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Schools' **a**ir quality **m**onitoring for **h**ealth and **e**ducation: Methods and protocols of the SAMHE initiative and project

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ABSTRACT

Background: Children spend significant amounts of time at school, making the school environment a potentially important contributor to air quality exposure.
Aim: The SAMHE initiative has a dual aim: 1) to develop and test a bespoke citizen science framework for collecting environment and indoor air quality data in classrooms, alongside contextual data capable of enriching analysis, at an unprecedented scale; and, 2) to simultaneously use these methods to raise awareness among communities regarding their exposure to air pollution in the school environment.
Methodology: To achieve this dual aim, the SAMHE project was initiated to deploy more than 2 000 low-cost indoor air quality monitors in school classrooms. A Web App has been co-designed with schools to support collecting a large comprehensive dataset (including school buildings characteristics, operation, and behavioural patterns) and to enable students and teachers to interact with the data gathered in their school.
Results and outlook: We present the design of the interface and visuals that have been co-designed with 20+ schools and tested with 120+ schools. Within one week of the SAMHE launch week, 537 schools had registered to join the project, and at the time of writing (just seven weeks later) this number had grown to around 800 schools. This highlights the potential for this novel initiative to provide a step-change in the way that indoor air quality datasets are gathered at a national and, potentially, international level while simultaneously enabling schools to better manage their indoor environment and empowering students and teachers to reduce their environmental health risks.

1. Background and motivation of the SAMHE initiative

Outside of their home, children typically spend the greatest proportion of their time at school, mostly indoors. While children are generally unaware of the air that they are breathing, their school can represent a significant exposure environment that can trigger health outcomes (Sin et al., 2005). School buildings are a challenging environment to design and regulate as they need to provide acceptable

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environmental conditions while accommodating periods of high and variable occupancy density. This results in high internal heat gains, emissions of body odours, and elevated levels of various indoor pollutants (Chatzidiakou et al., 2012). Typically, school classrooms have around four times as many occupants per unit floor area as a modern office building, frequently resulting in deteriorated indoor air quality (IAQ) (Wargocki and Wyon, 2013).

During the developmental stages associated with school ages, children are particularly vulnerable to air pollution because of their high activity levels and developing lungs, which intake more air relative to their body mass compared to adults (Schwartz, 2004). Cumulative evidence points towards an association between school-based exposure to traffic-related pollutants and health outcomes, including increased illness-related absenteeism (Zhang et al., 2022), asthma incidence (Gasana et al., 2012) and asthma exacerbation (Guarnieri and Balmes, 2014). A causal linkage between air pollution exposure and suboptimal lung growth has been further supported by analysis of consecutive longitudinal cohorts in the Children's Health Study (Gauderman et al., 2015) in which the proportion of children with clinically small lungs was reduced as air quality improved between 1994 and 2011. Rising respiratory disease has led to an increasing research focus on indoor air quality in schools and highlighted the need (see §1.5) for the collection and analysis of large-scale datasets of school environments. This can provide more reliable exposure estimates in epidemiological research to draw more reliable health associations. The methods of the SAMHE initiative seek to meet this need in the UK and support others around the world to follow suit; the SAMHE project is working to deploy these novel and scalable methods to around 2 000 schools, as described in this paper.

1.1. Evidence on particulate matter levels in school classrooms and recommended guideline values

IAQ is a complex interaction of constantly varying ventilation rates, indoor sources from occupants' activities, emissions from building materials, indoor chemistry, and deposition/re-suspension processes. IAQ depends strongly on the interaction between the building and the outdoor environment because outdoor air pollution can penetrate indoors through intended openings (ventilation) and unintended cracks in the building envelope (infiltration). Common pollutants in classrooms include those with predominantly outdoor sources (primarily traffic in urban environments), such as nitrogen oxides; air pollutants that have both indoor and outdoor sources, such as airborne particulate matter (PM); and pollutants with primary indoor sources, such as volatile organic compounds (VOCs) and carbon dioxide (CO_2).

Currently, there is no specific reference directive focused on IAQ in European legislation. Some EU Member States, have started to adopt specific guideline values (typically those developed by the World Health Organization) for IAQ, which in some cases are enforced in the legislative acts of those countries (Settimo et al., 2020). Based on cumulative epidemiological and toxicological evidence, the WHO provides the scientific basis for legally enforceable threshold values for selected pollutants with primarily indoor sources. Publication of World Health Organization (2006) specified that existing outdoor air quality guidelines can be applied to indoor air, while World Health Organization (2009) published guidelines for indoor dampness and mould. Indoor air guidelines were further updated in 2010 and in 2021 (World Health Organization, 2021) and updated guideline values for PM, see Table 1 (amongst other pollutants).

Table 1
Air Quality Guideline values for PM (World Health Organization, 2021).

Pollutant	Averaging period	AQG[a] 2021
PM_{10}	1 day	45 μg/m^3
	Calendar Year	15 μg/m^3
$PM_{2.5}$	1 day	15 μg/m^3
	Calendar Year	5 μg/m^3

[a] AQG = Updated Air Quality Guidelines 2021.

Unlike measurements of ambient outdoor air pollution levels, for which longitudinal datasets are routinely recorded in many countries around the world, routine measurements of indoor air quality are rarely recorded and centrally collated. A recent systematic review (Sadrizadeh et al., 2022) found approximately 300 eligible studies worldwide on IAQ in classrooms. One of the largest studies was initiated in 2012 by the European Commission (SInPHONiE - Schools Indoor Pollution and Health Observatory Network in Europe) (Csobod et al., 2014) to assess air quality in 114 primary schools (5 575 students) across 23 EU countries (including the UK). According to this study, about 85% of students were, in their classrooms, exposed to $PM_{2.5}$ and PM_{10} concentrations higher than those considered safe by WHO for the prevention of cardiopulmonary diseases.

A systematic review of the evidence (Son, 2023) showed that indoor levels of $PM_{2.5}$ and PM_{10} measured in 40 studies in elementary classrooms varied widely, falling in the ranges 4–100 μg/m^3 and 10–284 μg/m^3, respectively. It was found that the average concentration ranges of classroom PM measured in Asia ($PM_{2.5}$: 4–90 μg/m^3 and PM_{10}: 12–284 μg/m^3) and Europe ($PM_{2.5}$: 8–100 μg/m^3 and PM_{10}: 71–140 μg/m^3) were typically higher than those measured in Australia and North and South America ($PM_{2.5}$: 6–23 μg/m^3 and PM_{10}: 10–30 μg/m^3) with all sometimes exceeding WHO guidelines.

1.2. Indoor levels of total volatile organic compounds in school classrooms and suspected health effects

VOCs include a variety of organic chemicals that are emitted as gases from certain solids and liquids. Indoor sources may be continuous or intermittent. The most common indoor continuous sources in schools are building construction materials, furniture and textiles. Intermittent sources include occupants and a number of their activities. There is sufficient evidence from both human and animal studies to believe that some VOCs have carcinogenic and mutagenic effects on human health. For example, benzene is classified as a carcinogen and no safe limit of exposure can be recommended (World Health Organization, 2021). Some VOCs have health effects associated with chronic exposures at low concentrations, so symptoms may not completely manifest for years (Liu et al., 2022).

Most VOCs are typically much more concentrated (often up to ten times more concentrated) within indoor air compared with those within outdoor air. As hundreds of different VOCs have been detected indoors, each at a low concentration but higher than outdoors, the concept of total VOCs (TVOCs) has been introduced in the existing literature. The concentration of TVOCs given by different detector types when exposed to mixtures in an environment is not equivalent because of the different detection methods, exhibiting different sensitivities. In other words, the value of the TVOCs measurement will depend both on the type of detector used, and the specific mix of individual VOC species within the space. To date, this has caused confusion because TVOC recommendations are often not accompanied by a clear TVOC definition..[1] Despite these challenges, in some countries, thresholds for TVOCs within non-industrial indoor environments have been developed, and most of

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[1] The standardised way to measure TVOCs includes clearly defined analytical conditions. The first exposure-range classification relative to the TVOC level was suggested by a committee of the European Collaborative Action Indoor Air Quality and its Impact on Man (Commission, 1993), which has since then formed the basis for VOC measurement by means of gas chromatography/mass spectrometry following thermal desorption on Tenax TA (Mølhave, 1991). In this case, the range of VOCs to be included in the TVOC value is defined by the retention window between n-hexane (C6) and n-hexadecane (C16) under clearly defined analytical conditions (BSI 16000-6, 2021).

them are in the magnitude of 200 μg/m^3 to 600 μg/m^3 (Salthammer, 2011) to prevent discomfort and acute associated health issues. In the UK, the recent version of Building Regulations Part F (Department for Levelling Up, Housing and Communities & Ministry of Housing, Communities and Local Government, 2022) based on the European Collaborative Action (Commission, 1993) recommends concentrations below 300 μg/m^3 for domestic buildings, for example.

Other sub-clinical outcomes, such as sick building syndrome (SBS), a group of non-specific health symptoms, have no clear causation but are attributable to exposure to a particular building environment (Mølhave, 1991). Since the early 1980s, the WHO has compiled a list of the common symptoms reported in what they defined as SBS.[2] Questionnaires to investigate SBS symptoms have been developed and have become established research tools. Currently, little evidence is available on the association between specific indoor exposures with either perceived IAQ or SBS symptoms in schools. Suggestive evidence indicates that exposure to traffic-related pollutants and TVOCs may trigger SBS symptoms in schools (Vardoulakis et al., 2020; Chatzidiakou et al., 2015). Keeping the air dry and cool can reduce SBS symptoms and improve people's perceptions of IAQ (Norbäck, 2009; Norbäck and Nordström, 2008; Chatzidiakou et al., 2012). Higher ventilation rates have been reported to reduce SBS symptoms by diluting indoor-generated pollutants such as TVOCs and purging microbial concentrations (Bornehag et al., 2001).

1.3. *The effects of carbon dioxide on health, cognitive performance and IAQ perception*

Due to the difficulty and costs in collecting measurements of individual pollutant species in classrooms, most standards around the world, such as ASHRAE 62.1 (ASHRAE Standard Committee 62.1, 2022) adopt CO_2 levels as a basic assessment tool for ventilation rates, occupancy, bio-effluents, and perceived IAQ.

At very high concentrations, CO_2 has significant acute health effects. Emerging evidence indicates that chronic or intermittent exposure to CO_2 at concentrations as low as 1 000 ppm (a threshold that is already exceeded in many classrooms) is associated with potential health risks (Jacobson et al., 2019) including inflammation, bone demineralisation, kidney calcification, oxidative stress and endothelial dysfunction. CO_2 can also directly impair higher-cognitive abilities (Jacobson et al., 2019; Du et al., 2020) that may impact negatively the academic performance and learning of pupils. A previous systematic review (Chatzidiakou et al., 2012) reported measured indoor CO_2 levels in 53 classrooms in 14 studies ranging from outdoor levels to more than 4000 ppm with most studies exceeding the 1000 ppm threshold value.

Apart from the potential direct effects of CO_2 on health, in environments with high occupant density, such as classrooms, indoor CO_2 levels produced by occupants' breathing can be a useful indicator of ventilation rates. Ventilation is the process of exchanging indoor air with that from outdoors, which may lower indoor CO_2 levels and dilute pollutants from indoor sources but can introduce certain pollutants from outdoor sources (e.g. NO_x). Therefore, indoor CO_2 levels and corresponding ventilation rates are good indicators of levels of other indoor-generated pollutants. However, indoor CO_2 levels do not reflect all exposure risks (Lowther et al., 2021); for example, traffic-related pollutants, which must be considered separately. Therefore, low CO_2 levels do not in themselves guarantee a healthy school environment.

Ventilation is an important measure for reducing the risk of airborne infections in schools, including the flu, colds or COVID-19. Reducing pathogens' residence time in the classroom (Jendrossek et al., 2023) has the strongest effect in reducing disease transmission. Indoor CO_2 levels can, therefore, be used to estimate the probability of contracting airborne communicable infections which can only be acquired by inhaling air that has been previously exhaled (Rudnick and Milton, 2003; Riley et al., 1978). Decreases of indoor CO_2 levels by 1 000 ppm were associated with a decrease in the illness-related absence rate of students between 1% and 2.5% (Chatzidiakou et al., 2014).

While higher rates of illness-related absenteeism may have negative consequences on the health, social and educational outcomes of all students (Haverinen-Shaughnessy et al., 2015), a sub-population of school-aged children with pre-existing asthma can face even greater IAQ-associated challenges from their schooling. Respiratory infections (including COVID-19) and exposure to allergens (Abrams et al., 2020) trigger their asthma. In many countries, peaks in asthma-related hospital admissions among children approximately coincide with their return to the school environment each academic year (Sears and Johnston, 2007).

In terms of the impacts of IAQ on the academic performance of students, systematic meta-analyses of the literature showed that low ventilation rates, and thus high indoor concentrations of CO_2, impair attention span and increase concentration loss and tiredness (Mendell and Heath, 2005; Chatzidiakou et al., 2014; Pulimeno et al., 2020; Haverinen-Shaughnessy et al., 2015). The evidence shows that increasing ventilation rates from 5 L/s-p (litres per second per person) to 15 L/s-p was associated with a 7% improvement in academic performance (Wargocki et al., 2002; Chatzidiakou et al., 2014) and lower temperatures in the range of 25 °C–20 °C improved student performance by 2%–4% for every 1 °C reduction (Chatzidiakou et al., 2014). The effects of ventilation rates, thermal conditions and CO_2 levels in classrooms may, therefore, be both directly and indirectly linked to academic performance. While their effects might be confounded by other co-existing pollutants in poorly ventilated classrooms, emerging evidence indicates that CO_2 might also directly lead to reductions in higher-level cognitive abilities (Jacobson et al., 2019). Moreover, asthmatic symptoms and absenteeism increase at higher CO_2 levels (with the increasing probability of acquiring a communicable infection) and this might also indirectly impair academic performance through reduced attendance.

1.4. *Improving the evidence base for IAQ with low-cost sensor technologies*

The lack of data for IAQ levels within classrooms hinders the enforcement of existing regulations, and the formulation of more efficient regulatory frameworks. Thanks to their significantly reduced cost, smaller size and fast response, low-cost sensors have the potential to provide highly resolved reliable exposure metrics in a way that has not been possible previously. Instrument development has been accelerating with a growing number of companies utilising combinations of such sensors (Cross et al., 2017). The principles of operation of the low-cost gas-phase sensors are typically metal oxide semiconductors (MO_x), electrochemical and non-dispersive infrared sensors (NDIR) and photo-ionisation detectors (PID), while low-cost PM sensors commonly employ optical particle counters (OPC). By appropriate calibration, the performance of low-cost sensors can be comparable with reference instruments (Chatzidiakou et al., 2015; Mead et al., 2013). Studies have deployed IAQ monitors to quantify multi-pollutant personal exposure (and indoor concentrations) in diverse microenvironments for health research (Evangelopoulos et al., 2021; Han et al., 2020; Chatzidiakou et al., 2020, 2022). Low-cost sensors have also been widely used to provide useful qualitative information to citizens. Increasing evidence from low-cost sensor deployments in schools generates much-needed exposure data and increases air quality awareness among schoolchildren (Grossberndt et al., 2021; Chen et al., 2020; Kaduwela et al.,

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[2] These symptoms include: mucosal symptoms (eye, nose and throat irritation, sensation of dry mucous membranes); dermal symptoms (dry, itching and red skin); neurological symptoms (headaches and mental fatigue); respiratory symptoms (high frequency of airway infections and cough, hoarseness and wheezing); and general symptoms (nausea, dizziness and unspecific hypersensitivity). Further, the WHO panel lists odour and taste sensations. All except skin symptoms should improve within a few hours of leaving a problem building; apart from dryness of the skin, which may take a few days to improve.

2019).

The scientific community has raised concerns regarding the reliability and reproducibility of measurements collected with such sensors because previous studies in both the laboratory and field have shown that data quality from low-cost sensors is highly variable. A systematic review of the literature since 2012 (Chojer et al., 2020) showed that often these devices are used without appropriate calibration. Of 35 unique device development projects (Chojer et al., 2020), only 16 studies performed calibration/validation of sensors. An even smaller number conducted these tests with a reference instrument. This highlights that even when the same basic sensor components are used, real-world performance can vary due to different data correction and calibration approaches. Therefore, the reliability of low-cost sensors must be assessed on a case-by-case basis. It is worth noting that, low-cost sensors are not a direct substitute for reference instruments, especially for mandatory purposes; they are, however, an essential complementary source of information on air quality (Lewis et al., 2018), especially for indoor deployments.

1.5. *Critical knowledge gaps that underpin the motivation for the SAMHE initiative*

In addition to the demand for modern schools, retrofitting and maintenance are necessary because of the great age and many years of intensive use of much of the current school building stock. Currently, engineering decision-making tools for designing and retrofitting schools (and buildings in general) focus almost exclusively on energy performance as we adapt towards net zero in a period of high and increasing energy costs. Improving the energy efficiency of the school building stock introduces great challenges in reducing the unintended consequences, including the deterioration of indoor air quality (IAQ), condensation risk and associated mould growth, high CO_2 levels with associated increased risk of airborne communicable disease transmission (including the flu and COVID-19), reduced academic performance, and summertime overheating. The UK has one of the highest prevalence rates of childhood asthma worldwide (global burden of disease), with almost 8% of (1.1 million) children within the 5–17 age group suffering from symptoms (Bloom et al., 2019) making them particularly vulnerable to poor air quality in schools, stressing the urgent and increasing demand for data-informed design and retrofitting guidelines for healthy and comfortable school buildings.

In the UK, non-industrial environments have to comply with the Building Regulations Part F (Department for Levelling Up, Housing and Communities & Ministry of Housing, Communities and Local Government, 2022). HM Government's Department for Education (DfE) introduced the performance standard document, referred to as BB101, entitled 'Building Bulletin 101: Ventilation, thermal comfort and indoor air quality' (Department for Education, 2018) to extend Part F for schools. BB101 considers the thermal environment and indoor air quality (similarly focusing on CO_2 levels) to improve educational and health outcomes in schools. Within UK classrooms, neither environmental nor air quality data are routinely recorded centrally. Classrooms within new school premises, and those within refurbished school buildings, are required by the DfE to record temperature and CO_2 routinely via the iSERV/K2n platform (Department for Education, 2022). The recorded data are made available to the school, local authorities responsible for education, and/or the educational trust, but is not openly available, including for research purposes. As such, our knowledge of air quality in UK schools originates from a limited number of relatively small-scale research studies (e.g. see §1 and the systematic review of Chatzidiakou et al., 2012) with many recent studies motivated by the COVID-19 pandemic (e.g. Burridge et al., 2023).

The aforementioned challenges, and the opportunity to assist school staff and students to achieve their full potential, emphasise the timeliness of the "Schools' indoor Air quality Monitoring for Health and Education" initiative, which the SAMHE project was funded to kick-start.

1.6. *Aims and objectives of the SAMHE project*

The SAMHE project employs a multi-disciplinary methodology to collect a large volume of indoor air quality data and supplementary information from UK school classrooms in a highly efficient and scalable way. The project takes advantage of two recent interlinked opportunities: firstly, advances in low-cost air quality sensors (§1.4); and secondly, the increased awareness of the potential links between indoor environments and health/well-being (only accelerated by the COVID-19 pandemic) motivates the public to engage in current environmental challenges enabled by their familiarity with 'Internet of things' (IoT) devices and App interfaces (§3.1).

The SAMHE project develops and tests new methods for collecting an unprecedented volume of environmental and indoor air quality data in classrooms using low-cost sensor technologies and citizen science, potentially revolutionising the fields of building science, exposure science and education. This approach introduces a paradigm shift in how IAQ data are collected in large-scale studies while simultaneously empowering school communities to reduce their exposure.

The SAMHE initiative has a dual aim:

1. To produce an integrated longitudinal dataset concerning school environments, buildings, operation and behaviours that is capable of informing future policies, design, and retrofit for schools to improve health and education outcomes. It is intended that the SAMHE project provides an extendable data collection infrastructure and develops a legacy of ongoing indoor environment and air quality monitoring in UK schools, i.e. an Initiative for Schools' Air quality Monitoring for Health and Education; and
2. To raise awareness among school communities regarding their indoor environments, and to support them in exploring the potential links between indoor air pollution levels, behavioural patterns and operation/maintenance of school buildings. This will enable school communities to consider the effectiveness and consequences (e.g. energy impact) of certain measures that they might take to alter their indoor environments,

The broad scientific goals of the SAMHE project, within the Schools' Air quality Monitoring for Health and Education initiative, are: a) to work across stakeholder groups to improve the operation, retrofitting, and design of the UK school building stock via guidance and decisions informed by data gathered by monitoring school environments; and, b) to leverage SAMHE to inspire wider communities to take action to reduce environmental health risks and raise societal awareness of air quality exposures.

Within these goals, the SAMHE project research questions fall under three broad headings: (1) factors affecting indoor air quality and ventilation in UK schools; (2) interrelationships between knowledge and practice of behavioural patterns impacting air quality in schools; and, (3) uptake and engagement with the collaborative citizen science methods deployed with the SAMHE project.

Within this context, the SAMHE project team has defined over 40 specific research questions that are expected to be answered by the data gathered through to the end of the project. These research questions are linked to a set of 27 key performance indicators for the project. Examples of the research questions include:

- Do the classrooms monitored typically adhere to the UK guidance for schools, namely "BB101: Ventilation, thermal comfort and indoor air quality", and what are typical ventilation rates in the classroom?
- Do the classrooms typically meet current guideline value levels for PM, as currently set by the World Health Organisation and relevant governments within the UK, and what are the typical loss rate coefficients and penetration efficiencies of the particulate matter in UK classrooms?

- How does participating in the SAMHE project impact the knowledge within schools regarding air quality?
- Does having a classroom air quality monitor, linked to a Web App, actually change teachers', or pupils', behaviours and attitudes?

To answer the research questions and meet the project aims, the SAMHE project objectives were defined as:

- Recruit around 2 000 schools to the SAMHE project and within each 'SAMHE school' remotely establish longitudinal indoor air quality monitoring.
- Develop an Internet-based user interface, the 'SAMHE Web App', to enable SAMHE schools to provide data on their buildings, operation and behaviours.
- Ensure schools continue to provide data regarding their school activities and environment, by making the SAMHE Web App engaging, informative, and educational.
- Collate an integrated longitudinal 'SAMHE dataset' to strengthen the evidence base of UK classroom IAQ and influencing factors.
- Evaluate changes in school environments as a result of mitigation measures and behavioural changes.
- Develop, test, and deploy analytical methods and tools to maximise information content, findings and insights gathered from the SAMHE data.

The SAMHE project adopts a multidisciplinary approach and involves atmospheric and building scientists, software engineers, exposure and behavioural scientists and specialists in school engagement from six institutions across the UK. This paper outlines the four main components of the methodological framework developed by the SAMHE project to monitor IAQ in classrooms at a large scale, communicate the findings and engage pupils and teachers, and develop novel analytical approaches to influence policy and raise awareness towards reducing exposure in schools. We also present preliminary results of the recruitment rate since the launch of the project.

1.7. *Outline of the paper*

Section 2 describes the low-cost monitor that will be deployed to the SAMHE schools. The project will gift one internet-enabled SAMHE monitor to each participating school. The monitors record temperature, relative humidity (RH), carbon dioxide (CO_2), particulate matter $PM_{2.5}$, and total volatile organic compounds (TVOCs). A small screen at the front of the monitor displays the current reading. The monitors are expected to collect data for at least an academic year offering insights into the daily, weekly, monthly and seasonal variation in classrooms. Section 3 describes recruitment and ongoing education-focused engagement of teachers and students via the Web App (§3.1). Schools will be encouraged to carry out *'Activities'* to: a) explore and alter their indoor environment using as guidance the data that their monitor records, and b) move the monitor within their school environment and provide information about each new location. To deliver maintained engagement with the monitor, *'Activities'* have been co-designed (§3) with students and teachers to be interactive, educational and compelling by adopting an award-based 'gamification' approach. The collection of contextual information for data interpretation is detailed in §4. Section 5 describes methods to maximise the information content of the integrated dataset of monitored data and occupants' inputs. We will develop novel analytical techniques to understand factors affecting IAQ in classrooms (§5.1 and §5.2). To enrich insights, the SAMHE project will undertake small-scale, but highly detailed, in-person investigations of selected schools (§5.4). Section 6 discusses plans for the dissemination of the findings to relevant stakeholders to drive policy, and to empower students and teaching staff to better understand and improve their school environments.

2. The indoor air quality monitor and data architecture

The SAMHE project started deploying low-cost monitors to SAMHE schools in 2022 and will support data gathering and the Web App through to, at least, 2028, capturing long-term trends in classroom IAQ and behavioural patterns.

The overarching principles of the SAMHE data architecture are underpinned by scalability, flexibility, and openness. This includes developing a data workflow that can store and manage data from any monitor of an appropriate standard. However, at this stage of the project, it was desirable to select a single monitor manufacturer with whom to, initially, work. Selection of the monitor manufacturer was carried out following an open tender and a two-stage procurement process. Based on the cumulative evidence outlined in §1, the SAMHE project prioritised CO_2 measurements in classrooms because of the direct and indirect effects of this pollutant on IAQ, health, perception and cognitive performance. The first stage required manufacturers to supply monitors that met the tender technical specifications for testing at the University of Cambridge, UK. The performance of the sensors was characterised in indoor and outdoor co-locations next to reference instrumentation following the methodology outlined in Chatzidiakou et al. (2014). In the second stage, equipment was chosen after considering sensor performance, ease of use, size, robustness, price and low noise operation to minimise disturbance of the occupants. The monitor manufacturer selected as a supplier and partner for the project's initial phase was AirGradient (https://www.airgradient.com/). An initial order for more than 1 100 'SAMHE monitors' suitable for indoor static deployments was placed, with a further 1 000 monitors ordered in May 2023.

The SAMHE monitor is compact (Fig. 1, dimensions: 13 cm × 13 cm × 3.6 cm, weight: 300 g) and is silent. The sensor has low power demands, peaking at around 10 W and typically in the range 1 W–2W. Each SAMHE monitor provides an autonomous platform that incorporates multiple sensors suitable for measuring a range of physical and chemical parameters (see Table 2 for details). The specific sensor model selected has an on-monitor display (see Fig. 1 b) to display current readings.

The monitors transmit anonymised data when they are connected to the school's WiFi and plugged into a standard mains power socket. The AirGradient company provides and maintains the *'endpoint database'* that receives data at 1-min intervals, in near real-time. The SAMHE data architecture developed to support the project, and enable long-term data collection from diverse sensor platforms, consists of a *'mid-section database'* and a *'front-end database'*. The *mid-section database* is an InFluxDB timeseries database of measurements sent from the SAMHE monitors directly. The *'front-end database'* is a SQL relational database to support data associated with the SAMHE Web App.

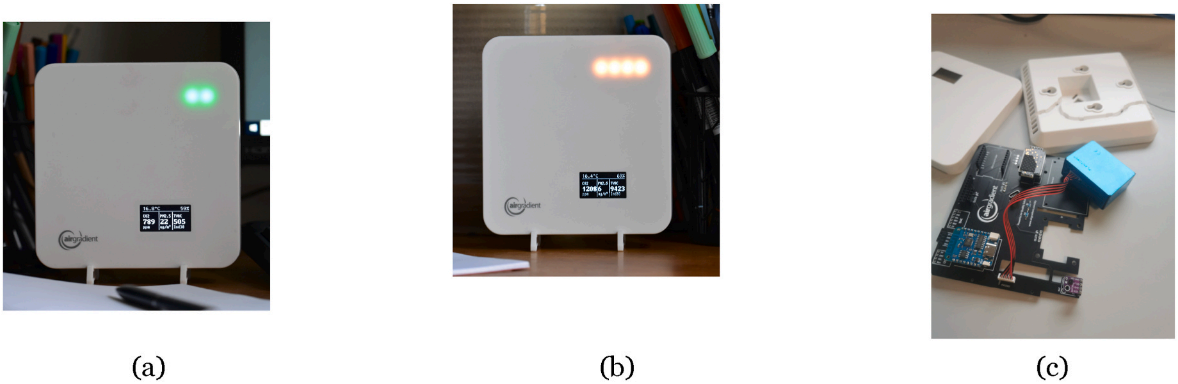
The SAMHE monitors are posted to the participating schools making this approach suitable for large-scale deployments. A video tutorial and a manual guides the users through the connection of the monitors to the schools' Wi-Fi, and guides users to place the monitors on a table or shelf approximately at sitting head height, away from external walls and windows while not disrupting normal occupants' activities (BSI 16000-1, 2006).

2.1. *Limitations in the measurement of total volatile organic compounds*

Currently, the TVOCs values are widely accepted as a screening parameter but are not recommended to be used as an indicator of health (§1.2). Due to the relative complexity of associating TVOCs with health outcomes, including individual susceptibility and the unknown interaction of the compounds, TVOCs can only be used as an indicator of sensory effects. This has been made clear in the Web App and the supporting explanatory materials disseminated to schools.

2.2. *Limitations in the measurement of particulate matter*

The operation of virtually all miniaturised low-cost particulate



(a) (b) (c)

Fig. 1. Pictures of the SAMHE monitors deployed to schools. The small size and quiet operation make it ideal for indoor deployments. **(a)** The sensor is mounted on plastic brackets to stand upright. It displays current readings of all pollutants and integrates colour-changing LED lights to encourage good ventilation practices. The green light indicates low CO_2 levels **(b)** The orange light in the display recommends increasing ventilation rates. **(c)** Internal configuration of the sensor. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Summary of parameters measured by the AirGradient sensor.

Parameter	Method	Range	Accuracy
TVOCs[d]	MOx[e]	0 to 10 000 ppb	indicative measurement[h] (§2.1)
$PM_{2.5}$ [f]	OPC[g]	0–500 μg/m^3	±10% @ 100–500 μg/m^3 ±10 μg/m^3@ 0–100 μg/m^3 (§2.2)
CO_2 [b]	NDIR[c]	0 to 10 000 ppm	±40 ppm or ±3%, automatic baseline calibration (§2.3)
Temperature	digital	−40 to 125 °C	±0.3 °C @ 0–90 °C
RH[a]	digital	0–100 %	±2% @ 0–100%

a Relative humidity.
b Carbon dioxide.
c Non-dispersive infrared sensor.
d Total volatile organic compounds.
e Multi-pixel metal oxide gas sensor.
f the fraction of particulate matter with an aerodynamic diameter smaller than 2.5 μg.
g Optical particle counter (Laser scattering principle).
h TVOC measurements are reported with a relative index.

matter (PM) sensors that are currently commercially available is based on the light-scattering principle, either volume scattering devices or optical particle counters (OPCs). Evaluating PM sensor performance is complex because optical PM instruments face inherent limitations which introduce potential differences from mass estimations made with reference gravimetric methods (Crilley et al., 2020). Firstly, the particle measurements may be affected by relative humidity, which at higher concentrations would result in hygroscopic growth and mass overestimation. However, this issue is less pronounced in indoor microenvironments where the relative humidity is generally low (< 60%). A further limitation of all optical methods is their inability to detect particles with diameters below a certain size, typically 200–400 nm (Morawska and Salthammer, 2003). Finally, optical methods cannot distinguish the physical and chemical parameters of the aerosol (e.g. density, hygroscopicity, volatility), which may have a large temporal variation, further increasing the uncertainty of mass estimation.

2.3. *Limitations in the measurement of carbon dioxide*

NDIR sensors are a low-cost way to measure CO_2 concentrations in the air. The selected sensor incorporates a built-in self-correcting algorithm. This algorithm constantly keeps track of the sensor reading over a pre-configured time interval (one week, or more) and slowly corrects for any long-term drift detected compared to atmospheric concentrations (~400 ppm). One advantage of NDIR compared with other spectroscopy techniques is its low power consumption (Dinh et al., 2016). The two main drawbacks of NDIR sensors are interference and precision. **Interference:** Water vapour can initiate cross-sensitivity at low CO_2 concentrations. This interference is stronger at higher RH concentrations ($\gtrsim$ 85%) that are less common in indoor environments. **Precision:** While the relatively low precision of the NDIR sensors (~30 ppm or less with appropriate post-processing) may be limiting for certain scientific applications, in indoor environments with high occupancy density, such as classrooms, the variability of the concentrations within a space when throughout an occupied day is large (often of the order of 1 000 ppm) often making the precision adequate for scientific needs.

3. Co-designing a multi-purpose air quality interface with school communities

Co-design in this context is defined as the ongoing involvement of teachers with the design of educational innovations, often involving technology, to support practice (Roschelle et al., 2006). It typically involves researchers, teachers and developers working closely together to design an innovation (e.g. a piece of software, or other educational product), creating prototypes and getting feedback on them (Roschelle et al., 2006). In the SAMHE project, we also involved pupils (ranging from age 6–18) in this process. Co-design is seen as essential for ensuring that the project meets schools' needs.

We have completed two different phases of co-design. The first was with a small number of schools (n = 20) enrolled as '*Co-Design* schools'. This phase was conducted via online sessions (using the Zoom communication platform) with either a group of teachers, a teacher and their pupils, or small groups of older students (aged 16–18). In this phase, we co-designed the project logo (Fig. 2), decided on the different types of activities that would be within the Web App, and obtained

Fig. 2. The SAMHE logo designed with 'Co-Design' schools.

information about where SAMHE activities could fit within the school curriculum.

The second phase was with a larger number of schools (n = 123) enrolled now as *'Pioneers'*, and took place after the prototype Web App had been developed. This phase focused on schools testing Web App content, functionality and educational resources. Since each school had to configure their own monitor, that had been posted to them, Pioneer schools were consulted on the processes for connecting the SAMHE monitors to the school WiFi and the instructions provided for logging in to the SAMHE Web App. Of these 123 schools, 77% were from England, 17% from Scotland, 4% from Wales and 2% from Northern Ireland. Compared to the proportion of schools in those countries, this is a slight under-representation of Northern Ireland and Wales and a slight over-representation of Scotland and England.

Schools are spread across all of the deciles of the Index of Multiple Deprivation, an index which allows comparison within England, Scotland and Wales of the levels of deprivation according to seven domains of deprivation. Of the 123 Pioneer schools, 22 schools were in the bottom two deciles (most deprived) and 29 were in the top two deciles (least deprived) with a fairly even distribution in the other deciles. A higher percentage of fee-paying schools (18.7%) than is representative for the UK were within Pioneer schools. Pioneer school sizes range from less than 100 pupils (3.3% of schools) to those with more than 1 000 (34.1% of schools), and educate ages 5–18, with the largest number of schools teaching ages 11–16. West 2023 (Under review) presents further details of the co-design process that developed the SAMHE Web App.

3.1. The SAMHE Web App development process and overall structure

The *Co-design* process and the *Pioneer* testing fed directly into Web App development, with early versions being shown to schools to get feedback. This feedback was then used to refine the Web App. The feedback on the Web App was provided via online video meetings, live sessions held on Zoom, and via interactions with virtual bulletin boards in which both school staff and the project team could upload, organise, and share content interactively. We used the existing free online tool 'Padlet boards' that gives the option for school staff to remain anonymous while providing meaningful feedback about the suitability of the activity functionality, the design and usability of the Web App, and ideas for new functionality. Early sessions highlighted the importance, for many schools, of having curriculum-linked materials to encourage the use of SAMHE as part of lessons which further directed the creation of new materials and revisions of existing materials.

The SAMHE Web App has three primary sections (described in detail below): *'Data Visualisation'*, *'Activities'*, and *'Achievements'*. Briefly, these sections arose from feedback in *Co-Design* sessions because pupils wanted the freedom to visualise and explore their data at first glance, but also move quickly into (the more directed) *Activities* within the Web App. Finally, pupils found being 'rewarded' for their efforts via *Achievements* motivating and this section contributed to maintaining their engagement.

3.1.1. SAMHE Web app: data visualisation

The visualisation of indoor air quality and environmental data monitored within their school was important for the immediate engagement of pupils and staff. The onboard monitor display (which displays current readings only) is small, and pupils and staff were keen to see how measurements vary over time. As such, *Data Visualisation* was a core provision of the Web App. The wide range of ages targeted by SAMHE meant that graphs of varying complexity needed to be designed. A time-series line plot was chosen initially (with schools' feedback refining this) and additional graphs were created later. Users are able to select different time periods and metrics according to their interests and abilities. At the time of launch, the *Data Visualisation* development included the interactive provision of: time-series (line) plots, gauge charts and single-axis and double-axis scatter plots. (Fig. 3).

3.1.2. SAMHE Web App: activities

Activities in the Web App are intended to play a critical role in maintaining the engagement of users with the topic of air quality, centring around the monitoring within their school. Moreover, *Activities* in the Web App provide a vital route for the project team to collect research data, including contextual data about school environments that would aid with the interpretation of the IAQ measurements. *Co-design* sessions and *Pioneer* testing helped determine the content, length and tone of *Activities*, with iterative feedback providing guidance for improvements during development. Regular project team meetings were then used to steer the balance between *Activities* as a provision for user engagement and as a source of research data (Table 3).

Core to this section is the concept of a 'Room List' (RL) as users are encouraged to move their sensor to different rooms periodically. Each school creates and maintains a list of unique rooms that are recognisable to users (staff and pupils) allowing them to associate data from many of their activities with a particular room. The *Activities'* created at the time of launch are shown in Table 3, with a tick in the RL column denoting activities for which users select an entry within the Room List, thereby providing contextual data useful for research. Illustrative examples of the Web App activity section are presented in Fig. 4.

As IAQ strongly depends on the characteristics of the built environment and usage of the room; this innovative method enriches the measurements by providing the opportunity for the necessary contextual information to be fed in by users to enable greater interpretation of measurements for research purposes.

3.1.3. SAMHE Web App: achievements

The co-design process highlighted the value to users of their effort and activities being appropriately recognised and rewarded; hence, the Web App incorporates *Achievements*. As *Activities* are completed, users gain virtual badges, which are categorised and scored accordingly. Pupil users can easily track their *Achievements*, and participating teachers can download and print physical certificates to accompany these virtual badges.

3.2. School recruitment through to primary launch and wider communication strategy

In the initial phases (see *Co-Design* and *Pioneer* in §3), schools were recruited through communications to teachers via various means: mailing lists to schools (held by participating universities, and non-governmental organisations working in schools education), articles in the newsletters and websites of school-facing organisations, directly emailing and telephoning schools (those known to the project team and in target under-represented areas), the project website, and Twitter. It was made clear to schools that this was an opportunity to help shape the project, and if they chose not to participate in this development phase, they could still join as a SAMHE school at a later date. Recruiting schools was time-consuming, particularly as we were keen to engage schools that are usually under-represented in citizen science activities (including schools based in low-income communities) and schools from all areas of the UK. Schools who contacted us after our *Pioneers* phase were invited to register to receive a monitor at launch, in April 2023.

Communications for the launch used similar mechanisms, but greatly scaled up. Additional promotion routes included a press release by the University of York and coverage in the SAMHE newsletter. Many more school-facing organisations and other stakeholders were directly contacted and the social media reach was much larger. Recruitment of schools in England was boosted by the inclusion of SAMHE information in the DfE sector bulletin, and coverage in a dedicated feature on the BBC Newsround programme. Following slower uptake in Scotland, Wales and Northern Ireland, additional efforts were made to reach schools in those countries, via government contacts and through direct emailing of schools. We also encouraged Co-Design and Pioneer schools to seek local media coverage of their activities as part of our promotion,

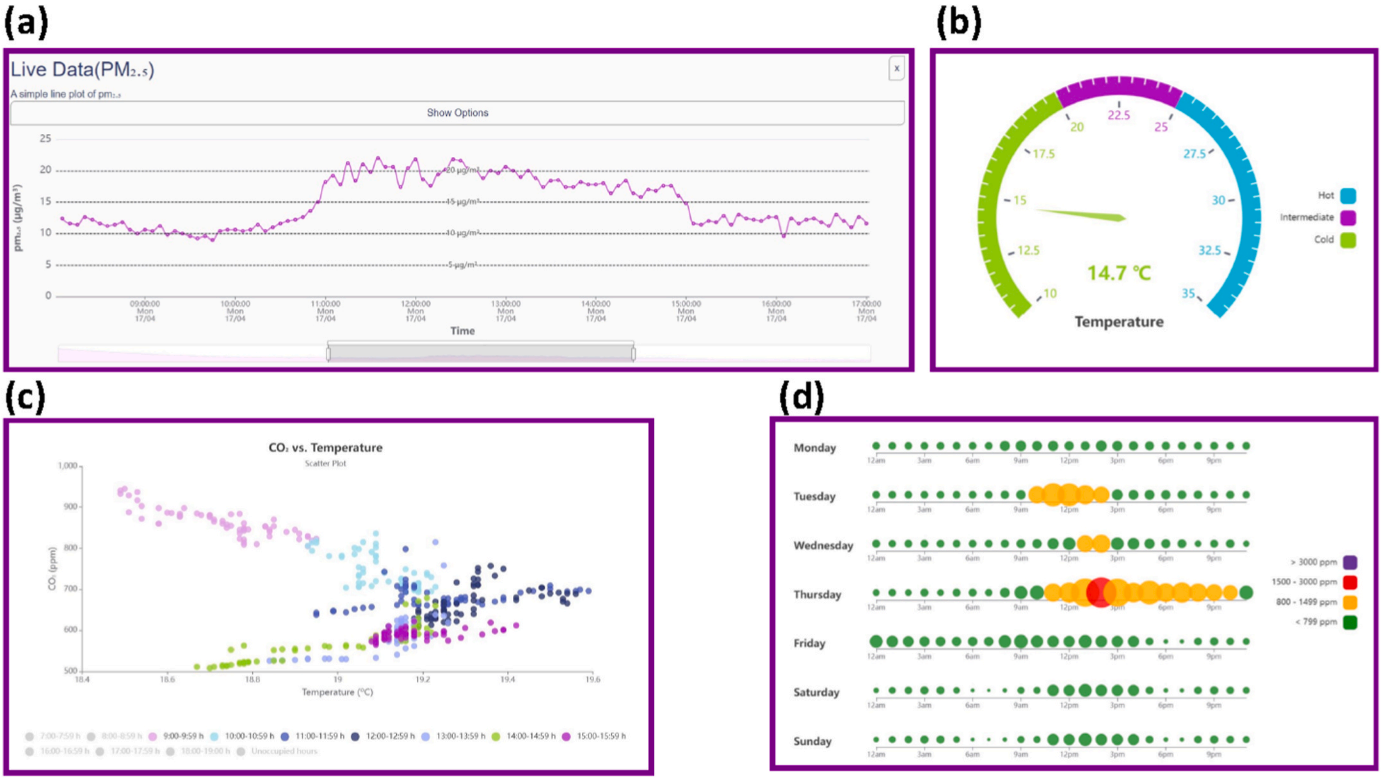


Fig. 3. An illustrative example of the *Data Visualisation* including (a) time-series line plots of live data with a scroll-in option; (b) gauge charts (in this case indoor temperature colour coded by comfort levels (c) double-axis scatter plots of two variables (in this case CO_2 vs temperature colour-coded by the time of day); and, (d) single-axis scatterplots to visualise hourly and daily concentrations (in this case CO_2 colour-coded by concentration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

supporting them by providing a template media pack and guidance. We are not aware that any did so.

The SAMHE project will use a broad range of communication channels to inform the wider public about the project findings regarding school air quality. At a national level, we will engage closely with media partners (including national television, radio, and print outlets) to promote relevant press coverage of key findings and outcomes. We will produce a range of online news articles, newsletters, blogs and video-based summaries of findings and their implications, and disseminate these using established social media channels (e.g. Twitter and YouTube).

4. Contextual information for data interpretation via the SAMHE Web App

Previous studies (see Chatzidiakou et al., 2012, for a review) have found notable differences in the characteristics of indoor air pollution between seasons, schools and classrooms depending on their microenvironments, building characteristics, operation and maintenance. With this in mind, the previous section highlighted that the SAMHE App provided a two-way exchange of information between the pupils and the scientists (§3). This section outlines the information that will enable the characterisation and comparison of school buildings for the interpretation of the fieldwork measurements. The first part (§4.1) presents the method for obtaining outdoor air quality measurements, which would enable us to develop a protocol for extrapolating external air quality to its internal equivalent for school classrooms. In the second (§4.2) and third parts (§4.3) the methodology for collecting descriptors of the physical indoor environment and behavioural patterns of the occupants is described.

4.1. *The outdoor microenvironment*

The SAMHE project will rely on other, predominantly publicly available, datasets of local and regional air quality and weather data. Outdoor air pollution measurements and meteorological parameters were retrieved from the closest urban background monitoring station using the package openair in R. Urban background stations are located such that they are relatively unaffected by local (outdoor) emission sources and are therefore more representative of the outdoor air quality which might affect indoor levels within SAMHE schools.

4.2. *Building characteristics*

The collection of suitably detailed building- and classroom-specific characteristics is critical for enriching the insights that can be made from the monitored data. However, overly burdening users with requests for data risk lowering, or curtailing, user engagement with SAMHE. Two main strategies have been developed to gather the necessary complementary data.

Firstly, exploiting the innovative methodological element that is the SAMHE Web App development where many of the *Activities* (§3.1) are designed (whilst also being enjoyable for users) to provide contextual data useful for research and modelling. Table 3 highlights that 7 out of the 14 Activities offered required users to associate the Activity with a specific room and provide some further data relevant to understanding the environment. This first method of contextual data gathering is highly flexible as, should a need for new data arise, then a new *Activity* can enable users to input the required data without it being overly burdensome or beyond their capabilities/knowledge.

Table 3
Activities in the SAMHE Web App at the time of the launch.

Name of activity	Description of activity	Details	RL
Tutorial	A video tutorial to introduce users to the Web App and help guide them through its functionality		
Quizzes	An interactive set of quizzes that takes pupils and staff users through a series of questions about each of the indoor air quality and environmental data metrics recorded by their monitor. The quizzes provide feedback on both incorrect and correct answers in an attempt to ensure users have a sufficient understanding before using the Web App	● Understanding the CO_2 readings on your SAMHE monitor. ● Understanding the $PM_{2.5}$ readings on your SAMHE monitor. ● Understanding the TVOC readings on your SAMHE monitor. ● Understanding the temperature readings on your SAMHE monitor. ● Understanding the relative humidity readings on your SAMHE monitor	
Move your monitor	Users associate a date, which defaults to today's date, on which the SAMHE monitor moves. Users are required to enter the room the monitor is moving from, and the room the monitor is moving to		✓
Min and max	Allows user to determine extreme value in their data and encourages questioning of their interpretive value relative to other metrics	Temperature	✓
Data detectives	Users identify an unusual short-term pattern, 'event', in their data they can use this activity to highlight the event and are then guided through a series of interactive questions in an effort to determine the cause of the event		✓
Something has changed	Allows users to record changes in a room, or usage of a room, that they expect might affect the air quality longer-term, e.g. the addition of an air cleaner or a change in the number/operation of windows		✓
Measuring CO_2 levels before and after exercise	Encourages a group of pupils to carry out light exercise in the presence of the SAMHE monitor and observe the changes in the carbon dioxide levels		✓
CO_2 levels in an empty classroom	Users are encouraged to test the effects on their air quality metrics when all windows are opened and everyone leaves the room. This activity is encourage to partner after 'Measuring CO_2 levels before and after exercise		✓
Classroom Data Entry	Enables pupils, or groups of pupils and staff, to enter data about the classroom environment and its usage; data that was deemed both useful for research and of relative ease for users to attain	Examples include the classroom size and volume, the typical class sizes and their ages, etc	✓
Write a letter to your MP	Encourage pupils to write creatively to their member of parliament (MP) to take action on air quality, and provides them with appropriate links to contact their MP		

CO_2: Carbon dioxide; RL: Room list

Secondly, the SAMHE project will exploit the richness of the existing "condition data collection" (CDC) database .[3] The CDC collects building condition, asset and management information on every government-funded educational establishment in England. The CDC database has been collected with the aim to direct future funding allocations to the areas with the greatest need, and to identify school buildings for inclusion in future rebuilding programmes. Cross-referencing parts of contextual data gathered by user's inputs into the Web App with that within the CDC data will enable a degree of quality assurance for both datasets.

Utilising the two distinct data-gathering methods will ensure that standardised contextual data (gathered by professionals) and a more dynamic set of contextual data (input by school users) can be simultaneously used within the analysis of the indoor air quality and environmental data. This comprehensive database can provide insights into the building characteristics that affect exposure in classrooms providing the necessary evidence to shape advice, guidance, and policies on how to build and refurbish the UK school building stock.

4.3. Behavioural analysis

IAQ can be strongly influenced by occupants' behavioural patterns. It was, therefore, important to map the occupants' knowledge of factors affecting IAQ and their understanding of the impact of their adaptive actions on the school's environmental quality (such as ventilating the space by opening windows and doors) which may significantly alter IAQ, positively or negatively. IAQ will also be affected by willingness and capability to take ventilation-related actions, as well as environmental/architectural factors that interact with personal capability. The SAMHE project offers the unique potential for regular, co-productive, interactive engagement with both school staff and pupils across a longer-term project.

A mixed methods approach will be used to understand knowledge and behavioural factors influencing IAQ. Knowledge, understanding, expectations, self-reported behaviour, and app usage will be analysed and any relationships between these variables explored. This analysis will complement the insights gained from the measurements and microenvironment data collected through the monitor network and the SAMHE Web App. Longitudinal surveys will be administered to measure participants' knowledge, understanding, expectations and self-reported behaviours. These surveys will ask questions about respondents' knowledge and perceptions of factors that influence indoor air quality. The responses received will be analysed using a variety of statistical methods such as regressions to explore relationships between variables (e.g. whether knowledge about ventilation behaviours is associated with self-reported ventilation behaviour) and analysis of variance (ANOVA) to explore statistical differences between the responses collected at

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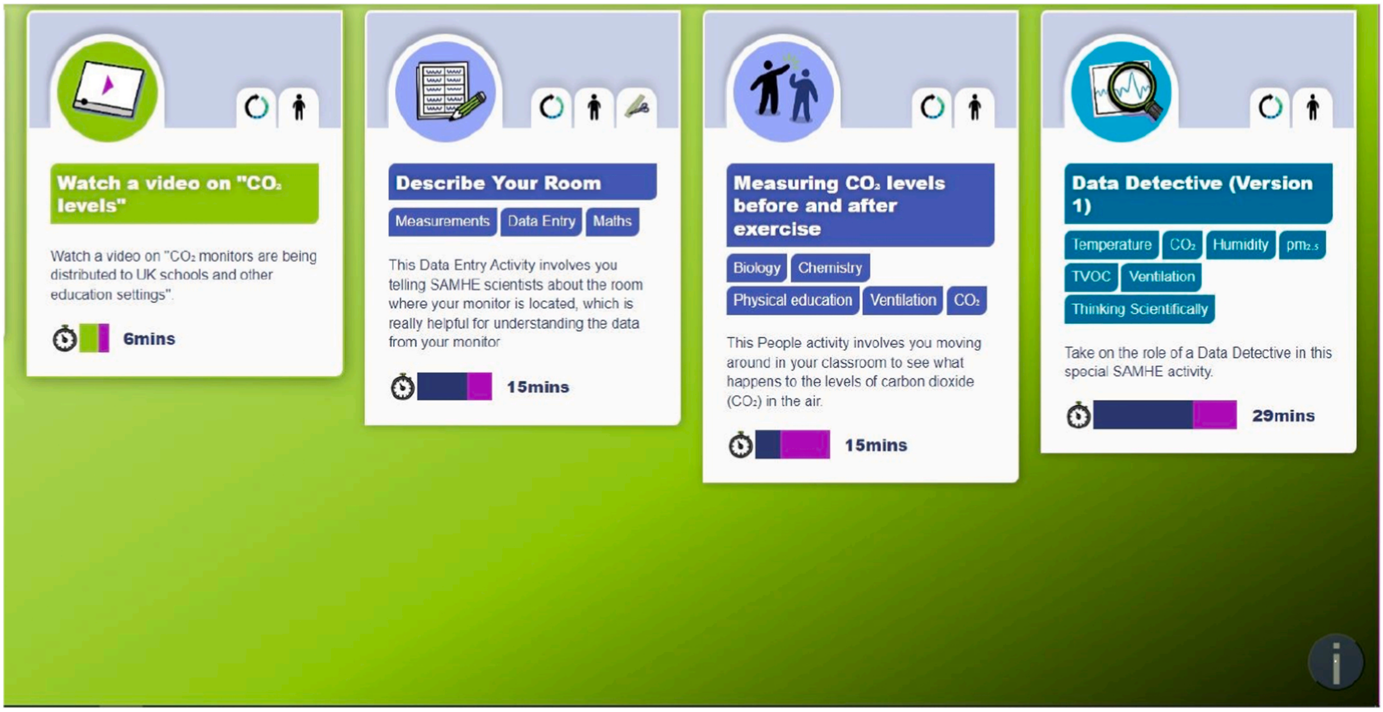
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652226/Condition_Data_Collection_CDC_Guide_for_Schools.pdf.



Watch a video on "CO₂ levels"

Watch a video on "CO₂ monitors are being distributed to UK schools and other education settings".

6mins

Describe Your Room

This Data Entry Activity involves you telling SAMHE scientists about the room where your monitor is located, which is really helpful for understanding the data from your monitor.

15mins

Measuring CO₂ levels before and after exercise

This People activity involves you moving around in your classroom to see what happens to the levels of carbon dioxide (CO₂) in the air.

15mins

Data Detective (Version 1)

Take on the role of a Data Detective in this special SAMHE activity.

29mins

Fig. 4. An illustrative example of the *Activities* in the Web App.

different time points.

Data collected detailing the extent of the engagement with *Activities* within the SAMHE Web App will be compared in relation to any clear changes in the IAQ data collected by the SAMHE monitors. This analysis will help to understand whether any additional activities suggested within the SAMHE Web App and any activities suggested within a behavioural intervention are accepted and utilised by the SAMHE users and within a wider educational setting.

The SAMHE project aims to understand how various users within schools are engaging with their SAMHE monitor and the Web App, and will do so by collecting Google Analytics and other metrics from the Web App itself. These findings will inform questionnaires sent to SAMHE users via the Web App to understand usage and guide improvements to various aspects of the project. The SAMHE project will also initiate the development of a behavioural intervention to empower individuals to take steps to improve indoor air quality. Co-design methodologies will be used to ensure that the intervention developed is feasible and useable within classroom settings and acceptable to both teachers and students.

As part of the longitudinal surveys, pupils will be asked questions about their knowledge of indoor air quality. This, combined with quizzes within the Web App, will give us some measure of whether the project has led to any increases in knowledge. Self-reported comments from teachers via our Newsletter and social media (§3.2) may also capture any educational outcomes in terms of pupils' concentration. Future funding permitting, there is great potential to evidence the scale of any correlations between the indoor environment and air quality metrics against education outcomes, such as national test outcomes, or factors such as absenteeism rates.

5. Maximising insights from SAMHE monitoring, Web App and existing datasets

SAMHE gathers high-temporal resolution (1 min) data for a range of key IAQ metrics, as listed in Table 2. The monitor represents a single-point measurement of these variables in the room where the monitor is located, and this location will change periodically as SAMHE participants are encouraged to move the monitor to other rooms within the school. Whilst this might be an efficient use of monitors, it does render the contextual information (that describes the characteristics of space where the monitor is currently located, and how that space is used, see §4) as being of increased importance for interpreting and drawing conclusions from the data. While the *Co-design* and Web App development (as detailed in §3) aims to maximise engagement of SAMHE schools to encourage the provision of contextual information, the detail of such information is expected to vary significantly between participants. For this reason, the SAMHE project team are undertaking research to understand the conclusions that can be drawn from monitored data when the depth and extent of contextual information varies. This includes conducting Monte-Carlo simulations of pollutant levels over a vast number of classroom-days (§5.1); separating pollution contributions from indoors and outdoors (§5.2 and quantifying drivers of IAQ §5.3); and performing detailed investigations ('deep-dives') of a small number of SAMHE classrooms (§5.4). These activities will maximise the information that can be extracted from the sensor data.

5.1. Inferring ventilation rates from CO$_2$ measurements

The levels of a pollutant in an indoor space can be approximated with the mass-balance equation (eq (1)) (Sherman, 1990):

$$\frac{dC_{in}}{dt} = \kappa_{vent}(C_{in} - C_{out}) - \kappa_{sink}C_{in} + S, \tag{1}$$

where C_{in} and C_{out} are the indoor and outdoor concentrations of the targeted pollutant respectively, and S is the total of the indoor source emission rates. κ_{vent} is the building ventilation rate and κ_{sink} is the rate coefficient of indoor losses (pollution sinks).

The exchange of indoor and outdoor air, i.e. ventilation, plays a dominant role in the transport of pollution that can be detrimental to IAQ (§1). Hence, the project aims to quantify ventilation rates in SAMHE schools, not least to provide some estimates of the variation in ventilation rates that might be typical within the UK school building stock. Ventilation is an important process in buildings not only for indoor air quality but also for energy requirements further expanding the value of the analysis.

Ventilation rates in buildings can be estimated with passive tracer gas techniques (Sherman, 1990) combined with conservation laws allowing a quantitative determination of the tracer transport mechanism (i.e. a measurement of the airflow). CO_2 is a useful tracer gas because indoor levels in occupied classrooms are significantly higher than outdoor levels, outdoor levels are reasonably stable over the timescales of interest, over which CO_2 can be regarded as inert ($\kappa_{sink} = 0$). Therefore, CO_2 is widely used in the existing literature to infer ventilation rates in building spaces, including school classrooms with the mass balance equation 1, by approximating them to be well-mixed rooms.

If occupants are the only significant source of CO_2 (e.g. no combustion sources present), then $S = \sum_{i=1}^{N} G_i$, where G_i is the CO_2 generation rate of each occupant and N is the number of occupants present. The individual generation rate G_i depends on a range of factors such as age, body weight, sex, and activity level (see Persily and de Jonge, 2017).

A convenient way to calculate ventilation rates (e.g. Batterman, 2017) essentially focuses on a special case of the mass balance equation for which the source term is taken to be zero (unoccupied periods), i.e. $S = 0$; widely termed the 'decay rate' method. This greatly simplifies the uncertainties and a constant (or average) ventilation rate can then be inferred by fitting exponential solutions of (1) to CO_2 measurements, see Fig. 5 for a solution fitted to measured data. Hence, from fitting to the measured data, the exponent κ_{vent} or the air change rate for a room of known volume (assuming the air is well-mixed within) can be estimated (Fig. 5).

A primary concern with this method is that it assumes that over the decay period, the ventilation rate is representative of the ventilation during occupied hours (which is obviously the metric of interest). Both of these assumptions might be violated in typical classrooms. For example, in naturally ventilated spaces ventilation rates are primarily driven by the wind pressure co-coefficients that change rapidly. Additionally, all windows are likely to be shut at the end of the day resulting in the estimation of a much lower ventilation rate than the typical ventilation rates during the occupied period. This would be the case in mechanically ventilated spaces too should the fans might be turned off at the end of the day.

In the SAMHE project, we aim to quantify the uncertainties in the estimation of ventilation rates with a sensitivity analysis to investigate how various sources of uncertainty (for example the well-mixed assumption) contribute to the model's overall uncertainty.

5.2. Source apportionment method of indoor and outdoor-generated pollutants

Inert pollutants: Indoor levels of 'inert pollutants' in a microenvironment (in this case a classroom) are the sum of outdoor concentrations penetrating indoors through ventilation plus the concentrations emitted indoors from sources 'local' to the microenvironment. This is described mathematically with the mass-balance equation (1). The levels originating from the outdoor environment are referred to as the "regional component of exposure" as they are often uniform over large spatial scales. Outdoor-generated indoor levels might have a small lag compared to outdoor levels due to the effect of ventilation. As indoor emission sources may elevate indoor levels within this microenvironment, they are referred to as the "local component of exposure". Other than ventilation, there are no other processes removing indoor levels and, therefore, κ_{sink} approximates zero.

The above processes determining indoor levels of an inert pollutant in an indoor microenvironment are simulated in Fig. 6A (in this case consider CO_2). Indoor levels follow closely the outdoor concentrations (with a small time delay). In the absence of indoor sources, the indoor-to-outdoor (I/O) ratio is equal to one (as shown in the green square between 13:00–17:00). During these periods, the indoor concentrations have originated solely from the outdoor microenvironment (outdoor-generated exposure shown in light blue).

Five instantaneous indoor sources with varying emission rates were introduced at different times. Following these events, indoor levels reach equilibrium with the outdoor environment following an exponential decay as shown previously in the experimental data (Fig. 5). The rate of this decay depends only on the ventilation rates. The locally generated component of the indoor exposure is shaded light grey.

Reactive pollutants: Fig. 6 B is the simulation of a 'reactive pollutant'. In this case, PM is considered reactive because once outdoor PM enter the indoor environment, they are affected by indoor processes with the most significant being deposition (simulated here with κ_{sink}). Therefore, in the absence of indoor emissions sources ($S = 0$), the indoor concentration of the reactive pollutant (case B) is lower than the outdoors ($I/O < 1$). For this reason, the I/O ratio is often used as a fast way to estimate loss rate coefficients and a straightforward screening method for calculating indoor concentrations originating from outdoor sources. The indoor environment provides protection from exposure to outdoor-generated pollution (shown in light blue colour). However, indoor emission sources typically cause a steep increase in pollutant

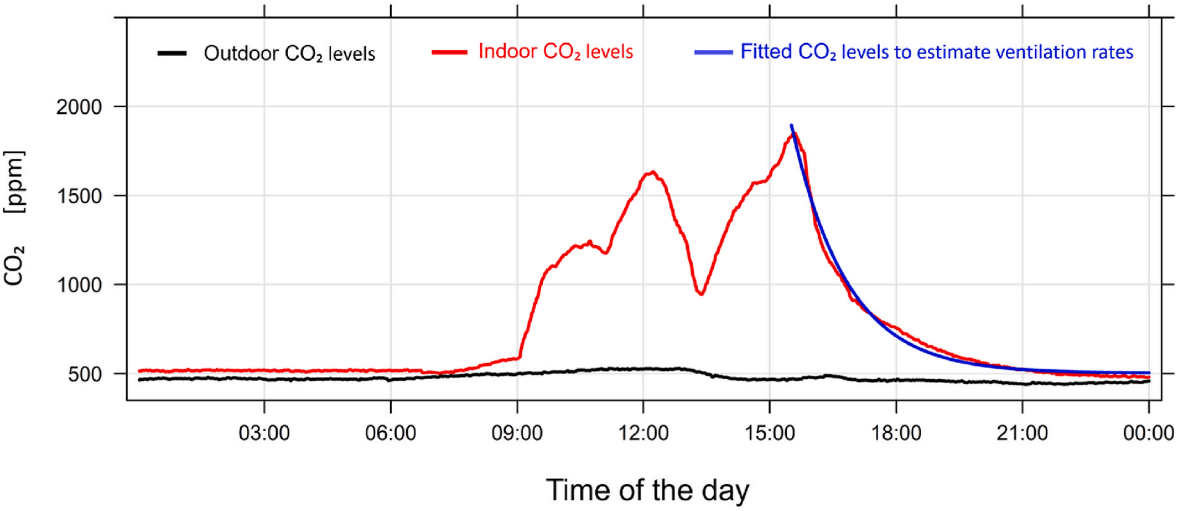


Fig. 5. An illustrative example of typical indoor CO_2 levels in a school classroom (red). Illustrating the two breaks during the teaching day (around 10:30–11:00 and 12:30–13:30). The outdoor CO_2 levels remain relatively constant during this period (black). After the end of the teaching day, indoor CO_2 levels decrease exponentially. Ventilation rates can be approximated using the decay method by fitting the CO_2 measurements (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

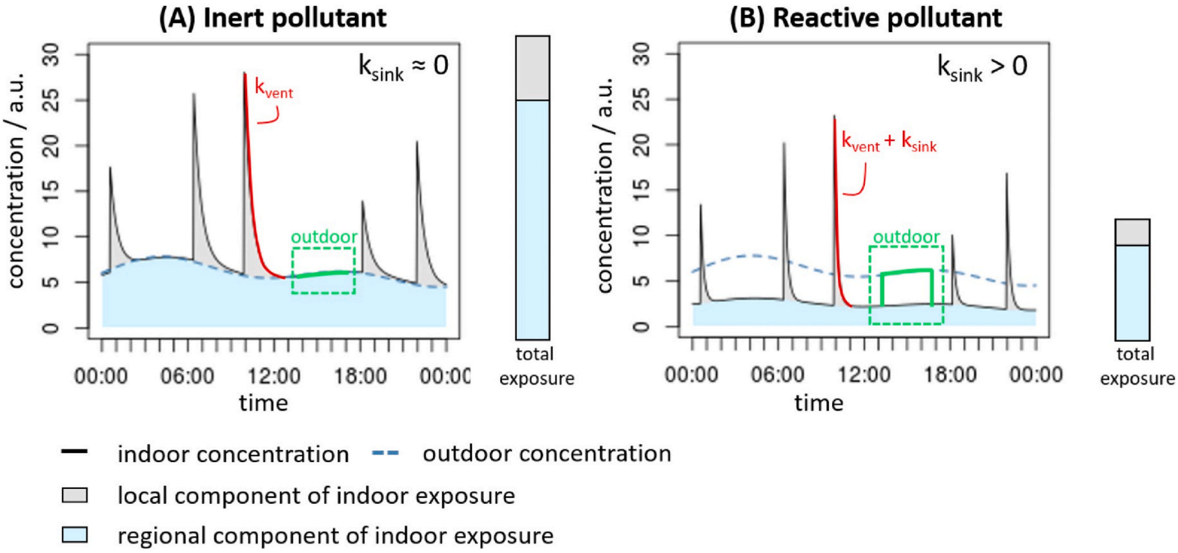


Fig. 6. Schematic indoor concentration model based on Equation (1). In both cases, the same five instantaneous sources with varying emission rates have been introduced at the same time instances. The ventilation rate is constant for both cases ($\kappa_{vent} = 2\ h^{-1}$). The exposure that originates from local sources is shaded in grey and exposure from regional sources is shaded in blue. The bar plot on the right of each graph represents the mean personal exposure for each case and how much the local and regional sources contributed to it. The green square between 13:00 and 17:00 shows how the indoor-to-outdoor ratio (and κ_{sink}) can be estimated during periods without indoor sources. (A) Inert pollutant unaffected by indoor sinks ($\kappa_{sink} = 0$) and (B) reactive pollutant ($\kappa_{sink} = 3\ h^{-1}$). a.u. stands for arbitrary units. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

concentration. In school environments, re-suspension is the most significant source of indoor particles and likely the main reason for the elevated PM_{10} concentrations often measured in previous studies. Levels then decrease approximately exponentially with a decay rate of $\kappa = \kappa_{vent} + \kappa_{sink}$. Therefore, the loss rate coefficients of PM can be estimated either during (§5.1) periods of exponential decay or from the I/O ratio when there are no indoor sources.

By applying this model to the comprehensive SAMHE dataset, we aim to separate the local- and regional-generated exposure components. This is crucial, especially for PM, because the chemical composition of the aerosol depends on the source and is likely to affect its relative toxicity. Future research will apply this methodology at a large scale, which would be required to draw more reliable health inferences. We will additionally be able to quantify common indoor emission rates and loss rate coefficients to aid modelling studies.

5.3. Assimilating sensor measurements and contextual information collected through the Web App

SAMHE enables multiple users (e.g. pupils) to input values for the

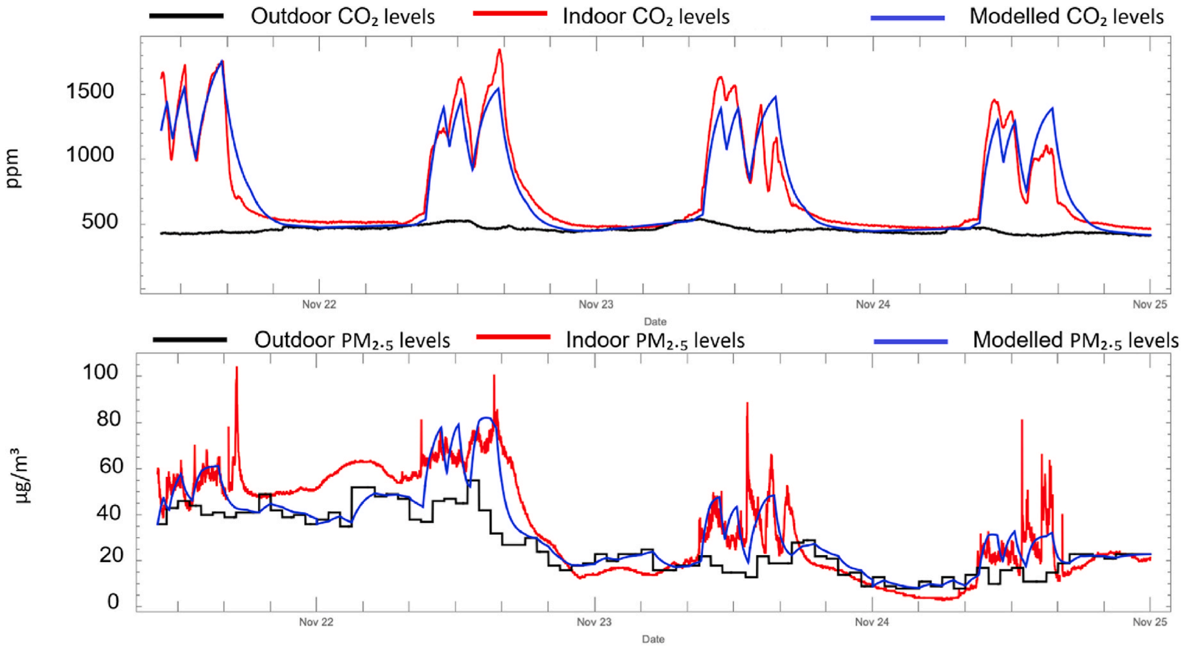


Fig. 7. An illustrative example of indoor (red), outdoor (black) and modelled (blue) levels of CO_2 and $PM_{2.5}$. Ventilation rates were estimated based on the method presented in §5.1, generation rates and loss rate coefficients were extracted from the literature based on observational studies. Indoor PM levels closely follow outdoor PM levels with short-term indoor peak concentrations recorded during occupants' activities primarily due to the re-suspension of previously deposited particles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

same parameter for a given room, (e.g. room volume, and use, occupancy profiles either typical or for a specific day). Hence, there is an opportunity to benefit from the ‘wisdom of the crowd’ (e.g. see Prelec et al., 2017) resulting in better estimates than might be provided by any particular individual. This approach also provides an opportunity to estimate the uncertainty of input parameters.

Using the estimated ventilation rates and data input from the Web App, such as, daily occupancy numbers and schedule, ventilation patterns and activity levels, SAMHE offers the opportunity to collect important information for the interpretation of the results and develop physical models (Fig. 7) for indoor-source apportionment (§5.2), to evaluate interventions, improve understanding, and for application in future health studies.

5.4. Detailed investigations (deep-dives) in selected case-studies schools

Deep-dives are often conducted to obtain a holistic view of the research field from different angles (Stübinger and Schneider, 2020). In the context of the SAMHE project, deep-dives refer to detailed investigations in a small number of classrooms, for example, by deploying multiple sensors in one room, or by testing the effects of specific interventions. These investigations complement the (less-detailed, but) larger volume of data collected with the SAMHE monitors.

A number of complimentary deep-dive studies have already been conducted under the funding that was extended to deliver the SAMHE project. These seek to evaluate the air quality within a complex classroom microenvironment and to identify possible causes of high air pollution levels, assess the impact of a specific or a combination of interventions, and propose mitigation measures while taking into account different ventilation strategies and varying outdoor micro-environmental conditions. So far, one of these deep-dive studies (Kumar et al., 2023) investigated the optimum placement of air purifiers in classrooms. The results of this study suggested that the use of an air purifier in the activity-intense zone can reduce classroom PM_{10} concentration by up to 62% while it had a negligible effect on smaller particles that in urban environments often originate primarily from traffic. A further deep-dive study investigated the optimum timing of window opening and air purifier use in naturally ventilated classrooms located in proximity to high-traffic-intensity streets. Finally, the deep dives focused on evaluating indoor air pollution levels in classrooms using different ventilation strategies (Rawat & Kumar, 2023). Mixed-mode classrooms had the lowest indoor PM and CO_2 levels compared either with natural or mechanically ventilated classrooms. Future work within the SAMHE project aims to investigate the impact of a CO_2 self-surveillance system on classroom air quality and thermal comfort.

6. The SAMHE routes to deliver knowledge and change

The SAMHE launch week began on the April 24, 2023, and within one week of its end, 537 schools had completed the registration process to participate in the project, thereby becoming ‘SAMHE schools’. The initial sign-up proved surprisingly effective at establishing an equitable socio-economic spread based on the ranking of each school location within the indices of multiple deprivation used by each of the governments of the four UK nations; for example, the two most deprived deciles accounted for 10.3% and 9.2% of the recruited schools respectively, indicating schools in the most deprived areas were suitably represented. Moreover, the spread across all deciles was relatively even; for example, the most underweight decile still accounted for 9.1% of schools, whilst the most overweight decile accounted for 12.0%. This level of equity, combined with the rapid uptake in recruitment, evidences the successful results of the SAMHE methodology.

The ambition of SAMHE is to improve IAQ and raise awareness, first, via direct engagement of a few thousand schools (§6.1 ‘bottom-up’ impact). In the next step, SAMHE aims to extract information from the data gathered in these schools to deliver scientific impact (§6.3) that will be translated to guide efficient and effective environmental policy (§6.2 ‘top-down’ impact). The project is supported by the Executive Board and the Steering Committee consisting of leading academics and stakeholders in relevant fields who are closely aligned with the project. A number of publications, conference presentations, outreach activities and engagement events have already been performed.

6.1. Bottom-up impact: working with school communities

In order to engage the pupils in the urgent issue of air quality, the SAMHE project has created educational material that is effectively communicated through the SAMHE Web App, particularly through the *Activities* to encourage active learning. The material is also freely available from the public-facing website (e.g. https://samhe.org.uk/resources/) to raise air quality awareness within grassroots school communities.

6.2. Top-down impact: collaborating with stakeholder groups across all levels of school governance

The SAMHE project will engage with all levels of UK school administration, which is complex and highly devolved both between and within each of the UK’s four nations. The SAMHE project has already made extensive efforts to develop close working relationships and consultation with HM Government’s DfE, local authorities and school academy trusts (responsible for, often large, groups of schools), and the Unions representing teachers and school leaders within the UK. The project aims to reach out to different levels of stakeholders ranging from local governments, academy trusts, and ultimately to headteachers and the board of governors. The project seeks to produce formal parliamentary and policy briefing notes. The SAMHE project will consult all interested local authorities, clean air initiatives within, and academy trusts to better understand challenges and opportunities in improving IAQ in educational settings. Finally, the project has worked to establish links with the Unions representing teachers and school leaders within the UK and will involve various pressure groups focused on clean air within the UK to co-create informed campaigns dedicated to school air quality and education around air quality more broadly.

6.3. Scientific impact of the SAMHE project and the future of the SAMHE initiative

The SAMHE project is testing a highly efficient and fully scalable method to collect and analyse large-scale longitudinal datasets of air quality in schools using collaborative citizen science approaches. The project is expected to test the viability of an economically efficient route to establishing these datasets at the national and potentially the international level.

As we are currently undergoing a period of rapid societal change (following both the emergence of COVID-19 and the ongoing climate and cost-of-living crises) detailed monitoring and modelling tools are necessary to support policymaking, and encourage actions to ultimately improve indoor air quality in schools. Little is known about the effects of other pollutants, for example, exposure to indoor microbial and chemical pollutants in classrooms as existing research is limited and lacks high-quality exposure measurements. Through the project, and beyond, the SAMHE initiative will attempt to address the need for both detailed and large-scale indoor data from diverse school settings.

We conclude that collecting and analysing large-scale datasets concerning school environments will provide the necessary scientific underpinning for top-down and bottom-up impact while simultaneously engaging the communities and supporting educational outcomes. We note that the use of such datasets must be integrated and analysed with appropriately recorded health outcomes and educational outcomes.

Ethics approval and consent to participate

Ethics approval was given by Imperial College London for Web App development, contextual data collection and supporting databases. Ethics approval was given by the University of York's Environment and Geography Ethics Committee for the schools' engagement activities, newsletter contributions from schools and use of images taken of school members.

Contributions

All members of the SAMHE project consortium edited the paper in addition to their numerous direct, and indirect, contributions. SAMHE project consortium members consist of the following: Imperial College London: Ben Barratt, Henry Burridge, Christopher Pain, Katherine Roberts, Samuel Wood; Stockholm Environment Institute, University of York: Rhys Archer, Victoria Beale, Sam Bland, Douglas Wang, Lucy Way, Sarah West; UKHSA: Holly Carter, Dale Weston, Natalie Williams; University of Cambridge: Lia Chatzidiakou, Hannah Edwards, Joshua Finneran, Roderic L. Jones, Paul F. Linden, Carolanne Vouriot, Mark Winterbottom; University of Leeds: Chris Brown, Claudia Fernanda Castro Faccetti, Marco-Felipe King, Mark Mon-Williams; University of Surrey: Sarkawt Hama, Prashant Kumar, Nidhi Rawat.

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Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

No data was used for the research described in the article.

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Abbreviations

CDC	condition data collection
CO_2	carbon dioxide
DfE	Department for Education
IAQ	indoor air quality
I/O	Indoor-to-outdoor ratio
IoT	Internet of things
LOD	limit of detection
MO_x	Metal oxide
NDIR	Non-dispersive infrared
PM	particulate matter
PM_1	the fraction of particulate matter with an aerodynamic diameter smaller than 1 μg
$PM_{2.5}$	the fraction of particulate matter with an aerodynamic diameter smaller than 2.5 μg
PM_{10}	the fraction of particulate matter with an aerodynamic diameter smaller than 10 μg
RH	relative humidity
SAMHE	School Indoor Air Quality Monitoring for health and education
SBS	sick building syndrome
TVOCs	total volatile organic compounds
WHO	World Health Organization

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