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EXPLORING THE ROLE OF CITIZEN SCIENCE IN INDOOR AIR QUALITY MONITORING AND SUSTAINABLE DEVELOPMENT

Bachelor's thesis
Faculty of Built Environment
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ABSTRACT

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The air we breathe contains what we need to live but it also contains pollutants with various health implications from short- and long-term exposure. While we understand the impact of air pollution in outdoor environments, the place where people spend up to 90% of their time is left unattended – that is, indoors. Studying indoor air quality is a challenge due to the ethical and high costs associated with large measuring devices. However, due to the development of low-cost indoor air quality monitoring devices, cloud-based services, and the portable new devices, indoor air becomes possible to study in detail. The challenge remains on how researchers can gather this data.

In the spirit of sustainability which considers societal and administrative perspectives, community based monitoring and citizen science become useful tools. Citizen science provides practises of collaborative projects, while community based monitoring in turn gives empowers citizens to make observations on their surroundings. Combined, these can help improve urban development and specifically fill the gap in indoor air quality research, while producing socially active and empowered communities to engage with policy. Collecting data directly from individual homes is important in understanding the variable factors influencing indoor air quality since this type of detail has been missed with previous studies modelling indoor environments.

This study follows the experiences of 17 participants in an Indoor Air Quality Pilot Project at Tampere University in 2024 lasting two and a half weeks. The participants were given AirGradient low-cost air quality monitoring devices to their homes, contributing to community based monitoring. Participatory practises were also implemented through two workshops: at the beginning and the end of the project. The workshops gave participants an overview of air quality matters, the research taking place during the project, and factors influencing their home environments. Through anonymous qualitative and quantitative questionnaires filled out by participants at the beginning and at the end of the project, this study explores how citizen science and community-based monitoring can enhance indoor air quality research and contribute to sustainable urban development.

The results of the questionnaires showed that participant motivations for joining the project were personal wellbeing and curiosity surrounding air pollution in their homes while some surprising findings they identified were on PM2.5 and CO_2 readings. Key behavioural changes were also identified through the questionnaires, as participants reported increased interest in IAQ, policy regarding IAQ, and citizen science as a whole. Participants also stated feeling more empowered regarding their home environments and showed an increased familiarity with the central topics of IAQ between the beginning and end of the workshops and measurements. This familiarity spread to participant sentiments toward having their home IAQ data being uploaded to cloud services, and participants said they would be more comfortable with their data being used for similar projects in the future.

The behavioural changes can be attributed to the use of citizen science practises where participants are not simply involved to collect data but were actively engaged on the research topics. Through workshops, they were taught how to interpret device results which contributed to their learning, familiarity with topics, and sense of empowerment. These results impact the usability of community based monitoring in indoor air quality monitoring research and show how these methods impact the sustainability of future research in this challenging field. Previous modelling of indoor air quality relies on outdoor factors and general building specifications, which overlooks

individual behaviour influences on indoor air quality. Community based monitoring therefore fills the gap by providing more detailed and qualitative data to be used in research of home environments.

Keywords:
Citizen science
Community Based Monitoring
Indoor air quality
Indoor air quality monitoring
Low-cost air quality monitoring devices
Participatory science
Sustainable development

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I have utilised AI tools in my thesis:

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Symbols and Abbreviations
Abstract
Results and Analysis
Discussion

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PREFACE

From inspiring me to learn about citizen science and indoor air quality, to tirelessly commenting on my writing, I could not have done this thesis without the support of Anna-Kaisa Viitanen. Thank you to Jonathon Taylor and the other SUD teachers for your insights and encouragement throughout the process as well.

While this research was made possible at the faculty of Built Environment at Tampere University, the community at Urbanum and INTO is what has carried me thus far. Citizen science and community based monitoring are an integral part of sustainable development, and I hope this is only the beginning of learning more about them.

Tampere, 03 July 2025

Ester Väisänen

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LIST OF SYMBOLS AND ABBREVIATIONS

BC	Belmont County
CBM	Community-based monitoring
CLO	Cornell Lab of Ornithology
CO_2	Carbon dioxide
CS	Citizen science
IAQ	Indoor air quality
LCS	Low-cost sensor
NOx	Nitrogen oxides
PM	Particulate matter
PM10	Particulate matter; diameter of 10 microns or less
PM2.5	Particulate matter; diameter of 2.5 microns of less
Q1	First questionnaire sent to participants in IAQ project
Q2	Second questionnaire sent to participants in IAQ project
TVOCs	Total volatile organic compounds
VOCs	Volatile organic compounds

1 INTRODUCTION

The air that all people breathe and the places where most humans spend their time can be detrimental to a healthy life. Understanding the air we breathe is crucial to mitigating health risks from exposure to pollutants, but more data is needed to truly understand urban indoor air pollutants (Koivisto *et al.*, 2019). Humans inhale various types of gasses daily which primarily consist of the gases we need to survive, such as nitrogen (78%) and oxygen (21%). The air we breathe can also include other gasses as well as particulate matter (PM) from anthropogenic sources such as fossil fuel combustion and industrial processes, or from natural sources like dust and wildfires (Koivisto *et al.*, 2019). While all health effects of every kind of particle have not been studied, many types of particle exposures have been linked to negative health effects and increased mortality rates and linked to diseases such as lung cancer, respiratory issues, decreased cardiovascular health and circulatory problems (WHO, 2021).

While measuring outdoor air pollution levels has become more common, understanding the sources and presence of various pollutants indoors becomes important for the safety of global populations as humans spend on average 90% of their time indoors (Duffield and Bunn, 2025). Indoor air pollution comes from outside and indoor sources, making identifying the exposure levels and factors affecting individual homes difficult due to the complexity of pollutants, accessibility issues, and measurement device costs (Mandin, 2020). This is why finding new ways to research indoor air quality (IAQ) in a cost effective and large-scale way becomes important.

Citizen science (CS) and community-based monitoring (CBM) are acknowledged as tools in researching biodiversity and environmental phenomena already (Bonney *et al.*, 2009). Research shows many benefits of engaging participants in research projects through citizen science and CBM: Social responsibility of participants, decision-makers being provided with more detailed data, trustworthy data for residents, community upliftment, and access to otherwise difficult locations (Segev *et al.*, 2021).

Using the lens of CS and CBM, this study aims to understand the benefits of CBM and CS within an IAQ pilot study conducted at Tampere University in 2024 for sustainable development. The project had participants collect air quality monitoring devices to their homes for two weeks, accompanied by two workshops surrounding topics of IAQ, pollu-

tion mitigation and citizen science. The participants answered two anonymous questionnaires regarding their experiences of the devices, workshops, perspectives, and possible changed behaviours to better understand the participant perspective of the IAQ pilot study. The questions were qualitative in nature, but the structure of the form was quantitative. Therefore, the analysis on the data regarding participants' prior knowledge of the topics of IAQ, perspectives on issues regarding IAQ, and possible changed attitudes, is conducted through quantitative methods.

Beyond the benefits of gathering research data in indoor environments, engaging participants from the beginning to the completion of a research project could be important in sustainable urban development. In a rapidly urbanizing society, would active citizens who are knowledgeable on their surroundings not only benefit future research projects as collaborators but also encourage participants to engage in local policy? When participants learn more regarding their surroundings and are treated as equal contributors within a project, could it not lead to more robust scientific discourse? Citizen science and CBM could therefore not just be a tool for future research projects, but also for more sustainable urban development.

Objectives and Aims

The question then is this: How does participation in an IAQ monitoring citizen science project impact participants and what insights can be drawn from this regarding sustainable urban development? The hypothesis is that participants actively involved in a CS project, actively involved in CBM, will gain a deeper understanding of the factors influencing their environment. This increased awareness will have an impact on their perspective on IAQ, and change behaviours related to it. Indirectly this would affect local politics and decision making through more involved and active citizens.

This thesis aims to explore the benefits of citizen science and CBM in projects researching urban environments, particularly IAQ. The research focuses on the value of CBM in research, as well as its impact on participants. Through the paper the aim is to understand the impact CBM used in CS projects could have on sustainable urban development, focusing on the benefits in the context of indoor air quality research. This thesis aims to identify the benefits of using low-cost sensors for monitoring indoor air quality (IAQ) in private homes, while also addressing the challenges related to privacy and cost of measuring this kind of data.

This study aims to understand two key components of citizen science research through a CS IAQ monitoring pilot project. This is done through two questionnaires sent to participants, one before measurements and one after. The first objective is to understand

participant awareness changes in IAQ issues. To do this participants' understanding of air quality issues before and after their involvement in the pilot project were identified. Secondly, CBM implications for sustainable urban development research is evaluated through participant interest in continued collaboration and interest in the topic of IAQ. This will be achieved by analysing the feedback from participants, gathered through two questionnaires, to identify common themes and insights regarding their participation.

2 BACKGROUND

Air pollution is an umbrella term for several factors which affect air quality. Air pollution is any kind of matter, gas, aerosols or particles, which float in air we breathe. The primary pollutants which the World Health Organization published exposure guidelines on due to them having the most significant effects on human health and mortality are ozone, nitrogen dioxide, sulphur dioxide, carbon monoxide, and also includes particulate matter 2.5 (PM2.5) and particulate matter 10 (PM10) (WHO, 2021). PM10 and PM2.5 are airborne particles which have a mean diameter of 10 microns or less, and 2.5 microns or less respectively (González-Martín et al., 2021).

According to the World Health Organization in 2016, in Finland, 327 deaths could be attributed to air pollution in 2012 (WHO, 2016). The problem with this data is that it only pays attention to the outdoor air pollution, and for example in Tampere that would be based on the measurements of only four stations that pick up PM2.5 as seen in Figure 1 (EPA, no date). A reason for the sparsity of measuring stations is their large size and high price, limiting air quality readings to only an overarching picture of an area's air quality due to the lack of data points.

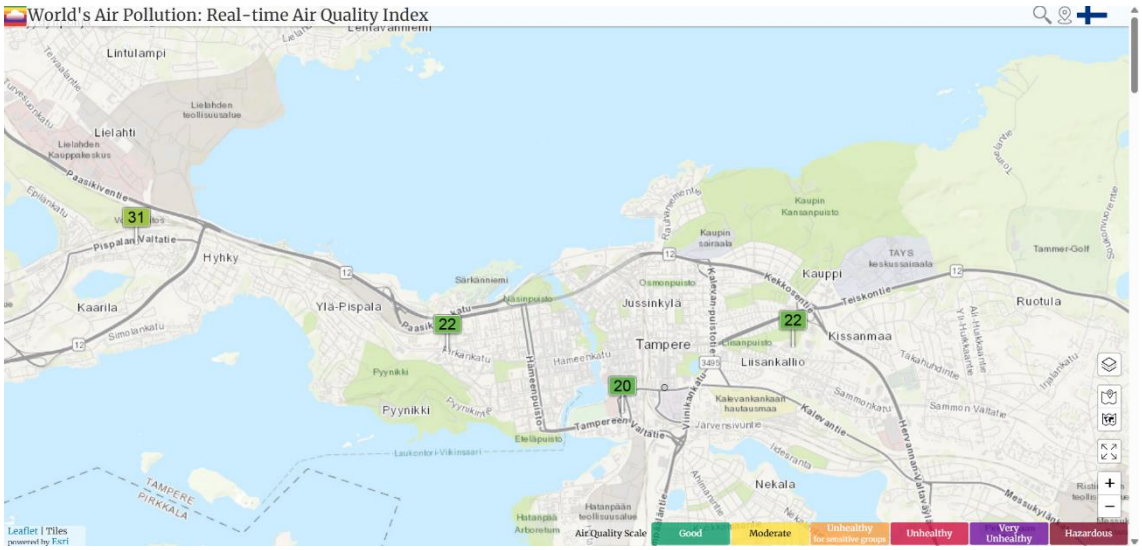

Figure 1 Snapshot of Tampere PM2.5 measurement indicators on 4 June 2025. Readings are on a scale of 0 – 100, with readings considered 'good' shown in green [https://waqi.info/#/c/61.511/23.768/11.1]

Particulate matter is an umbrella term for PM2.5 and PM10, which are liquids and solids suspended in the air, and are found to be especially concerning for health reasons (Lowther *et al.*, 2019). They enter the body through inhalation and land in the respiratory

system causing and aggravating respiratory diseases and cardiovascular problems (THL, 2024). The particles in this kind of pollution have a diameter of 10 microns or less and are referred to as PM10. For reference, an average human hair is approximately 60-80 microns in diameter (Khushally *et al.*, 2025). Fine particulate matter on the other hand, PM2.5, is small enough in diameter that it can enter deeper levels of the lungs and enter the bloodstream, and has even been found in the brain (Lowther *et al.*, 2019). Medical studies are researching the link between PM2.5 exposure and lung cancers, heart attacks and increased mortality rates, to better understand the health impacts of PM2.5 (THL, 2024). Since particulates are made up of varying chemicals and constituents, it is difficult to draw direct conclusions on a global scale, however there are clear links between cardiovascular and respiratory diseases and increased exposure to PM2.5 (Arnold, 2014; WHO, 2021).

2.1 Indoor air pollution

People spend approximately 90% of their time indoors (Duffield and Bunn, 2025) and while building regulations and technologies are getting better, indoor air quality can be found to be poor for various reasons. For example, indoor air has been found to be at least twice as polluted as outdoor air in places where pollutants are generated indoors or where outdoor pollutants get trapped indoors by ventilation systems which hinder airflow (González-Martín *et al.*, 2021). This is highly dependent on the type of pollution measured, the location of the measurements, and research being carried out. The factors affecting indoor air quality vary from climate to the type of building ventilation systems, as well as from outdoor conditions to the lifestyle of an individual.

Indoor air pollution has three overarching sources. These can be building constituents, external pollution, and occupants themselves (Mandin, 2020). Building constituents would include construction materials, paints, surface coverings etc. External pollution indoors would include pollution from transportation or industry emissions, wood fires, or natural environment such as dust making their way indoors through open windows or “leaky” buildings (Duffield and Bunn, 2025). Occupants themselves contribute to the production of varying sources of pollution, such as cooking, 3D printing, burning candles, and using cleaning chemicals or aerosols (Audignon-Durand *et al.*, 2023). These sources produce particles that remain in the air to be inhaled by residents.

Indoor air pollutants can further be categorized into chemical, biological, or physical, irrespective of their source. Chemical pollutants can for example be semi-volatile and volatile organic compounds (VOCs) or inorganic gases. Biological pollution then can be

moulds, viruses, or bacteria. Physical pollution can include small artificial fibres, asbestos fibres, or particulates, like PM10 and PM2.5. (Mandin, 2020)

2.1.1 Current understanding and research on indoor air quality

To understand indoor air quality (IAQ) and what affects it, different methods of research take place, from outdoor measurements to extrapolate IAQ and modelling. Large sensors, for example measuring PM2.5 outdoors in cities, take measurements in public space. This kind of technology is not practical for use in private residences due to their large size and high price. There has been an increase in research using low-cost air quality monitoring devices and sensors outdoors (Lowther *et al.*, 2019). These are much cheaper than the bulky outdoor sensors and are easily usable by individuals, however the ethical and logistical considerations of private residence measuring make IAQ research challenging.

There have been projects dealing with modelling indoor air quality based on external datapoints and building types, which provide better insights into urban IAQ than before (Taylor *et al.*, 2019). These models rely on information provided when a building is constructed instead of during its occupied lifecycle and need to generalise building specifications regarding ventilation systems in different types of residential stock. This leads to a lack in accurate readings from inside individual residences, which can vary drastically depend on the lifestyle of the occupants. While a model of estimated city-wide IAQ clarifies the distribution of pollution, these models do not provide enough data in conducting thorough IAQ research in urban areas, because they do not consider variable lifestyles and anthropogenic pollution.

2.1.2 Low-cost sensors and their challenges in IAQ

Low cost sensors (LCS), which measure various air pollutants, have been applied in the outdoor space already for some years and moving these sensors indoors would be a solution to understand what happens inside homes (Higgins, Kumar and Morawska, 2024), further than using outdoor ambient pollution and the building stocks to model IAQ. These sensors would need to be easily used by individuals, transportable and reliable in order to provide good data for researchers (Omidvarborna *et al.*, 2021), which has not always been the case (Kumar *et al.*, 2015). Today, various models exist on the market, ranging from general store level devices to higher end devices which connect to the internet, and measure VOCs, NO, carbon dioxide (CO_2), and PM2.5 (AirGradient, 2025). Collecting and using IAQ data reliably to understand indoor environments with LCS remains challenging from a few perspectives, however.

The LCS are not always accurate with their measurements due to the varying nature of indoor environments (Hayward *et al.*, 2024). Different methods can be used to combat the primary antagonist to the reliability of LCS data, like relative humidity and temperature changes, by calibrating the sensors to their environments. While efficient in producing accurate measurements, indoor environments change with seasons and activities. Therefore, the calibration does not hold over longer periods of time. Also, there is still no standardised protocol for LCS calibration which would bring the produced data to the reliability standards of reference-grade instruments (Hayward *et al.*, 2024).

Another challenge of LCS is the storage and collection of the collected data. This is due to the need for network connection of the sensors in order to upload data for collection, causing power consumption increases (Omidvarborna *et al.*, 2021). Alongside this, cloud storage systems pose the threat of privacy infringements (Higgins, Kumar and Morawska, 2024). The devices require onboarding of the users, especially in private residences, before they can be utilized for IAQ research efficiently. These issues cause monitoring IAQ in private residences to be challenging ethically due to privacy reasons, practically in the collection and storage of the data as well as logistically from the user perspective.

2.2 Participatory and citizen science

As a relatively new term, “citizen science” is difficult to define but it can loosely be considered as the practice of laypeople collecting valuable data used for scientific research (Conrad and Hilchey, 2011). Participatory science includes citizen science under its’ umbrella but tends towards a broader scope. Participatory sciences can include anything from scientist-led projects with community involvement as data-collectors, to crowdsourced science, or volunteered geographic information (*AAPS*, 2024). While citizen science and participatory science can be synonymous with each other, as well as terms such as community science, the general idea of both remains the same: connecting people to research.

The basics of science is observation and analysis turned into discovery, and asking a question about one’s surroundings, conducting measurements, and drawing conclusions from the findings has been around for a very long time. In fact, astronomy can be considered one of the oldest incorporators of citizen science, as everyday people have been contributing with observations since ancient times (Vohland et al., 2021). Citizen science in astronomy continues today, as planetary motion, stars, and comets are observed and shared online to support research. For example, citizen scientists have been given the task of classifying galaxies or light curves of variable stars, identifying clouds on Mars, and dozens of other astronomy related projects on Zooniverse’s platform (Vohland et al.,

2021). The platform brings together “virtual” citizen scientists and formal science to collaborate and gives a space for new project ideation. Zooniverse has active projects in many different sciences and is just one example of how citizen science can engage global communities and benefit scientific research (Fortson and Lynn, 2014).

One of the first official citizen science projects was done in the 1990’s by the Cornell Lab of Ornithology (CLO), who made use of for three large scale “National Science Experiments” to study bird migration and behaviour. The projects aimed to not only have volunteers collecting large-scale data on birds across the country, but also to educate participants on birds (Bonney *et al.*, 2016). Each participant received a “Research Kit” which gave information on the phenomenon being studied, explained the basics of scientific research methodology, and instructions for the bird observations (Bonney *et al.*, 2009). This kind of large-scale data collection was incredibly valuable at the time and continues to be a significant way of wildlife observation today.

The CLO project and Zooniverse platform citizen science projects differ from traditional scientific research because they aim to educate the participants and include them in the development of the research, beyond simply using volunteers for large-scale data collection (Conrad and Hilchey, 2011). There are many ways of approaching citizen science, and so the definition of it remains up to the individual researcher, according to their needs. For the sake of this paper, citizen science is defined as “the engagement of non-experts in research projects within their environments through learning, development and data-collection”.

2.2.1 Community based monitoring

It is difficult to talk about citizen science without talking about community-based monitoring. Community based monitoring (CBM) can be defined as a group of interested parties collecting information on an area of communal concern (Conrad and Hilchey, 2011). In CBM, the local expertise of the community increases the value of the data collected by adding a qualitative layer, as participants know more about their surroundings through expertise of experience as opposed to an outside researcher (Olson and Colston, 2024).The additional depth of local knowledge also raises the depth of the research possibilities in an area.

CBM specifically includes participants in citizen science projects through data collection and observation. The key difference between CBM and traditional research which makes use of volunteer crowd-sourced data, is that in CBM the participant is engaged in the project as whole through understanding perhaps the goals of the project or learning more about their environment through the data collection. CBM has been found to engage communities in an empowering way due to communities learning how to put together

monitoring projects, leading to the creation of nature conservation groups (Mamun and Natcher, 2023).

CBM becomes an invaluable tool in projects requiring a large number of data points, such as the National Science experiments needing national data around bird migrations (Bonney *et al.*, 2016) because of the capacity for individuals to collect larger numbers of data than otherwise would fit within a project scope. Formulating the data collection as an activity where the volunteer gets something out of participating, encourages engagement. In the case of IAQ, having a higher density data-network would enable more significant research on the movement of pollution and their spatial relationships. Higher density networks are becoming increasingly plausible through CBM due to lower costs of air sensors and technologies such as cloud based services.

2.2.2 Community based monitoring in air quality monitoring

Citizens of Belmont County (BC) in Ohio partnered with a volunteer network to put together a community based monitoring (CBM) project around air pollution, because of increasing concerns over unjust practises of reporting on oil and gas industry pollution in the area (Raheja *et al.*, 2022). It is an ongoing project which connected citizens and scientists to collect data on local air quality and pollution levels to take control over the health of the community and to be able to push for better policy.

Fracking is a major industry in BC, with the PTT Global Chemical Ethane Cracker Plant being permitted in 2015, even though local groups raised serious worries over the large quantities of air pollutants like VOCs and greenhouse gas emissions being released by it (Raheja *et al.*, 2022). The US Environmental Protection Agency's air monitoring infrastructure was seen to be lacking, as there were three sparsely situated monitors in a large area, which could not reliably represent the heterogeneous environment. While BC air was deemed to have lower PM2.5 concentrations than what was dangerous, according to National Ambient Air Quality Standards since 2018, experiences of residents in the area and the monitor sparsity brought this under question.

The CBM project began to take shape as the communities received support from AGU Thriving Earth Exchange (TEX). The community was able to put together a sensor network of low-cost sensors by raising awareness and advocacy of the issues around air quality within their own community, recruiting more individuals for the organized effort against pollution (Raheja *et al.*, 2022). The monitoring devices used in the project, PurpleAir sensors, were used due to their ability to upload real-time data and low costs of the devices themselves, enabling the network to model more accurately the movement of air pollution in the area. The sensors measured PM2.5 concentrations and total volatile organic compounds (TVOCs), as these were the pollutants of most concern. There were

35 households recruited to the CBM network who would install and maintain the sensors.

The results of the sensor network showed that PM2.5 measurements of the sensor network differed from the EPA sensors in the area, showing the need for more detailed data than provided by the sparse EPA monitors (Raheja *et al.*, 2022). When it came to the VOCs, residents took notes by hand of different conditions and the resulting health effects of air pollution events. This led to a finding that many residents experienced poor health effects on the same day, which coincided with tVOC measurements taken by volunteer scientists from nearby stations. Through this, plume models made of the movements of pollution in the area increased understanding of factors affecting VOCs and identifying the areas most at risk.

Through the CBM project, the communities became more educated on their rights and gained the ability to advocate for more policies to protect their health. The project found that the community grew in solidarity through shared experiences and gained technical capacity in making observations and measurements. Beyond the clear community benefits, the benefits of CBM in this project on air quality measurements shows the power of low-cost high-density monitoring networks. While this project measured outdoor air quality, the principle of sensor networks and CS can be applied to other cases or air quality monitoring, such as IAQ monitoring projects.

3. METHODS

The study focuses on the participant perspectives on researching IAQ and makes use of an IAQ Pilot Project run at Tampere University in late 2024. The project itself gathered data from low-cost air quality sensors from AirGradient (see fig 2) which were distributed to each of the 17 participants, to set up in their private residences (AirGradient, 2025). The participants were recruited via Tampere University intranet and there were no specific parameters on the participant selections, simply having an interest to participate in the study.

Two surveys were sent to participants for the purpose of this study. These were anonymous and voluntary for participant to respond to both at the first workshop and at the second workshop of the pilot project.

3.1 IAQ Pilot Project

The pilot project ran over the course of two and a half weeks. There was an initial workshop for participants where they were given general information on air quality, the IAQ pilot project, and this thesis research. At the first workshop they also collected the monitoring devices and received instructions on their use. Once they had gone home and set up the devices, they made observations of their own device from the device's monitor. The devices also automatically uploaded the data to the pilot project research team's platform. After two and a half weeks, there was a second workshop where participants came to return the monitoring devices and got a chance to see their collected data visualised as graphs. In this second workshop there were several lectures held about improving IAQ, pollution sources, citizen science and the collective data from the pilot study.

Figure 2 AirGradient Monitor

The data collected for this thesis was parallel to the pilot study, as participants filled out forms regarding their background knowledge, interest in the topics being studied, as well as possible changed perspectives at the two

workshops of the IAQ pilot project. The data collected from these two questionnaires is what is analysed to understand citizen science and CBM influences on research and individuals.

3.2 Data collection

The data was collected via two electronic questionnaires via Microsoft Forms. The first questionnaire was accessible to participants via QR code at the end of the first workshop and monitoring device pick-up. The participants that could not be there in person were sent the questionnaire by the researchers of the pilot study via email. The second questionnaire was also accessible to participants with a QR code at the end of the second workshop of the IAQ pilot study. The questionnaires themselves were filled out on Microsoft Forms, which did not require logging in and did not collect personal data. The results of both questionnaires were exported from Microsoft Forms on to Excel and descriptive statistics like graphs and pie charts are used to analyse the response data.

Having the second questionnaire available at the end of the second workshop and repeating some questions from the first questionnaire enabled identifying differences in some of the answers between the two questionnaires. Answers were collected before the participants took the measurements, and again post-measurements when participants had received more in-depth information around improving IAQ in their homes, causes of pollution indoors and citizen science, through the second workshop. This enabled a small-scale longitudinal study on the participants responses.

The goal of both questionnaires was to have several different types of questions, so that the participant remained engaged throughout the questionnaires. This included multiple-choice, closed and open questions, as well as Likert scale questions. This was to avoid the answers being clicked through without thought, but also to make the experience less boring for the participant, while collecting interesting data.

All questions were asked to answer one of three questions. Firstly, what motivated participants to join the pilot project? Secondly, what perspectives, sentiments, or behaviours changed between the beginnings and the end of the project participation? Thirdly, what were the participant experiences during the process of participating in a citizen science project?

The devices provided to participants were AirGradient One indoor air quality monitoring devices (AirGradient, 2025). The devices measure levels of PM2.5 and CO2 in indoor air and gave an index of TVOCs and nitrogen oxides (NOx). Beyond these, the device also indicated humidity levels, temperature, and the time. The AirGradient device had a small display for the readings in real time and connected to the internet via Wi-Fi for

uploading measurement data. This data from their own device was available for participants if they registered for the AirGradient platform, and as a total visualisation at the end of the measurement period provided by researchers. The devices needed to be plugged in to a power source at home and connected to Wi-Fi for the researchers to collect the data. The data from the researcher's side was not anonymous, because each device was identified to a particular participant. This data was not available for this research paper, as the actual measurements of the devices were out of the scope of research.

3.3 First questionnaire

The first questionnaire collected information on participant backgrounds while maintaining anonymity. The questions were about possible previous citizen science project participation and motives for participating in the IAQ pilot project. The listed motives were own wellbeing, scientific curiosity, interested in air quality monitoring, contribution to science, identifying pollutants in own home, interest in citizen science, data collection, hands on participation, networking, and other. There were questions which used a Likert scale, from strongly agree to strongly disagree, around interest in the IAQ pilot project topics and general scientific research. The goal with these questions was to identify participant backgrounds and potential biases. Questions were also asked about how accessible information is on air quality in general and personal living environments.

Other questions focused on the participant's familiarity with the themes of the pilot study, such as indoor air quality, air pollution, PM2.5 and gas phase compounds (such as VOCs). They were also asked how comfortable they felt with an IAQ monitoring device in their home in general and how comfortable they would feel having their home's IAQ data anonymously uploaded on a public online platform, where others could access the data. This was to gauge general openness to community-based monitoring in IAQ projects and previous knowledge on the topics studied in this project.

3.4 Second questionnaire

The second questionnaire collected data on the perspectives of the participants on the usability of the monitoring devices, ease of setting up, and the clarity of the instructions given. The participants were asked if they connected to the optional AirGradient online platform and if that was found useful. They also answered questions on the relevance of the IAQ pilot project workshop topics, whether they were easy to follow, interesting or difficult to comprehend.

To understand participant interest in the process, what they had learned, and to identify changed behaviours over the course of the project, several questions were asked as well. These included multiple choice questions regarding how regularly they had been checking the data values during the two-week measurement period. Tied to these were questions which asked if they had been surprised by any of the values shown by their monitor, and which ones those were, for example the concentration of PM2.5 or levels of VOCs. They were also asked if particular activities in the home resulted in changes that they had observed, such as cooking, cleaning, adjusting ventilation, number of people in a room, using a fireplace, or smoking. Following these questions the participants were asked if their behaviours have changed as a result of the participation. Some options given to choose from were cleaning, interested in IAQ, interest in IAQ policies, lifestyle, indoor humidity, types of air pollution, or citizen science projects.

Duplicating some of the questions from the first questionnaire in the second questionnaire identified possible shifts in sentiments through a small-scale longitudinal study. These were the questions regarding familiarity with the topics discussed, comfort with IAQ monitoring devices and sharing data. There were other repeated questions, such as the Likert scale questions on interest in scientific topics and research, data availability on air quality, and potential health concerns related to IAQ. To gain some insights post-measurements, some additional questions to the Likert scale section from the first questionnaire were questions. These included questions on feeling of power to change own IAQ and background in science and research. The participants were asked the likelihood of them participating in a citizen science project again as well as for an overall rating of participation too.

3.5 Ethical considerations

The data collected by the two questionnaires from the IAQ pilot project participants was completely anonymous. The questionnaire did not collect any personal data, such as name, age, gender, or place of residence. The questions themselves were formatted in a way that prevented the answers being possible to connect to an individual participant. Participants were aware that their answers would be used for this thesis and had the option to not respond to the survey if they wished. The participants also were given an information sheet regarding the purpose of the IAQ pilot study, as well as information on the purpose of the questionnaire itself. The data itself was dealt with anonymously, and the results drawn only from the questionnaire results.

4 RESULTS AND ANALYSIS

The first and second questionnaire sent to participants received 14 and 12 responses respectively. The total number of participants who took the devices home between questionnaire 1 (Q1) and the second questionnaire (Q2) was 17. Therefore, Q1 had an answering percentage of 82% and the had a 71% response rate.

4.1 Results from the first questionnaire

Out of the 14 respondents to the first questionnaire two said they had participated in a citizen science project before, with the majority not having had participated in a citizen science project previously. Of the two who had been part of a citizen science project, both had been a school/university led project, cutting out the options of a community or municipality led projects, as well as activism or hobby projects. With the majority of participants having had been recruited from within the university community, it is not surprising to find that the CS projects participated in before were university led. When asked in the second questionnaire, half of the participants stated that they are currently or have been before, involved in science fields wither through work or studies.

Participants were asked to choose from a multiple-choice list, with the option of 'other,' their reasons for participating in the IAQ pilot project. There was a suggested limit of three options, with a few participants selecting more, adding up to 42 total selections being made. As can be seen in Figure 3, 26% of the selections stated that their 'own wellbeing' and 26% of the selections stated 'identifying pollution in their own homes' were reasons for participating in the project. Other popular selections were 'scientific curiosity' at 17%, 'interested in IAQ monitoring devices' and 'contributing to science' both with 12% of the selections respectively. There were singular selections of 'interest in citizen science', 'data collection', and 'hands on participation' out of the 42 selections. This shows that prior to participating in measurements and workshops, most of the participants had an idea of IAQ health concerns and were curious to see pollution levels in their own home, as 52% of the selections made were around these topics.

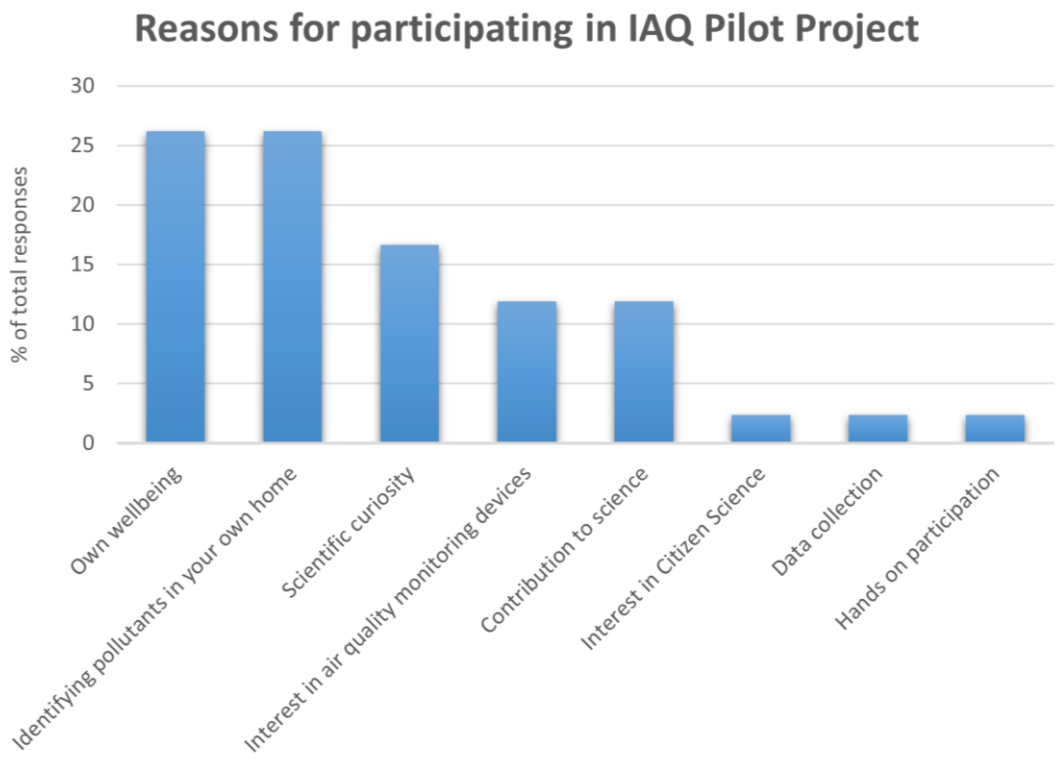

Figure 3 Reasons for participating in IAQ project

4.2 Results from the second questionnaire

The second questionnaire (Q2) consisted of 15 questions, which included similar questions to the first questionnaire about background and familiarity with topics, as well as a section specifically on the measurements and workshops of the project. There were 12 responses recorded from participants of the project in Q2

4.2.1 Participant measurements

Participants were asked about what readings they found surprising in their measurements, as they were able to see the device's live readings. All participants responded to this question, and they could select all options that applied. The bar chart in Figure 4 shows the percentage of the total number of selections per topic, with 20 selections made in total. Concentration of PM2.5 was the most unexpected according to participants with 35% of selections. CO_2 concentrations made up 30% of the total selections. VOC level and lack of PM2.5 were 20% together and NOx and humidity level were 10%, with 5% not finding any of the reading surprising or unexpected.

Participants identifying readings which were different from their expectations could make notes of factors possibly contributing to the changes or which readings specifically did not match their experiences. One participant expressed distrust in the readings of the device, particularly with CO_2 concentrations and humidity levels, wishing that they had known more about the reliability of the measurements beforehand. This kind of insight adds perspective when researching how accurately low-cost air quality measuring device's function and can help in identifying which measurements may be inaccurate.

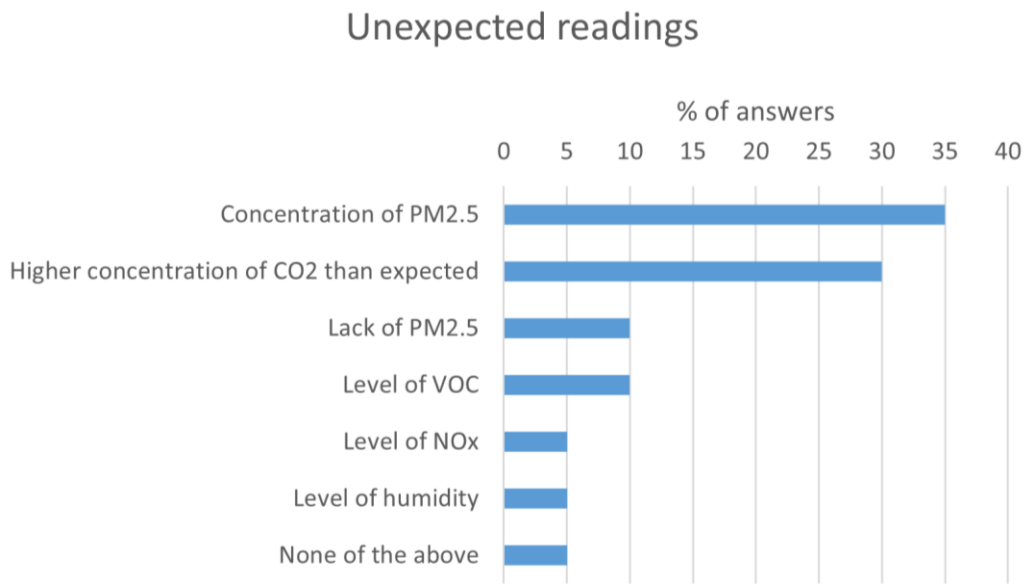

Figure 4 Readings that were unexpected to participants

Another perspective to the participant measured data are their notes of factors affecting the readings on their devices. They were asked to identify activities or contexts that changed their device readings to help see what human aspects affect IAQ. The participants could choose as many options as they felt were relevant from the list, with 48 selections being made in total. 83% of participants noted that the number of people in a room affected the reading and 66% identified that cooking affected the readings as seen in Figure 5. Half of the participants also noted ventilation adjustments affected the readings, for example opening a window in the room or turning on a stovetop fan. Using sprays or aerosols also changed readings, as did cleaning and burning candles or incense. Cleaning could include activities such as using chemicals, dusting, vacuuming, or moving around furniture. Three participants reported outdoor conditions affecting the readings, which could include the presence of smoke, dust, or the weather. Time of day was reported by two participants, as was the option of 'other.' Using a fireplace and vaping or smoking were reported to affect readings as well once, while one participant said they could not say which factors affected their readings.

The notes from participants regarding their observations gives a more qualitative view of the raw measured data. The data also shows the variance in experiences of individuals within their homes and their activities.

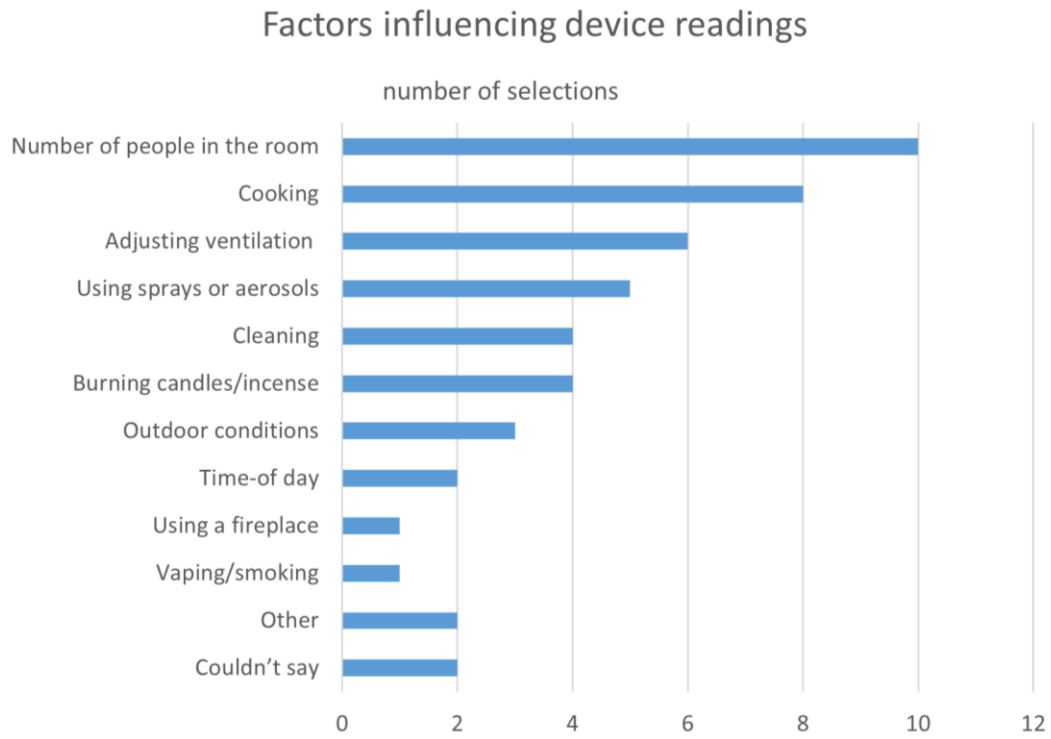

Figure 5 Participant identified factors affecting device readings

IAQ modelling and outdoor measurements cannot accurately indicate the individual behaviours of people inside their homes, for example how many people spend time in which room or how a person chooses to use ventilation. This goes to show why CBM along with CS is helpful in identifying factors that may not be known or are not possible to start modelling

4.2.2 Changed behaviour during project participation

The participants were asked if they experienced changed behaviour in any areas of their lives, after measurements and participation in the project. The results show self-evaluated changes in behaviour or awareness of issues related to IAQ. To indicate what areas they experienced a change in behaviour in, the participants were given unlimited selections from 11 options to choose from, one being 'other', and one being 'none of the above'.

In Figure 6, changes have occurred, since most participants selected at least one option. The most common selection of changed behaviour is related to general interest in air quality monitoring, with eight participants selecting this as an aspect. Another common response was interest in air quality policies. While the data does not indicate the direction

of interest, i.e. whether individuals are now more interested or less interested in the topics of monitoring and policy, both topics being seen as changed due to project participation is a good indicator that the CS method of research does produce a change. It would have been ideal to ask the direction of change so that it could be said for certain that individuals may become more aware and active regarding legislation about the topic being studied through CS and CBM project participation.

Four selections were made regarding interest in CS projects, pollution sources, and windows being opened. Fewer selections were made regarding public data on air quality and cleaning, as well as other areas of changed behaviour. These results also show that change was self-identified by participants in these areas too. It would be unlikely that someone would have been interested in paying attention to pollution sources before the project and throughout the project decided to not be interested in pollution anymore. Therefore, it can be assumed that participants experienced an increased interest in the areas charted in Fig 6 below. Only one participant did not experience a shift in behaviour in any area through participating in the study and one made changes to humidity adjustments in their home.

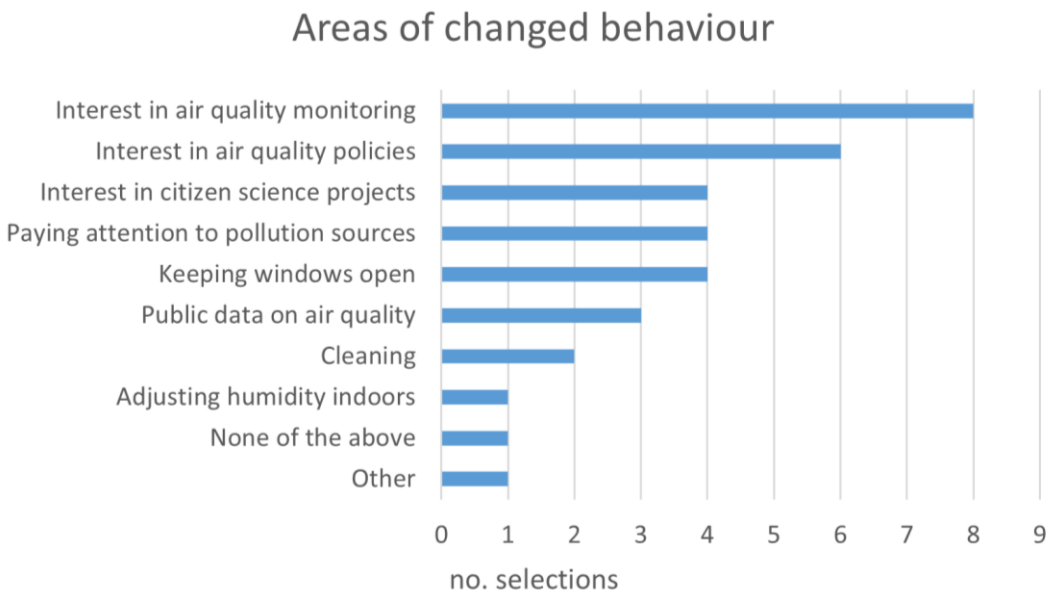

Figure 6 Self-Identified areas of changed behaviour post-participation

4.2.3 Experiences of the project

While the data regarding participants experiences with devices and their perspectives on the format of workshops and contents is more useful for reflecting on the logistics of the IAQ pilot project, it is also helpful in extracting participant sentiments towards this style of research. Participants felt that the instructions and usability of the devices was good.

All participants felt that the instructions given regarding the devices and purpose of study were sufficient and all except one respondent felt that they had no trouble with the measurement devices once they were set up. Participants gave comments that the topics of the workshops were interesting, and they received plenty of useful information on factors affecting air quality. One participant felt that they would have understood better if the presentations were in Finnish, however they still felt that the topics were interesting. Another participant did not trust the measurements of the device and would have wished for more information on the reliability of the LCS readings. The data shows that participants had an overall pleasant experience and that felt they learned something and were given tools to take control of their environment.

This is especially visible when asked how much they agreed with the statement of "I believe I have control over my home's IAQ" on a scale of strongly disagree to strongly agree, the majority chose answers between neutral and strongly agree. In total, 12 selections were made. This shows that most participants did feel empowered to make changes in their homes, as seen in Fig 7.

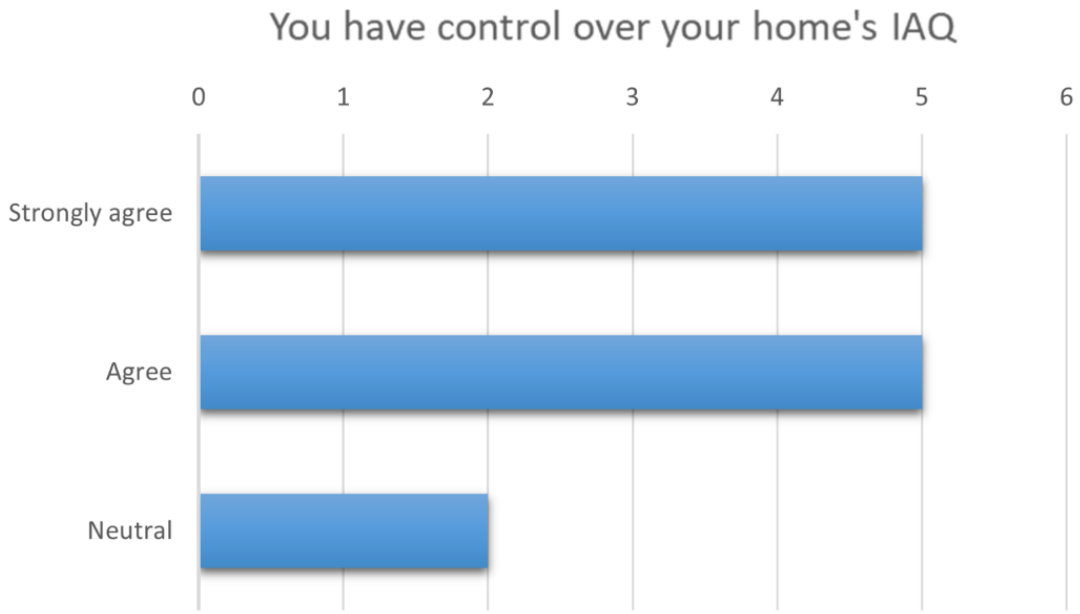

Figure 7 Feeling of control over personal IAQ

When asked if they would participate again in a CS project, none of the eleven respondents to this question said 'no'. The results show that 59% would participate again in a CS project and 41% said they 'maybe' would. This indicates that participants enjoyed participating in the IAQ Pilot project, enough to feel that they would most likely do something similar again in the future. This can boost the long-term sustainability of IAQ research projects, with participants being willing to continue with being involved.

4.3 Change in knowledge between Q1 and Q2

The first of the question pairs asked how familiar participants felt with topics surrounding the project, on a scale of 1 to 5, 1 being not at all familiar and 5 being very familiar. The topics included IAQ, types of indoor air pollution, PM2.5, and gas phase compounds (e.g. VOCs). The first questionnaire had 14 responses, where not all questions were answered in one of the responses. The second questionnaire received 12 responses in total. To compare Q1 and Q2, averages of the answers related to each topic were calculated and graphed as seen in Figure 8. Since the questionnaires had different answering percentages, the results were adjusted by comparing the averages instead of the number of responses.

As seen in Fig 8, between Q1 and Q2, IAQ understanding decreased slightly. There was no change in indoor air pollution knowledge and slight increases from Q1 to Q2 in familiarity with PM2.5 and gas phase compounds. This indicates participants being fairly familiar with IAQ and indoor air pollution to begin with and becoming more familiar with PM 2.5 and gas phase compounds over the course of the project.

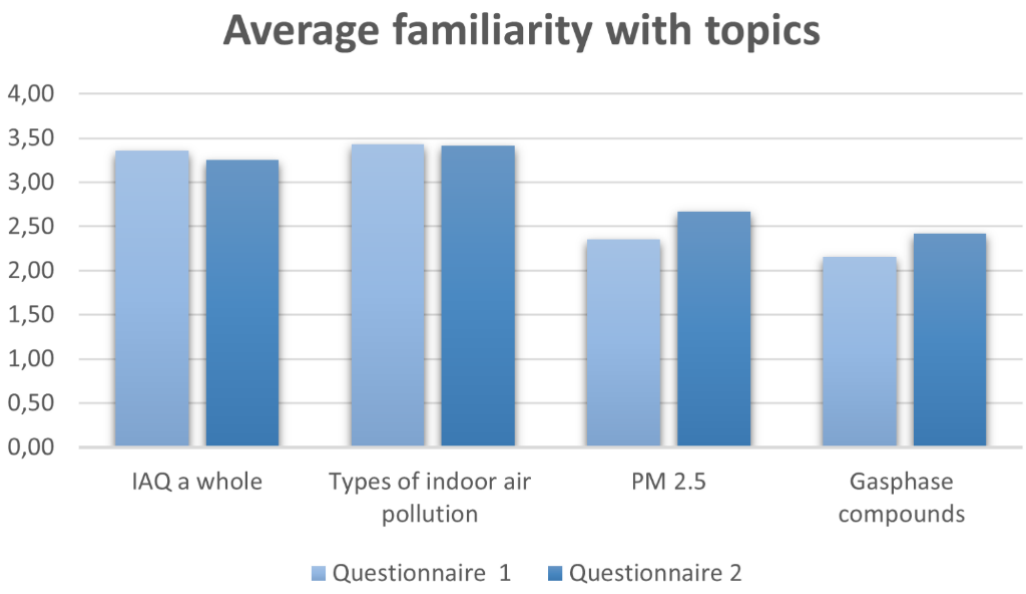

Figure 8 Average familiarity with topics

4.3.1 Comfort with indoor air quality monitoring devices

The participants were asked if they would be comfortable with a monitoring device in their house overall, both before and after the measurements in Q1 and Q2. In either case, no participant would have felt completely uncomfortable, and in Q1 2 participants

and in Q2 one, felt that they would ‘maybe’ be comfortable with the monitoring devices in their home. The ‘maybe’ responses decreased by 1 response between the two questionnaires and ‘yes’ increased by that amount, showing a small rise in comfort with IAQ monitoring devices over the course of the study.

The participants also evaluated how comfortable they would be with an IAQ monitoring device uploading their data anonymously onto an online platform outside of the project. Between Q1 and Q2, we can also identify a slight increase in more receptive sentiments towards the data from their homes being collected online. This could indicate a participant understanding more about the topics surrounding IAQ and familiarity with the devices, which leans them towards feeling more comfortable with the devices in their homes. From becoming more comfortable with devices, a participant may also become more open to contributing data through CBM to a data network.

4.3.2 Did the participants learn?

Participants were asked how much they agreed or disagreed with certain statements in both questionnaires. As found in the reasons for participating (Fig 3), participants are interested in their own home IAQ. Therefore, it is not surprising that all participants in the first questionnaire either strongly agreed or agreed that they want to learn more about IAQ in their own homes. When compared to the results of Q2, where participants identified how much they agreed with the statement ‘I know about IAQ at my place of residence’, 82% of the participants either strongly agreed or agreed. Of the participants 8% were neutral and 8% somewhat disagreed. This comparison shows that the desire to learn more about IAQ was met and the majority of participants felt that they knew about their IAQ after the project was completed.

Participants were asked about IAQ pollution and factors which affect urban air pollution in Q1. 86% of the responses indicated a desire to learn about it while 14% felt neutral. Most respondents in Q2 felt they knew about what factors affect urban indoor air quality, with 8% staying neutral, and 8% somewhat disagreeing. While the results between Q1 and Q2 are loosely comparable, they highlight the general positive attitude of the participants towards the topics of IAQ. Participants had a high desire to learn more about the topics they were involved in studying, and by the end of participation they felt at least somewhat knowledgeable on home and urban air quality factors.

4.3.3 Concerns regarding IAQ

In both Questionnaire one and two, participants marked how worried they felt about air quality and pollution in general. In Q1 this indicates the concern participants had at the beginning of the project, and Q2 measures the concern shown after participating in the project. It was found that strong feelings of worry decreased by 6% between Q1 and Q2, while moderate worry increased by 21%. Neutrality regarding air quality and pollution in general decreased completely between Q1 and Q2, indicating participants forming an opinion, whether it was one of worry or not. There was a small increase of 8% in moderate lack of concern. Overall, there are no significant changes in sentiments towards worry about air quality and pollution in general, but there can be value in seeing the change in neutrality. This shows that understanding more about a topic makes it easier to have opinions about the topic. In this case knowing more about air quality and pollution leads to individuals having a clearer concern (or lack of concern) surrounding this.

5 DISCUSSION

Indoor air quality data that is accurate is difficult to collect due to many factors surrounding high prices of sensors and ethical considerations (Mandin, 2020). One solution to this has been modelling indoor air quality based on building stock (Taylor *et al.*, 2019) but a more accurate data network for IAQ is attainable by CBM ((Lowther *et al.*, 2019). The IAQ pilot project is an example of how researchers not only used volunteers to do research on low-cost air quality monitoring devices, but they also engaged participants during the process through workshops and information sharing. Using citizen science and CBM is beneficial in future IAQ research and can support sustainable urban development.

5.1 Benefits of CS combined with CBM for the participants

Participants were curious about their home IAQ and 77% were worried or somewhat worried about their indoor environments prior to the project, as was found through the questionnaire responses. It is often concerns over environments which initiate a person to want to participate in CBM or CS projects (Raheja *et al.*, 2022; Olson and Colston, 2024), which in turn explains why many already concerned about IAQ may have volunteered for the pilot project. Participating in a study regarding the preexisting areas of concern for participants has two-fold benefits.

Firstly, participating in the study enabled them to monitor their home environments without needing to buy devices for themselves and could follow their own air quality from the Air Gradient devices. If they had simply collected the data and had not seen it nor learned how to interpret it, collecting the data would have been useless to them. Instead the CS format increases knowledge of the topics for the participants (Schaefer, Kieslinger and Fabian, 2020). Their knowledge on topics of IAQ also grew during the project because of the workshops, showing that the citizen science approach to the research benefitted them.

Secondly, through being engaged in the topics and process of the study, individuals were able to identify sources of pollution and were given tools to tackle possible issues related to IAQ in the organised workshops. Like in case examples from Canada and Belmont County, CBM can provide empowerment for individuals to make changes in their environments (Raheja *et al.*, 2022; Mamun and Natcher, 2023). From this study participants felt more empowered to make changes to their environments through participation in the project as well, as shown by the selections of areas of changed behaviours.

5.2 Benefits of CS combined with CBM for future research

While the benefits for CBM and CS for individuals and communities is significant in terms of engagement, empowerment and learning, according to our research and past studies, there are also benefits from the perspective of research itself (Raheja *et al.*, 2022; Olson and Colston, 2024).

Participants are willing to engage with CBM and CS going forward when they have been included in the project and analysis instead of simply collecting meaningless (to them) data. This phenomenon was seen in the enthusiasm of amateur astronomers to continuously upload information on research topics to Zooniverse, which functions as a platform where participants can engage with topics and make observations in their surroundings (Fortson and Lynn, 2014). This dynamic interaction between research and participation creates a basis for more collaboration going forward. Particularly in a field with difficult to get data like IAQ, having sustained interest from potential contributors is important for long term studies (Mamun and Natcher, 2023). From this study we found that 41% of participants felt that they would maybe join a CS project like this again, and 59% said that they would. From the feedback of the project, the participants gave an overall rating of their experience in the CS pilot project a 4.9 out of 5. This shows that using CS methods and engaging participants with CBM makes participants more likely to join CS projects again because of the enjoyability of it.

Layers of data which otherwise would not be collected, were made possible with CBM and combining it with a citizen science approach in the case of Belmont County (Raheja *et al.*, 2022). In that case, the notes taken during various pollution scenarios by the citizens showed symptoms experienced at different times. This filled out the quantitative data being uploaded to the cloud and gave further insights into the research at hand. Through interactions between participants and researchers perspectives, the participants were able to bring up their perspectives more easily (Raheja *et al.*, 2022). In the case of the IAQ pilot project the IAQ monitoring devices' accuracy was questioned by participants, because what their devices read was contradictory to their own experiences, particularly with CO_2 readings. This finding enables researchers to investigate the discrepancies between readings and experiences of participants and find solutions to increase the accuracy of low-cost monitoring devices (Kumar *et al.*, 2015). The qualitative element of the data also helps in seeing what individual lifestyle choices do to IAQ. For example, the amount one cooks, or smoking indoors was said to affect IAQ in the Pilot study, and through CBM those changes can be taken into account better than in, for example models, which cannot collect that level of detail (Taylor *et al.*, 2019).

The use of low-cost monitoring devices is increasingly viable in research as they are more available, they are more portable than traditional measurement devices, and are more user friendly (Kumar *et al.*, 2015). The AirGradient devices used in the IAQ pilot project were simple to use and they were low-cost as well with the ability to upload data onto a cloud. After participating in the IAQ pilot study, most participants felt more comfortable conceptually with uploading IAQ data on to an online platform or cloud. This indicates that having easy to use devices and transparent data collection builds trust with participants regarding their personal data (Gabrys, Pritchard and Barratt, 2016). This type of trust will enable larger sets of IAQ data, as participants would be more willing to join a CBM project, as mentioned earlier with regards to the sustainability of project participants. With the device's ease of use, any participant can set one up and contribute IAQ data which would lead to CBM produced large scale, detailed indoor data.

5.3 Limits of the study

Since there were 17 participants in total but the number of responses to the questionnaires varied, some of the changes between questionnaires can be attributed to different participants responding between the two. The overlap is good enough to be able to draw conclusions from the comparisons between similar questions. The analysis in this thesis was done graphically and interpreted without using SPSS, therefore the results cannot be defined as statistically significant.

Insight was found through this two-questionnaire method into the participation aspect of an IAQ study, like what factors participants enjoyed, what would motivate others to join, and that participants found it informational – enough to feel more interested in policy afterwards even! Some of the questions in the first questionnaire could have been formulated better with the second questionnaire in mind. Especially the comparison type-questions should have been identical in both questionnaires. This would require better formulated questions to support a better longitudinal study.

5.4 Further research using CBM for IAQ

To get accurate data networks through CBM, there need to be tests for the accuracy of the low-cost monitoring devices in varying environments (Kumar *et al.*, 2015). This could be done by completing a larger-scale low-cost IAQ monitoring study to get a better idea of their accuracy in changing environments (Yatkin *et al.*, 2022). The studies investigating the accuracy of monitoring devices should also include the CS principles and collect

feedback from participants throughout the study, as it adds the layers of qualitative insights, as found in previous research using CBM data (Raheja *et al.*, 2022). Participant perspectives, questions and ideas can give better insights into the data itself (Gabrys, Pritchard and Barratt, 2016; Raheja *et al.*, 2022).

In an ideal world of IAQ research, there would be an accurate sensor in all individual homes, uploading data regularly to create a dense sensor network, which in turn would deepen our understanding of IAQ. While this has not been possible yet, Taylor, et al., conducted research on modelling IAQ based on external building factors (2019). This gave good insights into pollution distributions within a city; however, it lacked the detailed insights into the lifestyles of occupants in homes. Community based monitoring could fill the gap of these models, by providing more detailed insights into the activities contributing to fluctuations of IAQ. From the IAQ pilot project study, we were able to identify activities which participants specifically felt contributed to increased levels of CO_2 for example.

Sustainability is not only about changing the type of concrete that is poured into foundations and fuels that we use, but is the paradigm shifts in decision making that takes into account social sustainability too (John, 2025). This is why citizen science and CBM are a natural next step in sustainable urban development research methods. Since CBM provides data networks that give better insights in IAQ issues, and adds a layer of qualitative information, it is helpful in planning spaces to be healthier. Implementing CS feedback practises can help prevent design and planning that ignores marginalized groups and further grows the inequality gap around air quality. Citizen science methods of feedback loops and citizen engagement in research add to the participatory nature of sustainable planning, which is needed in many aspects of sustainable urban development (John, 2025). As was seen in the IAQ pilot study, engaging participants through CBM and CS grew their interest in policies around IAQ, further enhancing the socially sustainable aspect of planning and policy too.

6 CONCLUSION

The question was this: How does participation in an IAQ monitoring citizen science project impact participants and what insights can be drawn from this regarding sustainable urban development research and planning? While the health impacts of poor air quality have been researched and addressed in many cities, through better technologies and policy, the need to understand indoor air quality remains. Since people spend most of their time indoors, being able to accurately research IAQ conditions is important, since these spaces can be polluted in various ways. A method to understand IAQ has been to model it using available outdoor air quality data and information of various building types to build a city-wide model of pollution distributions. This method of modelling IAQ however, has the limitation of not being able to consider the individual variances of lifestyle which affect IAQ. Community based monitoring and citizen science paired together with low-cost air quality monitoring devices can be one solution to this research gap.

Through the IAQ pilot project, 17 volunteers participated in workshops around IAQ, pollution, citizen science and how to mitigate pollution in their homes. Each participant had a monitoring device in their home, and they made observations with it over two weeks. Before the measurements and after the measurements, participants filled out anonymous questionnaires surrounding the topics of IAQ. By answering the questionnaires, the participants made it possible to draw insights of their motives for participating and potential changed behaviours over the course of the project. These perspectives supported the claim that CBM and CS practises engaged participants more than a traditional study with volunteers would have. By engaging with the project, participant interest in IAQ measurement and IAQ policies grew. Many participants said they would join another CS project again and found the process informative and pleasant.

Ultimately this small-scale study highlights that if done on a larger scale, CBM and CS could engage larger communities and collaborate well in future research. Going forward, research making use of CBM should keep using CS principles and work on limiting the variables in the volunteer pool. This type of research in in line with sustainability principles where citizen participation is a tool to prevent marginalisation and unequal development.

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