indoors and outdoors) and introduce a new community tool that allows researchers to define their own indoor air measurements based on our findings.

Methods

Our network was split into six working groups (WGs) that carried out activities over 4.5 years. These covered: a review of the existing literature on indoor air chemistry measurement and modelling studies (WG1), what the indoor and outdoor air quality communities can learn from each other (WG2), which pollutant species we should measure indoors based on different ranking criteria (WG3), how we best measure these species (WG4) and in what sort of buildings we should make measurements (WG5), to make our results as representative as possible. Finally, WG6 aimed to define a framework for future indoor air chemistry field campaigns, based on our findings from the first 5 WGs. In terms of timing, WGs1-2 ran in year 1 to provide the foundations for WGs3-5, which ran in years 2 and 3. The information from WGs1-5 was then used in year 4 to complete WG6. The framework for our WGs and the links between them are shown in Figure 1.

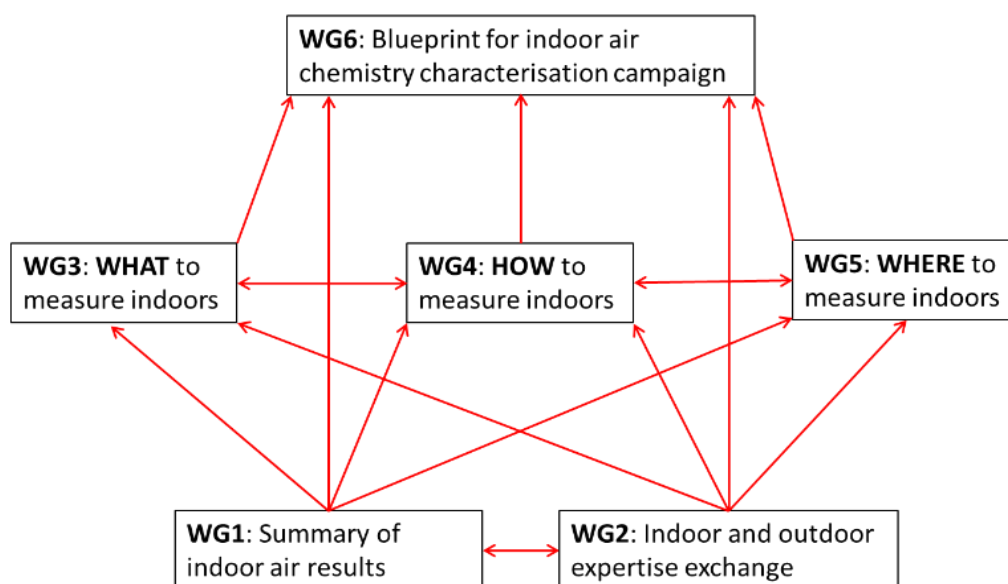


Figure 1: A conceptualisation of the Working groups (WGs) within INDAIRPOLLNET and the links between them.

The aim of WG1 was to identify species to measure indoors based on existing results from the literature. We divided our work into the following subtasks/topics:

- Chemical transformations (gas phase, surface chemistry, secondary organic aerosols, impact of moisture/hydrolysis, oxidation, role of ventilation).
- Indoor air chemistry in relation to six specific areas: Buildings (building materials, HVAC system); Occupants (human emissions, bioeffluents, clothes and their chemical transformations); Occupant behaviour/household products (cleaning agents, electronic equipment, cooking, smoking, appliances, furnishings); Microbial activity; Role of particles; Source apportionment of select chemical and particulate compounds.
- Modelling indoor air chemistry (identify existing models, compare their complexity, usefulness, weaknesses, experimental validations).

Our literature search focused on peer-reviewed literature, primarily reviewing articles and original papers published in the preceding 10 years when we started INDAIRPOLLNET (January 2009-December 2018). Non-peer-reviewed literature was excluded, except government reports and reports published by authoritative organisations such as WHO, EPA, UN. Older landmark studies were included, especially when a particular field was not well covered in recent literature. We focused on indoor air chemistry, rather than reports of indoor air pollutant concentrations alone. Exposure studies (studies reporting air and dust concentrations, exposure pathways, intake, metabolism, elimination, and health effects) were included to only a limited extent. The literature on particulate pollution is overwhelming. We focused on the aspects most relevant for indoor chemistry and chemical mechanisms for indoor particulate formation. The reports and publications associated with WG1 contain much more detail on the approach used [16-19] and key findings are covered in the next section.

The overall aim for WG2 was to *use existing outdoor air quality expertise and develop it for use indoors*. Outdoor air chemistry measurements and models have been developed over a much longer period of time than for indoors, and we wanted to exploit research of potential relevance for indoor environments. However, important differences exist, particularly with respect to surface-to-volume ratios, temperature and humidity ranges and photochemistry. WG2 therefore aimed to review outdoor measurement and modelling studies to date to identify: (i) the key challenges for outdoor air chemistry field campaigns, including the chemistry, the instrumentation (e.g., temperature, humidity, noise, space) and models, and how these can be overcome (ii) the sources, transformations and sinks of air pollutants with relevance for indoor air and how to apply this knowledge to mitigation and (iii) areas of indoor research relevant for the outdoor community.

Rather than focus on measurements or modelling of actual species and their concentrations, four broad areas and processes were identified based on our own knowledge of, and experience in, atmospheric chemistry, that could be useful for the indoor community. These four areas were outdoor field campaigns, outdoor models, simulation chamber studies and linkages between WG1 and WG2. More details summarising the approach can be found in our WG2 publications [20,21] and the key results are summarised in the next section.

The main aim of WG3 was to *identify the key species of chemical and biological origin to measure indoors and the rationale for doing so* (including through a consideration of chemical reactivity, health effects etc.). The work was divided into 8 sub-groups, with 2 main aims. Four of the sub-groups focused on different sources of indoor air pollutants (from building materials and activities, innovative materials and technologies, material ageing and biological processes). This led to identification

of approximately 900 distinct chemical species that had been detected indoors in the literature.

The other four sub-groups then focused on methods to rank the important species according to chemical reactivity, direct health effects, ability to form particulate matter (and hence have indirect health impacts) and impact on model uncertainty. The specific scientific objective will guide which of these ranking systems is most appropriate for a specific user. However, there are limitations, not least the lack of toxicity data associated with many of the species that have been measured indoors. Nevertheless, our database of species is now available to use (see '*identified species list*' in [22]), as well as the final report from WG3 that details more of the methodology [23].

WG4 aimed to *identify the best techniques to measure the species identified in WG3*. Instrumentation in the following groups was considered:

- inorganic gas-phase pollutants,
- free radicals,
- organic gas pollutants,
- particulate matter (physico-chemical characterization),
- bioaerosols,
- surface chemistry techniques, and
- use of low-cost sensors.

We reviewed the most common methods used in the literature, many of which are described through international standards. We also report on more sophisticated techniques for continuous monitoring of some of the key indoor air pollutants. Technical characteristics of the instrumentation, costs, limits of detection and quantification, and advantages and disadvantages of the different methods were all considered, with the aim of helping to choose the most appropriate technique according to the specific research objective. We also considered sampling methods used outdoors, as long as the equipment was suitable for an indoor space given its size, sampling rate and noise. This is especially important for measurements in residences or schools. Our WG4 summary report (INDAIRPOLLNET, 2023a) contains a brief summary of all of these techniques. More detailed sub-reports can also be found on the project website [22] and in publications covering inorganic gas-phase pollutants [24], free radicals [25], VOCs [26], particulate matter [27,28], multi-pollutant monitoring [29], surface chemistry [30] and low-cost sensors [31].

For WG5, the main aim was to *identify the best buildings in which to measure indoors*. The task was split into 8 sub-groups, 3 of whom explored general issues around building classification, guidelines and regulations, and parameters affecting IAQ. The other 5 reviewed specific types of buildings, namely residences, offices, educational, health care and sports facilities. A literature review was carried out, focusing on peer-reviewed literature, primarily review articles and original papers published between January 2010 and December 2020). The current regulations, standards, and guidelines for indoor environments with respect to measurement methods, building types, and pollutants were also summarised. As well as a final report and a published article [32,33], this WG also produced a list of parameters to be measured in all types of buildings, a list of existing IAQ regulations, and a document detailing where to measure based on target buildings or groups.

The aim of WG6 was to *define a blueprint for an Indoor Air Chemical Characterisation Campaign* using the results from WGs1-5. However, given the

different research needs, instrument and expertise availability, and numerous other variables involved for different groups approaching indoor air measurements, it was decided that a framework would be more flexible. Our main findings and our new framework are discussed in the *Results and Discussion* section.

INDAIRPOLLNET produced 16 deliverables. These included two training schools (in Spain and Hungary) and two training workshops (in Portugal and Spain) for the ECIs in the network, as well as recommendations from each of WGs1-5 based on their activities, an editorial, a summary of indoor air chemistry of relevance for outdoor air chemists, a list of building parameters and logistical requirements to accompany indoor air measurements, a strategy for determining efficacy of mitigation measures, the framework produced as our major output and a publication on this framework. All of these deliverables (or reports on them in the case of the ECI events) can be found on the project website (<https://indairpollnet.york.ac.uk/deliverables>).

Like numerous projects in recent years, our networking opportunities were limited by the Covid pandemic and many of our activities moved online. However, given the topic of our network, we took the opportunity to use our collected expertise to produce some pandemic-relevant guidelines for ventilation in classrooms [34] and public buildings [35].

Results and Discussion

(i) General observations and recommendations based on previous research

The INDAIRPOLLNET project produced a wealth of resources that can all be accessed freely on our project website [22]. In this section, we use the key findings from WGs1-5, to provide some observations and general recommendations for future measurements:

Increase the temporal and spatial scale of measurements: Few indoor air measurements to date have been made on a long-term basis (longer than a few weeks), and most studies focused only on one building (or even one room in one building). Interpretation and understanding of the significance of future measurements would benefit from longer-term studies in a wider range of locations, both within and between buildings.

Standardisation of measurement techniques: Direct comparison of indoor air pollutant concentrations is challenging as previous research has been conducted over different time periods, using different sampling techniques, and in a range of different indoor environments. We recommend that future scientific studies be conducted following standardised procedures, which will allow for easier intercomparisons between studies. This item is discussed in more detail in Saffell and Nehr [36]. For instance, they recommend the identification of standardised techniques for short-lived radicals and nitrous acid indoors and the need for health risk to better inform air quality standards.

More discussion between indoor and outdoor air quality communities: These two communities can learn much from each other (e.g. HOMEChem as described in Farmer et al., [11]) and we recommend referring to relevant research by the outdoor air community before planning indoor measurements (e.g. [18]). One particularly important point to note stems from some recent research highlighting that indoor emissions of volatile chemical products and their release outdoors may explain a

significant fraction of the gap in emission inventories for urban VOC sources [37]. A more exhaustive characterization of indoor emissions is therefore of interest for outdoor scientists to better assess this potentially important urban emission source.

Consider the building as well as the air inside it: Future measurements must consider the impact of building parameters (such as ventilation rate, lighting, temperature, and humidity) on IAQ, to be able to fully interpret the concentrations. Our work in WG5 identified the essential building parameters that should be measured in all future indoor air studies [33]. As well as building characteristics and furnishing materials, Baeza-Romero et al. [33] also suggested that renovation/retrofit, occupant demographics and activity, and indoor combustion sources needed to be considered.

Consider the impact of occupancy in a building: Our review of existing literature in WG1 [16,17] and the identification of key species indoors as part of WG3 [23] has highlighted the potential impact of the occupant on IAQ (also see Bekö et al., [38]). An empty building will experience different IAQ compared to when it is occupied (all other things being equal), and recent work has also shown that the impacts of occupancy can be sustained for several days after the occupants leave the building [39]. Such differences must be considered when trying to understand the IAQ in a specific building, or compare between measurements in different buildings and again, point to the need for standardised procedures.

Consider future changes to IAQ: Lifestyles, materials and products used indoors may change in the future and emerging pollutants may provide new challenges. Consequently, IAQ is also likely to change in the future. Outdoor O₃ is increasing in many cities owing to NO_x reductions through vehicle technology improvements, and with a warming climate, it may increase even more in the future [40]. Given that O₃ can ingress into buildings and interact with other indoor pollutants, there could be consequences for IAQ.

The main focus for INDAIRPOLLNET was to consider the chemical processes occurring indoors. However, the endpoint for much IAQ research is to identify pollutants formed through different activities/processes and highlight the potential implications for health. In the course of our work, we identified several questions linking IAQ and health, which we believe would make excellent research topics for those working in health science around air pollution. These include investigating how IAQ impacts the health of vulnerable groups, including school children in classrooms (especially in seasons with a high incidence of respiratory disease) and the sick in hospitals. There is often an interplay between biological and chemical pollutants in health care settings [41] and it would be beneficial to understand more about whether chemical or biological air pollutants are worse for health. It would also be interesting to understand how IAQ affects cognition (moving beyond carbon dioxide as the pollutant of concern) and, how this effect varies depending on age, sex, etc. Another area of interest is how IAQ in sports facilities impacts health. When assessing the health risk of indoor air pollutants, it is important to take into account the inhaled dose rather than only concentration, and this is particularly important in venues such as sport facilities, where pulmonary ventilation is higher due to exercising.

We also reviewed the literature regarding microbiological processes indoors and their relation to indoor air chemistry and highlight the following research gaps. There is a need for a better understanding of the relative VOC load from microbial activity (microbial VOCs or MVOCs) in a 'normal' versus a 'problem' (i.e. mouldy) dwelling, the role that MVOCs play in indoor air chemistry, and whether mouldy building materials produce significant levels of MVOCs indoors. It would also be

beneficial to better understand the role of biofragments, PM, surfaces and human activities as microbial carriers, and finally, whether microbial or human occupants in a building have a larger impact on IAQ.

(ii) Checklist for future experiments

Although the design of a specific indoor campaign depends on the final objective (e.g., IAQ assessment, source identification, health risk assessment, routine monitoring (perhaps around compliance) versus innovative research etc.), there are some key considerations that are applicable for all measurements. We recommend that before embarking on a measurement campaign, the parameters summarised in Table 1 are considered to facilitate experimental design.

Table 1: Summary of parameters to consider when planning indoor air measurements

Parameter	Notes	Reference
Type and number of pollutants to be investigated	Depends on the sources and activities of interest and the funding available	[23]
Monitoring approach	Personal sampling is most suitable for exposure assessment. Mobile monitoring units/fixed sampling most suitable for routine IAQ assessment. Outdoor instruments may be suitable if they can operate reliably indoors. Intercomparison exercises may be useful.	[42]
Methods or instruments to be used	Depends on availability and funding, but there are a range of reference grade methods linked to ISO standards, but also low-cost sensors.	[42]
Monitoring timescale	Depends on the scientific question, but as long as possible, within the constraints of the project time frame.	
Sampling time and temporal resolution	Depends on lifetimes of key pollutants, or whether resulting acute, subacute or chronic health effects are of interest.	
Sampling density and location	Depends on the research question, but representativeness needs to be ensured. CFD modelling to identify pollutant hotspots before measurements could be useful, as could the use of test-houses. With occupied houses, the impact of measurements on room layout and	

	occupant activities needs to be considered.	
Key parameters to be measured	Thermal and lighting characteristics, ventilation, building material composition etc. need to be considered	[33]

Given the summary we provided in the preceding section, the more measurements that can be made, in a large number of locations and for a substantial period, the better. However, these ideals will increase the costs substantially, and a pragmatic approach would maximise these ideals given the available funding. Careful consideration of these parameters at the planning stage should enable researchers to maximise the efficacy of the available funding.

(iii) A new framework for future indoor measurements

Using the results from WGs1-5 and a review of the more recent literature that had been published since we undertook our reviews for the working group activities, 5 broad research areas were identified for future studies to enable better understanding of indoor air chemistry. They are:

- Reactivity in Indoor Environments.
- Mapping organic constituents indoors.
- The role of the occupant in indoor air chemistry.
- Indoor modelling studies.
- Novel materials and technologies indoors.

Within each of these categories, there were then typically 2-4 more specific research objectives identified, with focus on indoor air chemistry. Figure 2 shows the conceptualised framework, with the main topics and specific research objectives identified. The identified objectives are by no means an exhaustive list of indoor air chemistry research needs, but they are some of the most pressing to address in future studies.



Figure 2: The conceptualised framework, showing the main research areas and specific research objectives within each.

The conceptualised framework has been used to form the basis of a Decision Tool, which can be accessed on our website [43]. The Decision Tool aims to provide advice to the community on how the specific objectives identified in Figure 2 could be addressed through measurements. For each of these 15 objectives that have been identified, the following questions are addressed:

- **Why is this specific objective important?** Based on the findings from WGs1-5, context is provided on the knowledge gap, such as identifying which processes we do not yet understand and why it is important to do so, what

might be the potential impacts on buildings and their users of gaining further understanding in this topic area and why might there be health effects.

- **What do we already know about the topic?** This section provides the user with links to our publications (and those of others) that provide information on what is already known about the topic. This information is mainly available in the final reports of WGs1 and 2 [17,18].
- **What species should we measure?** Based on the specific objective, there are key species that need to be measured to achieve it. The output material from WG3 [23] provides information on what pollutants might be emitted in different scenarios, and also a ranked list of the most important ones according to their reactivity and known health effects.
- **How should we measure the species identified above?** Based on the specific objective, available time and costs, appropriate measurement techniques are suggested. These recommendations are based on the output from WG4 [42], and the numerous publications that have resulted from it [24-31]. For every set of indoor measurements, a key set of building parameters should also be determined (e.g. ventilation rate, temperature, humidity, lighting, building orientation, and layout, etc.), together with guidelines on how to evaluate these parameters [32,33].
- **Where should we measure the species identified in the specific objective?** There may be a particular study group (e.g. children) such that identification of a type of building is obvious (e.g. school). However, where it is not obvious, information is provided around what can be gained from measurements in a range of different settings, namely residences, offices, schools, health-care settings and exercise facilities, based on our reports and publications from WG5 [32,33].

As an example of this process, the first specific objective within the '*Reactivity in Indoor Environments*' research area, is '*The sources of reactivity indoors*'. If the user clicks on this objective on the website [43] they will find the texts elaborating on the five questions outlined above, with numerous hyperlinked publications. Figure 3 provides an example of the information that can be found around what species to measure and how to measure them.

What species should we measure?

As the gas phase reactivity is linked to the presence of oxidants, there is a need to measure oxidant concentrations (Ozone, OH, HO₂, RO₂, Cl, NO₃), those of their precursors HONO, HCl, HOCl, ClNO₂, and the concentrations of their key reactants (VOCs) in order to understand chemical processing in the gas-phase. For more information, see the [WG1 editorial](#), the [WG1 summary report \(Part. 1. Chemical transformations, Brief summary of the state-of-the-art\)](#) and the list of oxidants and their precursors ([WG3 table indoor oxidants precursors gas](#)). In terms of species to measure around surface reactivity, more information can be found here in this table: [Table WG3 aging reactive](#). Outdoor concentrations of NO_x, O₃ and VOCs also need to be measured to understand the role of ingress from outdoors.

How should we measure these species?

- **Ozone**: WG4 work described in Part 5.2.1, p13 in [Sampling and analysis techniques for inorganic air pollutants in indoor air](#)
- **HO_x/RO_x**: WG4 work described in Part 2.1.1-2.1.3, p6 for OH, 2.1.6 p10 for HO₂, 2.2 p 11 for RO₂ in [Techniques for measuring indoor radicals and radical precursors](#). Note that no instrument is yet available for speciation of RO₂ (with the possible exception of CH₃O₂) but some instruments are under development (based on mass spectrometry). OH reactivity can be a useful measure for understanding total formation and loss processes.
- **Cl**: No technique is currently available, so precursors should be quantified and models [used](#).
- **NO₃**: WG4 [Techniques for measuring indoor radicals and radical precursors](#)
- **HONO**: WG4 work described in Part 2.3, p13 in [Techniques for measuring indoor radicals and radical precursors](#)
- **HCl, HOCl, ClNO₂**: WG4 work described in Part 2.4 and table 5 p 596, in [Techniques for measuring indoor radicals and radical precursors](#)
- **VOCs**: refer to Mapping organic constituents and WG4 Full article: [An overview of methodologies for the determination of volatile organic compounds in indoor air](#)
- **Surface characterisation**: WG4: [A review of microbial and chemical assessment of indoor surfaces](#)
- **Particles**: WG4: [Full article: Particulate matter indoors: a strategy to sample and monitor size-selective fractions](#)

Figure 3: User view of the information provided on what species to measure and how to measure them for the specific objective ‘The sources of reactivity indoors’.

Our framework is based on the research that has been carried out to date. As more studies are carried out, the answers to some of the research questions we have highlighted will be answered. A review of this process would be useful every 5-10 years to benchmark the most pressing research questions as the science advances.

Conclusions

INDAIRPOLLNET has summarised the existing indoor air chemistry research and used it to identify gaps in our knowledge, and to construct a new framework to guide future indoor air measurements. The work of INDAIRPOLLNET has also highlighted the need for standardised approaches towards indoor air measurements and the expansion of the spatial and temporal dimensions of indoor air measurements in the future. Such information would better help us to understand how indoor emissions and their impacts vary by location and change over time.

Although this work has been carried out predominantly by European scientists, we believe the framework is more widely applicable. Our suggestions on how to make measurements of different species will apply wherever measurements are needed, and the list of building parameters to consider alongside those of air pollutant measurements are also universal. Of course, in different parts of the world, the research questions may differ.

A series of indoor air observatories set up across Europe (or indeed globally), where activities could be coordinated across the continent, would allow us to better understand some of the variations in indoor air quality caused by differences in location (temperature, humidity, lighting, etc.) and cultures (ventilation, cooking styles, etc.). Such a network of well characterised test facilities with a minimum set of

controlled variables in conjunction with a coupled indoor chemistry/dynamics model framework, could enable the study of many of the specific research questions identified by INDAIRPOLLNET. The EUROCHAMP network of simulation chambers for understanding outdoor air quality [44] provides a good model.

Finally, we believe there is the potential for new modes of data collection (and analysis, e.g., using machine learning) to significantly move this field forward. Wearable devices that embed sensors for environmental parameters, cardio, and respiratory signals of users, as well as chemical and biological pollution concentrations could be used to provide a wealth of citizen data. Such data would enable us to understand more about personal exposures to air pollution, and to understand how to better design appropriate mitigation to reduce these.

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