Evaluating Asthma Symptoms in Relation to Indoor Air Quality: Insights from IoT-enabled Monitoring

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Abstract

Air pollution appears in the form of outdoor air quality and indoor air quality (IAQ). Particulate Matters ($PM_{2.5}$ and PM_{10}) and CO_2, among many air pollutants, are responsible for worsening IAQ. IAQ has been linked to lung illnesses such as asthma, chronic obstructive pulmonary disease (COPD), and lung cancer. This linkage is related to how much any individual gets exposed to poor IAQ, individuals' daily indoor activities, and related health risks. The study presented in this paper focused on the analysis and identification of the relationship between IAQ, daily indoor activities and health concerns and their effect on breathing issues in five asthma patients in Bradford, UK. IAQ data were collected using an IoT-enabled, low-cost device capable of monitoring CO_2, $PM_{2.5}$, PM_{10}, relative humidity, and temperature. In addition, indoor daily activities and breathing issues that relate to asthma severity are also recorded using a digital platform. These recorded data are statistically analysed using correlation and measure of central tendency. Results indicate a strong positive correlation between breathing issues and indoor measured pollutants (0.72, 0.62 and 0.63 correlation coefficient with CO_2, PM_{10} and $PM_{2.5}$ respectively). IAQ is strongly correlated with indoor activity in terms of window opening hours and breathing issues as asthma symptoms. It was observed that when the mean readings of $PM_{2.5}$, PM_{10} and CO_2 are higher (22µg/m3, 24µg/m3 and 700 ppm respectively - in this study), the asthma patients reported experiencing worsening symptoms. This study highlights the importance of managing IAQ and window-opening habits to potentially mitigate asthma symptoms and improve patient care.

Keywords— IoT, Low-Cost Sensors, Indoor Air Quality, Asthma, Breathing Issues, Indoor activities.

1. Introduction

People in urban areas often suffer from a disproportionate burden of air pollution caused by the presence of dangerous compounds (air pollutants) in the air [1]. Air pollution appears in the form of outdoor (ambient) and indoor pollution in corresponding environments. Often, many air pollutants are found at higher concentrations in indoor environments than outside [2]. In general, indoor environments are a mix of outdoor pollutants commonly associated with vehicular traffic and industrial activities, which can enter through infiltrations and/or natural and mechanical ventilation systems and indoor contaminants that originate inside the building with indoor human activities (cooking, cleaning, vacuuming) emissions from building materials and furnishings, central heating and cooling systems, and so on (i.e., smoking, painting, etc.) [3].

IAQ refers to the presence of harmful chemicals and biological factors in the air that are found in non-industrial buildings [4]. Various factors including the concentration of pollutants such as CO_2, $PM_{2.5}$, PM_{10}, and thermal conditions such as temperature, relative humidity light, and noise affect IAQ [5]. Besides, IAQ also includes oxides of nitrogen, endotoxin, airborne allergens, particulate matter, and organic compounds. Various sources can affect indoor air quality (IAQ), especially in homes. This is because air pollution comprises components from both outdoor environments and indoor origins. Indoor activities in the form of the use of wood logs, open fires, ventilation and poor cooking styles are responsible for contributing towards poor IAQ and they influence health significantly [6].

There is growing evidence that air pollution is a concern, and pollutants can cause respiratory diseases [7]. With the increase in work-from-home culture, the risk of IAQ has increased resulting in a significant drop in immunity due to the increased likelihood of respiratory health issues [8]. The consequence includes increasing the underlying symptoms of various chronic and respiratory health issues, such as asthma [9]. Studies have indicated that IAQ is more dangerous than outdoor air pollution and responsible for poor health [10]. Indoor pollutants including particulate matter ($PM_{2.5}$ & PM_{10}) are associated with symptoms in human beings with asthma. It is believed that the cause of asthma is poor IAQ and exposure to PM [11]. Asthma is a prominent non-communicable illness that affects both children and adults, with high morbidity but a low fatality rate when compared to other chronic diseases [12].

According to the International Study of Asthma and Allergies in Childhood (ISAAC), there has been a 2% to 40% asthma prevalence from country to country [13]. The indoor factors amend asthma severity due to pollutants like nitrogen oxides, particulate matter, allergens, and second-hand smoke [14]. Indoor exposure to air pollutants can result in serious consequences in terms of non-atopic and atopic asthma

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depending on the extent and timing of exposure due to overlapping interactions between biological, chemical, and physical agents from childhood to adulthood [15]. In other words, the probability of exacerbating or developing asthma is influenced by the complex relationship between varied exposures to air pollutants in the indoor environment such as ventilation and heating patterns, building fabric, and indoor habits [16].

The occurrence of asthma poses a significant social and economic threat to the entire world. The prevalence of asthma and related symptoms is well documented, but limited research has been conducted in indoor environments among asthmatic patients [17]. In this research, an IoT-enabled low-cost IAQ monitoring device in combination with a digital platform has been employed to measure indoor air pollutants and daily indoor activities and breathing issues among asthma patients. The interactive digital platform allows participants to record indoor activities and asthma symptoms. The research aim of this study is to investigate how poor IAQ and indoor activities are related to the severity of breathing issues in asthma patients. For this study, statistical data analytics have been applied to the recorded IAQ and indoor activities data to investigate the relationship between IAQ, indoor activities and the severity of breathing issues in asthma patients. The results indicate a strong correlation between IAQ data, indoor activities, and breathing difficulties—a symptom of asthma. The analysis reveals that participants with asthma symptoms experienced more severe breathing issues when windows were opened less frequently and pollutant levels were higher, compared to those with more frequent window openings and lower pollutant readings.

The rest of the paper is organized as follows. In section 2, a comprehensive review of (i) relationship between IAQ, indoor activities and its impacts on health and (ii) the use of low-cost sensors (LCS) devices to asthma symptoms are presented. In section 3, the methodology used for the research is presented. In section 4, data analysis and discussion are presented. Section 5 completes the paper with a conclusion and future work.

2. Literature Review

This section presents the literature review summary on IAQ, indoor activities and its impact on health. The reviews are summarized into two subgroups covering Linkage between IAQ, indoor activities and Asthma and LCS-based monitoring IAQ, indoor activities and asthma symptoms.

2.1 Linkage between IAQ, Indoor Activities and Asthma

In developing nations, most of the population spends upwards of 80% of their time indoors, encompassing a diverse range of environments from homes and offices to educational institutions [18]. In the past, the focus on air quality was mainly on outdoor environments, given the visible and palpable effects of industrialisation and urbanisation. However, with the realisation that individuals, especially in urban settings, spend the majority of their time indoors, the focus has shifted. This transition has been further catalysed by a growing body of evidence linking poor IAQ to various health issues, from respiratory ailments to cognitive impairments [19].

Daily indoor activities can significantly change the air quality. For instance, cooking releases pollutants such as particulate matter and carbon monoxide that can penetrate deep into the lungs when proper ventilation is lacking [20]. The type of food being cooked, the cookware used, and the cooking method can all influence the type and quantity of pollutants released [21]. Other indoor activities like cleaning, using aerosol sprays, burning candles, and hobbies like painting can release volatile organic compounds (VOCs) and other pollutants into the air. These activities can significantly reduce IAQ, particularly in poorly ventilated spaces [22]. Raaschou-Nielsen et al. [23] conducted a study using range hoods, avoiding candles and fireplaces. The study results have shown that opening windows effectively reduced $PM_{2.5}$ concentrations.

Studies have also been conducted to study the relationship between IAQ and asthma which showed a negative relationship between pulmonary function and particular matter ($PM_{2.5}$) [24]. According to epidemiological research, air pollution, particularly exposure to PM, is a major contributing factor to the rise in paediatric asthma incidence across the world [25]. High levels of exposure to particulate matter (i.e., diesel exhaust particles), ozone, Sulphur dioxide, and nitrous oxide (O_3, SO_2, and NO) are major airborne allergens which can increase the risk of atopic sensitization and exacerbation of asthma and asthma symptoms and increase the hospitalization rate [26]. In a similar study [27], it has been observed that indoor $PM_{2.5}$ levels and the risk of wheezing symptoms, 70% of $PM_{2.5}$ comes from indoor sources such as vacuum cleaning. A study in California on 19 children showed that indoor PM exposure resulted in lower lung functions [28]. In another study [29], conducted to evaluate the impact of PM on asthma disease, showed that PM concentrations were high as compared to coarse PM when participants of the study felt asthma condition worsening.

Studies have been executed to explore the association between IAQ and indicate the importance of a person's age, gender, and the existence of related diseases [30]. Most asthma patients reported that air pollution exacerbates their symptoms, perhaps leading to a severe asthma attack showing a potential link between high-pollution days and respiratory-related hospitalizations [10]. Indoor pollutants can cause physical irritation of the airways, leading to inflammation and bronchoconstriction, triggering asthma attacks [31]. Studies [32, 33] have shown that exposure to indoor pollutants, particularly PM, is associated with increased asthma morbidity. Madureira et al. [34] conducted a study and found that indoor pollutants are linked to the onset of asthma symptoms in paediatric populations. In addition, a study by Den et al. [35] investigated the role of specific indoor pollutants as allergens. The findings suggested that indoor pollutants cause physical irritation and act as allergens, intensifying asthma symptoms in individuals already sensitised to them.

Ventilation, a key determinant of IAQ [36], has been the subject of renewed interest, especially concerning its impact on respiratory health. Windows, simple architectural features, play a surprisingly complex role in this narrative. On the surface, opening a window seems straightforward – it introduces fresh air and facilitates the exchange of indoor and outdoor environments. However, the relationship between window openings and respiratory health, particularly asthma, is nuanced [37]. Tong et al. [38] found that opening windows can often improve IAQ by diluting indoor pollutants. A study by Hernandez et al. [39] demonstrated that opening windows for just a few hours daily significantly reduced the concentration of volatile organic compounds (VOCs) in indoor environments. Another research by Shin et al. [40] found that window ventilation was adequate for decreasing carbon dioxide (CO2) levels, especially in densely occupied spaces. However, it's essential to consider the potential risks that come with it [41]. It could inadvertently worsen the IAQ in certain situations if the outdoor air is polluted or contains allergens. Recent studies [42-44] have delved into this problem, with findings suggesting that strategic window opening, informed by real-time outdoor air quality data, can strike a balance, optimising IAQ without introducing harmful elements.

2.2 LCS for monitoring Asthma Symptoms

Researchers argued that IAQ is the biggest health risk for people with asthma since it has high levels of carbon dioxide (CO_2), higher levels of PM reading and low levels of oxygen. Recent studies have highlighted the potential of IoT-enabled devices in monitoring IAQ [45, 46]. These devices, equipped with an array of sensors, can continuously track various indoor pollutants, from particulate matter to volatile organic compounds. The continuous nature of this monitoring allows for a more granular understanding of IAQ fluctuations, which traditional periodic measurements might miss. Moreover, these devices' real-time data can be crucial for timely interventions, especially in environments where pollutant levels can change rapidly due to various indoor activities or external factors. Continuous monitoring offers a significant advantage in enabling researchers to identify patterns IAQ [47]. Researchers can establish more reliable correlations between specific indoor activities and asthma symptoms with the monitored data [48]. For example, cooking can release various pollutants, especially when using solid fuels or even simple vacuuming. By clearly understanding how these activities affect indoor air quality in real time, it becomes possible to determine which activities are the most harmful to individuals with asthma.

Although technology provides the necessary tools to monitor and understand IAQ better, the key to mitigating the adverse effects of poor IAQ lies beyond technology. A comprehensive approach that combines technical solutions with behavioural changes holds the most promise [49]. For instance, while an IoT device can monitor IAQ levels and residents can get alerts through a visualisation platform about increased levels of pollutants during cooking, behavioural changes such as ensuring proper ventilation or using cleaner cooking methods can prevent these spikes in the first place [46]. Moreover, the data collected from these devices can help educate individuals about their habits and environmental impact. Over time, this awareness can lead to more IAQ-friendly behaviours, reducing the overall risk of asthma exacerbations [47, 50].

In summary, the literature has shown that IAQ is one of the main causes of respiratory disease causation apart from other factors (socioeconomic status, inadequate health care, life and working conditions). With the deployment of IAQ devices, monitoring IAQ and daily indoor activities, its impact on human health can be observed. In other words, establishing the association between IAQ, indoor activities, and asthma symptoms is a growing need for public health policies promoting better IAQ. Monitoring these pollutants can allow understanding the severity of breathing issues in asthma symptoms which could potentially be used for asthma care.

3. Methodology

In this study, five participants were selected for the deployment of IAQ monitoring devices (see our previous research on development and calibration of IAQ monitoring devices [45, 46, 49]) at their homes to collect and analyse pollution data, and indoor activities. The ethical approval for this study has been granted by the university chair of the Humanities, Social, and Health Sciences Research Ethics Panel.

In addition, this IoT device has the approval of the Health and Safety Department at the University. Before the device deployment, participants were asked to sign the consent form and fill out the initial questionnaire based on house type, annual income of house etc. before starting the study. Moreover, an interactive digital platform has been developed to visualize IAQ and record the daily log activities using a Sensor ID and password which were allocated to participants by the research team.

3.1 Study Area and Design

This study was conducted in Bradford, a city in West Yorkshire, England. The pilot study involved five volunteer families, each with asthma patients in their household. They completed initial questionnaires about their daily indoor activities and the medical history related to asthma within their home. The participants were also asked to sign a consent form before starting the study and then the air quality monitoring device was deployed in individual houses. They have been also informed how to access their house air quality data. At the time of device deployment, participants were also requested to fill in a pre-study questionnaire. Participants were guided on how to complete daily logs detailing their indoor activities. Five indoor parameters were recorded: $PM_{2.5}$, PM_{10}, CO_2, temperature, and humidity. Additionally, indoor activities like window opening duration, cooking, cleaning, vacuuming, and breathing issues (symptoms of asthma) were noted.

3.2 Selection of Participants

In this study, participant selection was diversified based on various housing features, including building type, building age, proximity to the main road, and cooker types, as detailed in Table 1

Table 1: Summary of Building Characteristics and Participants

Variables	***Description***	***Ratio***
Building Types	Terraced	40%
	Semi-Detached	40%
	Back-to-Back House	20%
Building Age	Built before 1985	40%
	Built after 1985	20%
	I don't know	40%
Distance from Main Road	Within 0.1 km from the main road	80%
	Within 0.1 km - 0.5 from the main road	20%
Cooker Type	Gas	80%
	Electric	20%

The table indicates that the majority of participants reside in semi-detached and terraced houses. Additionally, most of these homes are within 0.1 km of the main road. Around 40% of participants live in houses built before 1985, while another 40% are unsure of their home's construction date. In terms of cooking methods, 80% of households use a gas cooker, which is four times the number of those using an electric cooker.

Additionally, diversity was also ensured by considering socio-economic factors, with variables based on combined annual household income and education level, as depicted in Figures 1.a and 1.b From Figure 1.a, it's evident that many participants' households include members with advanced educational qualifications, including university degrees.

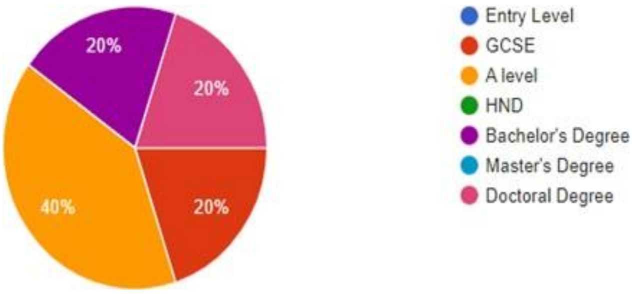

Fig. 1.a : Education level of the household

From Figure 1.b, it can be observed that there has been mixed family income participation. 60% of the participants have an income in the range of medium-earning families whereas 40% of the participants are in the category of lower-income families.

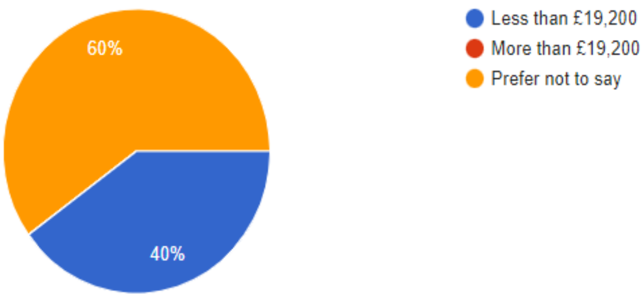

Fig. 1.b: Combined annual household income.

3.3 Activity Monitoring

This IoT-enabled device was connected to the power supply socket and household's Wi-Fi configuration. The data from these devices were collected securely for three weeks on the university's cloud server using RESTful API and only authorised people from this study had the right to access it. A digital visualization platform was developed to track IAQ data and daily activities [49]. On the platform, participants can visually compare their home's pollution levels (CO2, PM2.5, and PM10) in a graphical format. Once participants log in, they were able to see bar graphs which represent the indoor pollution of their houses, as shown in Figure 2. a. In this figure, five different plots: WHO limit, UK limit, Today's average value, this week's average value and last week's average value have been presented. These five different plots help participants to compare their indoor pollution readings with two defined guideline readings from WHO and the UK (we have used the outdoor pollution reading guideline to be applied in indoor air pollution context in the absence of indoor guidelines). This digital platform also has a digital diary which is used to record daily activity logs with daily activity questionnaires, as shown in Figure 2. b, which allows the participants to enter the daily activity records. This digital dairy record is stored at the secured university cloud storage.

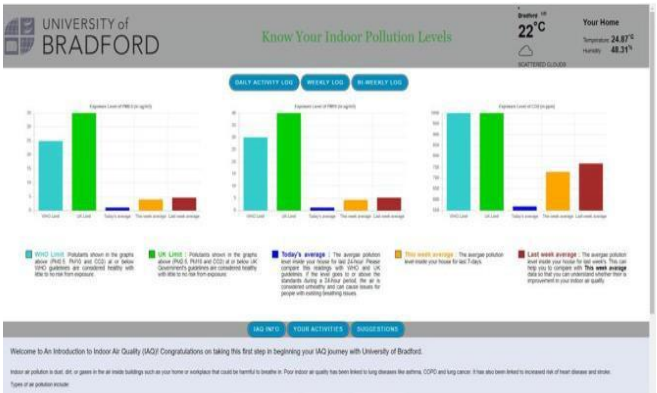

Fig. 2. a: IoT- IoT-enabled digital dashboard for IAQ reading monitoring

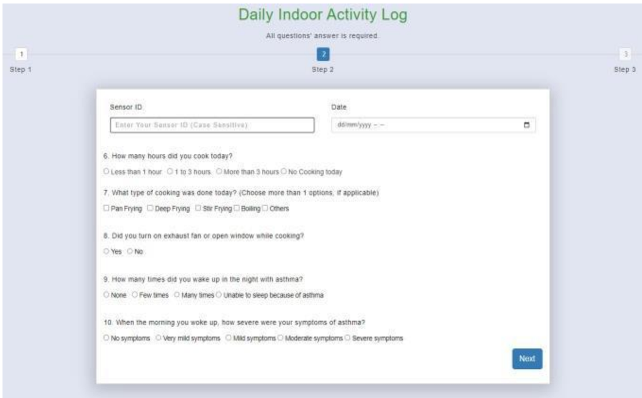

Fig. 2.b: Sample page of IoT-enabled digital platform to enter daily activity.

4. Data Analysis and Discussion

With the data collection from the participant's household using IoT-enabled devices and digital platforms, different aspects of analyses have been performed. This analysis aimed to observe the IAQ level, and the association between IAQ data, indoor activities, and breathing issues.

4.1 IAQ Readings Analysis

The IAQ readings have been collected half-hourly. This collected data has been pre-processed and converted into daily mean data. These daily mean readings of the pollutants CO_2, $PM_{2.5}$ and PM_{10} have been analyzed to see the overall IAQ of each household. From the analysis, it has been observed that LIAQ2 (Household 2) has the highest values of CO_2 and LIAQ4 (Household 4) has the highest $PM_{2.5}$ and PM_{10} which are 840.71ppm, 36.78 μg/m^3 and 33.51 μg/ m^3 respectively as shown in Figures 3.a and 3.b.

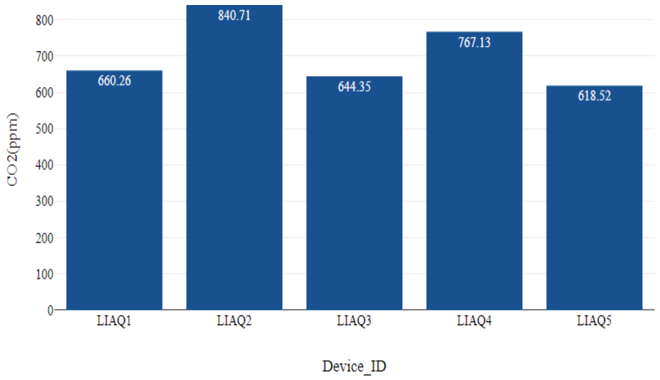

Figure 3. a: Mean CO_2 by Device IDs

These figures also articulates that the CO_2 readings have been in the lower range with nearly similar values for the LIAQ1 (Household 1), LIAQ3 (Household 3) and LIAQ5 (Household 5) in comparison to the other two households. Considering the $PM_{2.5}$ and PM_{10} there has been variation in mean value reading across different households varying from the lowest mean reading of 8.3 μg/m3 at household 3 to the highest mean reading of 36.78 μg/m3 at household 5 for $PM_{2.5}$ and the lowest mean reading of 9.25 μg/m3 at household 3 to the highest mean reading of 36.78 μg/m^3 at household 5 for PM_{10}. These figures also summarized the comparative readings of pollutants CO_2, $PM_{2.5}$ and PM_{10} among the five participants. This variance in pollutant readings gives the scope for additional depth analysis of the observed data.

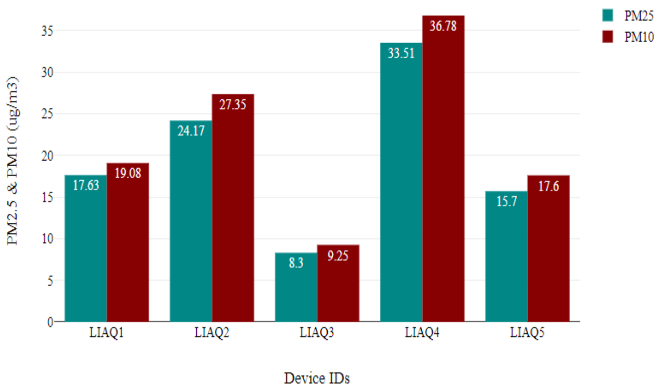

Fig. 3. b: Mean PM2.5 and PM10 by Device IDs

4.2 Association between IAQ data, Indoor activities, and Asthma Symptoms

In further analysis, the relationship between IAQ pollutant readings and household activities was explored. o explores the association, a Pearson correlation analysis was performed, generating the corresponding correlation coefficient matrix as shown in Figure 4. The correlation matrix illustrates that there has been a different level of association among pollutants, different household activities and asthma symptoms. It has been noted that there has been a strong association between IAQ data and indoor human activities. Analyzing the coefficient matrix at a granular level revealed that CO_2, $PM_{2.5}$ and PM_{10} have a positive correlation with indoor activities: cooking, cleaning, heating, and window opening. Among these four activities, window opening hour has the strongest correlation with IAQ in comparison to the cooking, vacuuming, and heating of the house. The correlation matrix also revealed that there has been a strong positive correlation between the asthma symptoms: breathing issues, wheezing and use of the inhaler with the pollutants CO_2, $PM_{2.5}$ and PM_{10}. Among these symptoms, breathing issues have the strongest correlation with the pollutants in comparison to wheezing and the use of the inhaler. These two separate association analyses raise the question of how these factors are correlated among themselves. To do so, relationships between the highest associated household activity (window opening hour), and the highest correlated asthma symptom (breathing issues) have been analysed to explore the potential links between them.

4.3 Association between Window Openings and Asthma Symptoms (Breathing Issues)

In the next step, further analysis was conducted to explore the association between the frequency of window opening hours and its impact on breathing issues due to poor air quality. For this analysis, the participants were initially asked with five different categories related to breathing issues listed in Table 1 with the field ‘Parameters’. To simplify the analysis and understand the relationship, these five categories of breathing issues have been transformed into two categories Good or Bad as shown in Table 2 with the field ‘Converted Parameter’. This transformation of the parameters was also verified by a clinician specializing in asthma care at Bradford Teaching Hospitals NHS Foundation Trust (BTHFT), ensuring the converted parameters align with asthma severity.

Moreover, analytical data has been plotted for the frequency of the breathing issue condition against the window opening hours, as shown in Figure 5. The plot indicates a relationship between the number of hours a window is open and the prevalence of asthma symptoms, suggesting that indoor pollutants play a role in asthma care. The figure reveals that households which keep windows open for over 3 hours daily experience fewer instances of severe breathing issues. Interestingly, in instances where windows remained closed, participants reported both positive and negative breathing experiences almost equally. This suggests that the direct relationship between window opening and breathing issue might not be straightforward.

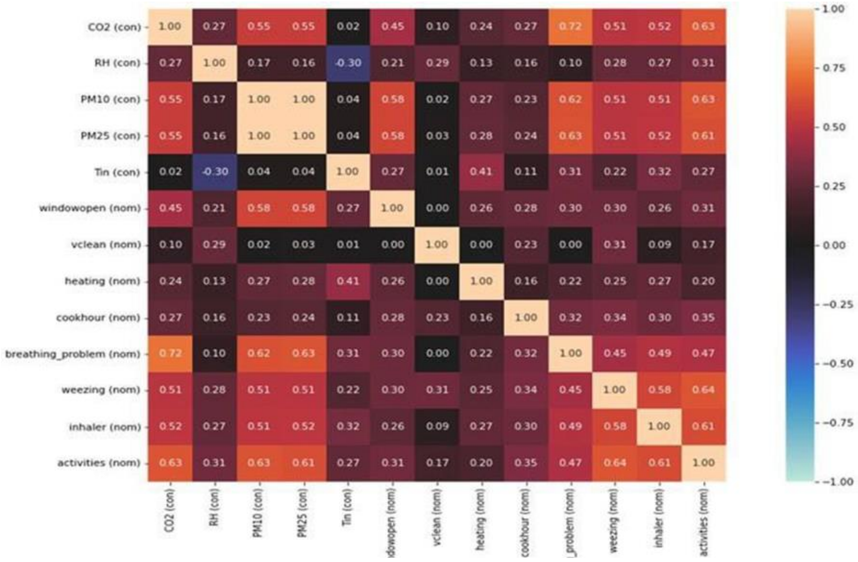

Fig. 4: Association Between IAQ data, Indoor Activities and Asthma symptoms

TABLE 2: TABLE OF NEW PARAMETERS FOR BREATHING ISSUES AND USE OF THE INHALER

Features	***Parameters from daily diary***	***Converted Parameters***
Breathing Issues	None	Good
	A Little	
	A moderate amount	
	Quite a lot	Bad
	A great deal	
	A very great deal	

However, for window opening durations of less than 1 hour and between 1-3 hours, there were fewer instances of severe breathing issues compared to positive breathing experiences. Overall, this categorical analysis indicates that keeping windows open tends to reduce the severity of asthma-related breathing problems. This also underscores the influence of human behaviors on asthma symptoms and its management.

In a more detailed analysis, the breathing issues were examined at a granular level, taking into account each household's IAQ readings, as depicted in Figures 6.a to 6.c. These figures provide comparative plots between breathing issues and individual household readings. The data suggest that the breathing issues were more pronounced in households where pollution levels were higher. Notably, households 2 and 4 experienced more breathing issues than the other households. The figures indicate that when the mean CO2 value ranges between 700 ppm and 1000 ppm (considered the higher range in this study), households tend to face more breathing problems. In contrast, at levels below 700 ppm, households generally did not report any breathing issues.

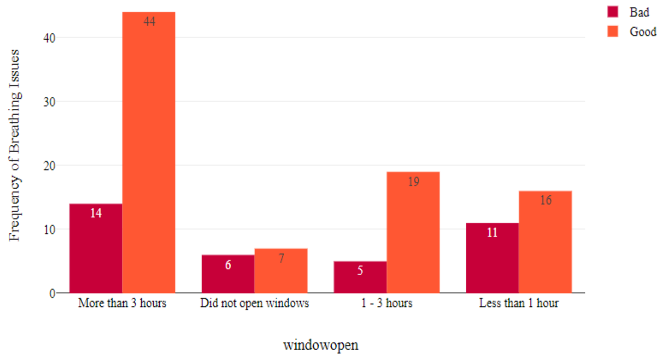

Fig. 5: Association between indoor activity (windows opening) and asthma symptoms (breathing issues)

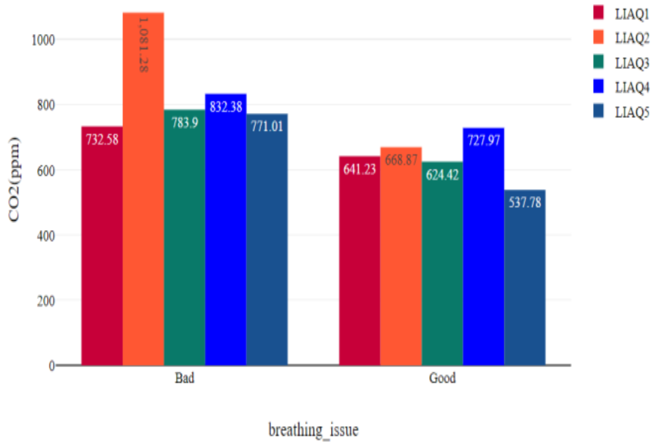

Fig. 6. a: Mean of CO2 (Breathing Issue).

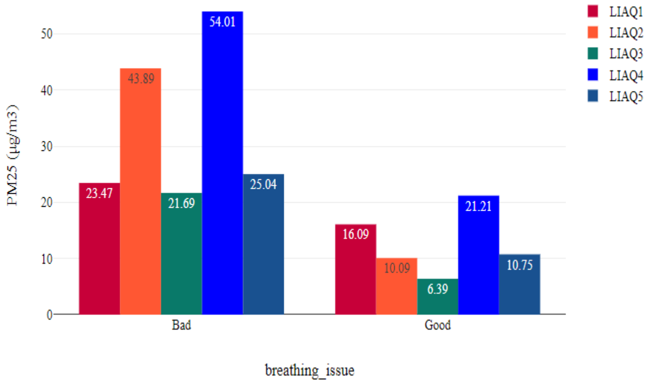

Fig. 6. b: Mean of $PM_{2.5}$ (µg/m3) (Breathing Issues)

When the mean values of PM2.5 increase, asthma patients tend to experience worsened symptoms. However, when the mean PM2.5 level is below 22 µg/m3, patients generally feel more comfortable. In essence, within this range, the impact of IAQ on asthma symptoms appears to be minimal. Additionally, in analyzing the impact of PM_{10}, it was observed that asthma symptoms worsened when the mean PM_{10} value exceeded 24 µg/m3. Conversely, when the mean reading was below 24 µg/m3, asthma patients typically felt comfortable.

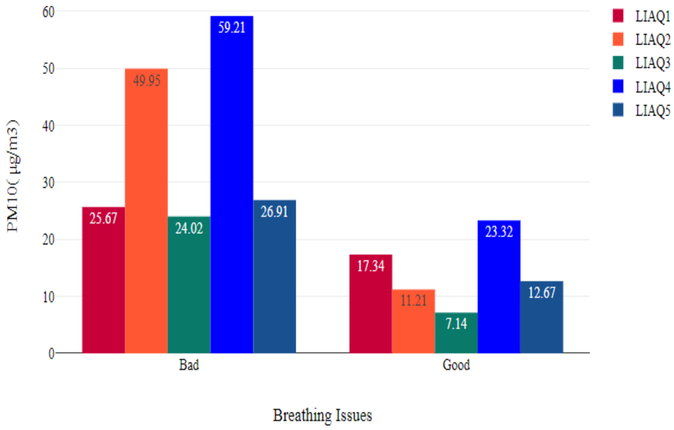

Fig. 6. c: Mean of PM10 (µg/m3) (Breathing Issues)

In order to enrich the analytical depth of this study, a statistical analysis was conducted to examine the relationship between measured indoor pollutants (CO2, PM2.5, and PM10) and breathing issues. The Point-Biserial Correlation (rpb) was employed to gauge the correlation between two variables, a choice influenced by one of the variables being categorical. The results indicated a statistically significant positive correlation between CO2 and breathing issues (rpb = 0.72, n = 122, p < .001). Likewise, the correlation between both PM2.5 and PM10 with breathing issues also exhibited a statistically significant positive relationship (rpb = 0.63 and 0.62, n = 122, p < .001 respectively). This supplemental statistical analysis bolsters the conclusion that poor IAQ exacerbates breathing problems.

5. Conclusion and future work

Asthma severity has emerged as a critical concern in modern society, and various strategies have been developed to predict its intensity. Monitoring IAQ and understanding its health impacts are becoming increasingly important, especially for families with health-related challenges. In this study, an IoT-enabled air quality monitoring device was deployed in the homes of asthma patients to measure IAQ and maintain a daily diary. The research recorded asthma symptoms (specifically breathing issues), indoor air pollutants (CO_2, $PM_{2.5}$, and PM_{10}), and indoor activities using an interactive digital platform. Various data analysis and visualization techniques were employed to investigate the effects of IAQ and indoor activities on asthma severity, aiming to discern the relationships among these elements. The correlation analysis revealed that of the four listed indoor activities, IAQ correlates most with window opening hours. Moreover, the analysis showed that IAQ is more strongly associated with breathing issues compared to other asthma care monitoring parameters. The study also found that higher levels of indoor pollution exacerbate breathing issues (an asthma symptom). Conversely, increased window opening hours tend to alleviate asthma symptoms.

In conclusion, it's evident that poor IAQ significantly exacerbates asthma symptoms, particularly breathing issues. This concern is especially relevant in the context of smart cities, where technology plays a pivotal role in addressing healthcare challenges. To manage asthma symptoms effectively, individuals must be acutely aware of the relationship between IAQ, indoor activities, and breathing complications. The insights gleaned from the effects of poor IAQ and window opening hours on asthma patients offer practical applications for asthma care. By adopting healthier indoor habits, families can mitigate some of these risks. However, a limitation of this study is that the analysis was based on daily mean values of indoor pollutants, activities, and asthma symptoms. This approach doesn't pinpoint the specific hours when breathing difficulties intensify in relation to IAQ and indoor activities. Future iterations of this study could benefit from an hourly analysis. This would provide more timely and specific information for individuals, allowing for more proactive interventions. Additionally, expanding the scope to monitor other pollutants like NO2, additional indoor activities such as log burning, and other asthma indicators like wheezing or inhaler usage would add depth to the analysis. Ultimately, a broader study encompassing diverse socio-economic backgrounds would yield a more holistic understanding.

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