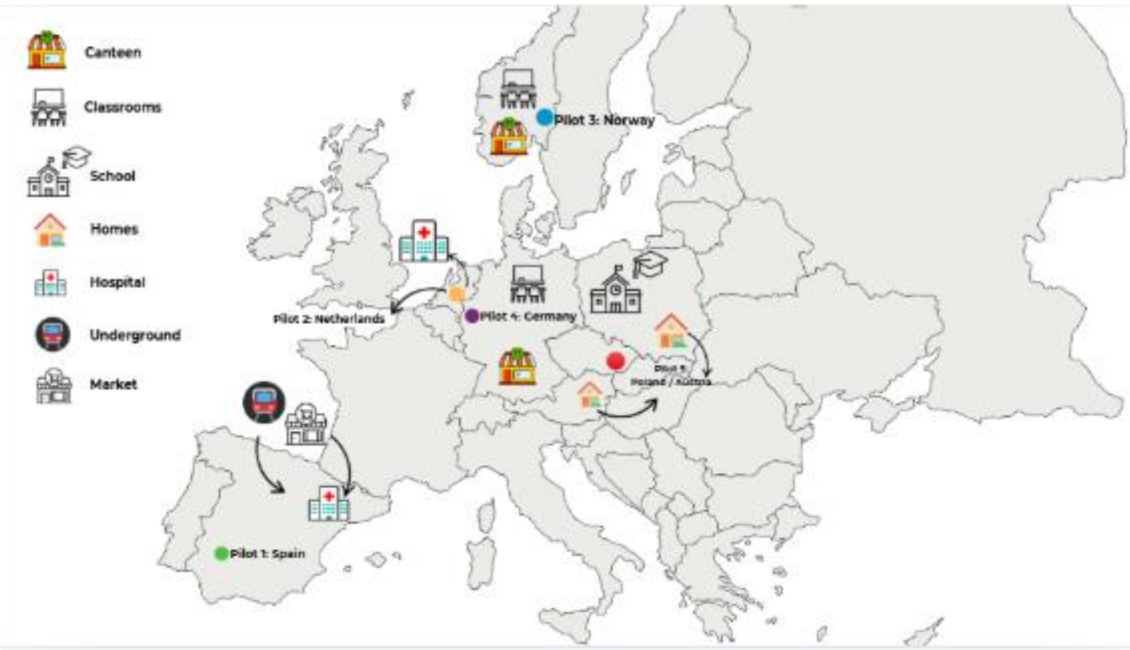
Digging Deeper: Where Indoor Air Pollution Comes From
Insights from K-HEALTHinAIR's second phase of monitoring

Tracing the sources of poor Indoor Air Quality

This brief summary presents findings from the second stage of the K-HEALTHinAIR project, which builds on the initial scan of indoor environments across Europe. While the first phase focused on characterising conditions and refining methods, this second phase turns attention to uncovering the sources and key determinants influencing indoor air quality (IAQ).

Through detailed analysis of the data collected across multiple real-life scenarios, the project begins to map how different pollutants enter and accumulate indoors—whether from human activities, building features, or outdoor infiltration. These insights provide a foundation for understanding pollutant pathways and shaping effective mitigation strategies.

This work marks a key step in moving from observation to explanation. While it does not yet link these sources to health outcomes, it lays critical groundwork for the next research phase, where such connections will be explored more fully.



K-HiA pilots' scenarios

1. Methodology

Continuous indoor air quality (IAQ) monitoring was conducted across the scenarios using advanced sensors that measured PM_1, $PM_{2.5}$, PM_{10}, CO_2, VOCs, temperature, and humidity. To contextualise indoor readings, outdoor air quality and meteorological

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data were obtained from the AerisWeather platform for comparison over time. Data were collected over several months, synchronised into centralised databases, and subjected to strict quality control to detect gaps, outliers, and sensor issues, ensuring only validated records were analysed. Analytical methods included statistical correlations, indoor/outdoor ratios, time-series visualisations, and machine learning techniques—such as unsupervised clustering—to identify pollution episodes and classify risk profiles.

2. Key findings

For each type of environment, the main pollution sources and associated key contaminants were identified based on the data collected between months 7 and 18 of the project. Key finding for each pilot and specific scenario are described in the following lines:

Barcelona pilot:

- Homes.
- Hospital
- Schools.
- Metro stations.
- Markets.

Homes

- Cooking (gas, biomass): Linked to increased levels of CO_2, PM2.5, VOCs, and formaldehyde. Peaks in particle and formaldehyde concentrations were observed especially in poorly ventilated kitchens using gas or biomass
- Smoking: Associated with high emissions of VOCs and PM, and to a lesser extent formaldehyde
- Heating (biomass, electric): Mainly contributes to CO_2, PM, and some VOCs, depending on the system used

Hospitals

- Cleaning / disinfection: Directly linked to VOCs (from cleaning products) and formaldehyde (from disinfectants). These sources also impact the microbiome balance
- High occupancy: Increases levels of CO_2, PM, and microbial load due to human presence and activity

Markets

- Crowd density: Leads to elevated CO_2 from human respiration, and PM2.5 due to movement and air exchange with outdoor environments
- Poor ventilation: Exacerbates the accumulation of VOCs, CO_2, and PM already present in the space

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Schools

- Use of wood materials (e.g. furniture): Associated with formaldehyde and VOCs emitted by wood composites and surface treatments
- High occupancy + cleaning: Combination increases CO_2, PM, VOCs, and alters the microbiome, particularly in classrooms with limited ventilation

Metro Stations

- High occupancy: Main source of CO_2, also contributes to PM resuspension and accumulation.
- Limited air exchange: Results in build-up of formaldehyde, VOCs, and CO_2, especially during periods of high foot traffic or low ventilation rates

Rotterdam Pilot

- Homes (Outpatients)
- Hospitals
- Senior Homes

Homes (Outpatients)

- Cooking and heating: Variable impact on CO_2 and VOCs depending on appliance type and ventilation practices.
- Limited ventilation: Episodes of elevated CO_2 and PM2.5 during occupancy peaks.
- Cleaning activities: Occasional increases in VOCs from household products.

Hospitals

- Controlled ventilation systems: Generally low pollutant concentrations across monitored areas.
- Occupancy: Moderate increases in CO_2 during busy periods.
- Cleaning/disinfection: Small fluctuations in VOCs, but well below critical thresholds.

Senior Homes

- Occupancy density: Slight elevations in CO_2 during visiting hours or communal activities.
- Mechanical ventilation: Maintains stable PM and VOC levels.

Conclusions and open lines of work:

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Overall, IAQ remained stable across most environments, particularly in hospitals and senior residences with good ventilation systems. However, variability was observed in outpatients' homes, mainly due to differences in heating and ventilation habits. Next steps include completing VOC and formaldehyde sampling, analysing seasonal trends, and assessing the effectiveness of ventilation behaviour.

Norway Pilot

- Canteens
- Lecture Halls
- Student Residences

Canteens

- High occupancy: Associated with increased CO_2, PM2.5, and microbial contamination during meal times.
- Cooking activities: Contribute to episodic peaks of PM and VOCs, especially in serving areas.
- Limited ventilation: Amplifies accumulation of pollutants, particularly in winter periods.

Lecture Halls

- Crowding: Results in elevated CO_2 and higher bacterial/fungal loads during lectures.
- Natural ventilation reliance: Causes fluctuations in pollutant concentrations depending on weather conditions.
- Cleaning routines: Contribute modestly to VOC and aldehyde levels.

Student Residences

- Heating systems: Influence indoor PM and VOCs, with variation across buildings.
- Occupant behaviour: Strongly affects CO_2 levels and ventilation adequacy.
- Incomplete chemical sampling: Some VOC and formaldehyde measurements were pending during the reporting period.

Conclusions and open lines of work:

Preliminary results indicate generally acceptable IAQ with some pollutant peaks linked to crowding, cooking, and limited ventilation. Key priorities are completing VOC and formaldehyde analyses, improving ventilation during high occupancy, and correlating microbial contamination with occupancy density.

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Germany Pilot

- Canteens
- Lecture Halls

Canteens

- Cooking activities: Generate peaks of PM and VOCs during meal preparation and service times.
- High occupancy: Leads to elevated CO_2 and increased microbial contamination, especially during lunch hours.
- Seasonal variation: Higher aldehyde concentrations observed in winter due to reduced ventilation and heating practices.
- Mechanical ventilation: Generally effective but shows variable performance depending on occupancy.

Lecture Halls

- Crowding: Causes notable rises in CO_2 and microbial load during full sessions.
- Seasonal accumulation: VOCs, especially aldehydes, tend to increase in colder months.
- Ventilation systems: Primarily mechanical but sometimes insufficient during peak use.
- Cleaning routines: Minor contributor to VOCs.

Conclusions and open lines of work:

IAQ in German canteens and lecture halls showed clear patterns of seasonal and occupancy-related variability. Future work will focus on comparing results across seasons, linking subjective perceptions with measurements, and developing targeted measures to mitigate pollution during peak activity.

Poland / Austria Pilot

- Schools
- Homes

Schools

- Poor ventilation: Frequently resulted in CO_2 concentrations exceeding 1500 ppm during classroom occupancy.

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- Heating systems (combustion): Associated with elevated PM_4 containing PAHs, especially in winter.
- Building materials and furnishings: Emission of formaldehyde and VOCs from wood composites and surface treatments.
- High occupancy + cleaning: Combination contributed to increased VOCs, CO_2, and microbial contamination.
- Limited air exchange: Amplified accumulation of pollutants during cold seasons.

Homes

- Heating practices (biomass, gas): Major source of PM, PAHs, and CO_2 during the heating season.
- Poor ventilation: Led to elevated concentrations of VOCs and CO_2, particularly in winter.
- Cooking activities: Contributed to increases in PM and VOCs.
- Occupancy density: Associated with microbial load and indoor air stagnation.

Conclusions and open lines of work:

The monitoring revealed significant impacts of heating practices, poor ventilation, and occupancy on indoor pollution, particularly in winter. Upcoming priorities include completing summer campaigns for seasonal comparison, promoting ventilation improvements, and clarifying the contribution of heating versus outdoor infiltration.

The following table summarises the key finding for each scenario:

Pilot	Environment	Main sources of indoor air pollution	Key contaminants
Barcelona	Homes	Cooking (gas), smoking, heating (biomass/electric)	CO_2, PM, VOCs, formaldehyde
	Hospitals	Cleaning, disinfection, use of chemicals, moderate occupancy	PM, VOCs, formaldehyde, microbiome
	Schools	High occupancy, cleaning, use of wood materials (furniture)	CO_2, PM, VOCs, microbiome, formaldehyde

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	Metro Stations	High occupancy, limited air exchange	PM, VOCs, formaldehyde, CO_2
	Markets	High crowd density, poor ventilation, food-related emissions	PM2.5, VOCs, CO_2
Rotterdam	Homes	Cooking (electric), heating, poor ventilation	CO_2, PM, VOCs
	Hospitals	High occupancy, cleaning, HVAC system emissions	PM, VOCs, formaldehyde
	Senior Homes	Aging population, heating, low ventilation	CO_2, PM, VOCs, formaldehyde
	Outpatients	Intermittent occupancy, portable monitoring devices	CO_2, PM, VOCs
Noruega	Canteens	Wooden surfaces, heating, occupancy	CO_2, PM, VOCs, formaldehyde
	Lecture Halls	High occupancy, limited ventilation	CO_2, VOCs, formaldehyde
	Residences	High occupancy, indoor activities	CO_2, PM, VOCs, formaldehyde
Alemania	Canteens	Cooking, cleaning, use of HVAC	CO_2, PM, VOCs, formaldehyde, microbiome
	Lecture Halls	High occupancy, seasonal differences in use	CO_2, VOCs, PM, formaldehyde
Polonia / Austria	Homes	Heating (solid fuels, gas, electric), cooking, low ventilation	CO_2, PM, VOCs, PAHs, formaldehyde
	Schools	Cleaning, wood furniture, varied traffic exposure	CO_2, PM, VOCs, formaldehyde, microbiome

3. Impact of activities on indoor air quality

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Typical indoor activities such as cooking, smoking, cleaning, and human occupancy were found to significantly influence concentrations of particulate matter (PM2.5), volatile organic compounds (VOCs), and in some cases formaldehyde, across the monitored environments. The impact was assessed through comparative analysis of sensor data and targeted sampling campaigns.

- High-impact activities:
  - Smoking and cooking, particularly using gas or biomass, consistently led to sharp peaks in both PM2.5 and VOCs levels, especially in residential settings. In homes with poor ventilation, sensor readings showed persistent elevations in pollutant levels after cooking episodes. Similarly, smoking was identified as a key contributor to localised spikes of fine particles and VOCs, with higher indoor/outdoor (I/O) ratios confirming indoor origin
- Moderate-impact activities:
  - Cleaning routines, especially in hospitals and schools, were associated with detectable increases in VOCs and formaldehyde, depending on the disinfectants and surface materials involved. Hospital environments with more intensive disinfection protocols showed higher baseline VOC levels, suggesting accumulation or frequent use
  - High occupancy density contributed to increased levels of CO_2, and indirectly to PM2.5 and bioaerosols, particularly in enclosed environments like classrooms and hospital wards. These increases were most evident during periods of sustained occupancy and limited ventilation, with peak levels aligning with daily use patterns

These findings support the role of behavioural and functional patterns in shaping indoor air quality and highlight the need for targeted interventions—such as improved ventilation, material selection, and activity scheduling—to mitigate pollutant exposure in sensitive indoor environments.

The analysis is qualitative; the report does not include specific numerical values, emission rates or time-series plots linked to individual activities

4. IAQ variability and influencing factors

Indoor air quality (IAQ) levels varied significantly across pilot sites and timeframes, driven by factors such as building characteristics, ventilation performance, climate conditions, and occupant behaviour.

- Environmental differences. Each monitored environment exhibited a unique IAQ profile, shaped by a combination of factors such as building typology, materials used, ventilation strategies, climatic context, and user behaviours (e.g., frequency of window opening, type of activity).

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- Effectiveness of ventilation. Sensor data showed that ventilation events (natural or mechanical) led to immediate reductions in pollutant levels, particularly CO_2 and VOCs, in homes, schools, and healthcare environments. This supports ventilation as a key driver in controlling indoor pollutant accumulation.
- Microbiological contamination. Airborne microbial concentrations (bacteria and fungi) were found to correlate strongly with ventilation quality and occupancy density, especially in hospitals and schools. Poor ventilation and high occupancy were linked to elevated microbial loads, reinforcing the importance of air exchange for bioaerosol control.

In addition to activity-related factors, IAQ variability is also influenced by external climate conditions, seasonal changes, and the type of ventilation (natural or mechanical) present in each environment. These contextual elements, which are more extensively discussed in the full deliverable, play a critical role in explaining differences observed across pilots and time periods.

5. Conclusions and recommendations

Improving indoor air quality requires environment-specific strategies that reflect the unique conditions and uses of each space. Effective interventions include scheduled or demand-controlled ventilation, careful selection of interior materials to limit emissions, and active management of occupancy levels. Among all measures, ventilation consistently emerged as the most critical factor, particularly following activities known to increase pollutant concentrations. Continuous IAQ monitoring is essential to enable timely responses and reduce prolonged exposure risks. Looking ahead, the project aims to integrate medical data in future phases to directly evaluate the health impacts of indoor air quality.

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