Indoor Air Quality Vulnerability Mapping of Urban Dwellings in Bangladesh

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Abstract: Unwanted summer, extreme heat waves and air pollution have created severe human health and well-being issues. For instance, in Bangladesh, these phenomena have been noticed, particularly between March to July. As opposed to the norm, the dwellings' indoor air quality (IAQ) tends to be unacceptable, resulting in a severe impact on human health. Current research identified that the number of heatstroke patients increases every year in the tropical region where the children and elderly are being affected severely. Besides the IAQ issue, local housing is responsible for the relatively high energy use through space cooling in the tropical region for ensuring indoor thermal comfort and air quality. IAQ enhancement in line with energy efficiency measures through passive design strategies is becoming a significant challenge in the housing sector. Thus, this study investigates the IAQ-related issues around typical urban apartment dwellings in Bangladesh's major cities as case studies. The transient data to monitor the levels of T_{VOC} (mg/m^3), $PM_{2.5}$ (μg/m^3), PM_{10} (μg/m^3), HCHO (mg/m^3), air temperature (°C) as well as relative humidity (%) were collected using environmental data loggers. At the same time, a questionnaire survey related to occupants' socio-demographic profile, health and well-being was also conducted to grasp their living conditions. Finally, in line with the data analysis, a parametric simulation was conducted to develop a correlational vulnerability mapping between the collated IAQ results and the occupants' health and well-being circumstances.

Keywords: Indoor air quality; Heat stress vulnerability; dwelling; tropical climate

1. Introduction

Being one of the most challenging problems, air pollution has significant impacts on human health and well-being. Air pollution kills more than thousand people in Bangladesh each year. In recent times, Dhaka, one of the world's megacities, is facing a rapid growth of urban inhabitants [1]. Besides the extreme outdoor AT (summer: 32°C<AT<42°C), air pollution like carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrocarbons (HC), ozone (O_3) and suspended particulate matter (SPM) in Dhaka city are testified as severely detrimental to the health and causes poor IEQ [1]. Previous studies have also identified that people living in polluted environments with foul air have a 23% increased risk of heart attack and a 40% increased risk of fatal heart attack [1] [2].

On the other hand, a survey report of Economist Intelligence Unit (EIU) associated with the UK-based weekly Economist shows that for the second consecutive time Dhaka has become 'the worst city to live in' [3-4]. In such a context, the impact of households IAQ on human health is becoming a crucial part of society. In Bangladesh, environmental pollution and excessive outdoor heat are causing severe hazards which are the most challenging nowadays [5]. The field monitoring also observed an adverse impact on most of dwellings in Dhaka, Bangladesh for extremely hot environments and poor IAQ without standard adaptive criteria. This study investigates the IAQ-related issues around the typical urban dwellings as case studies in the major cities of Bangladesh. Finally, in addition with the data analysis, a parametric simulation has been conducted to develop a

correlation vulnerability mapping between the collated IAQ results and the occupants' health and well-being circumstances.

2. Study Methods

Environmental field monitoring of local urban dwellings by data loggers was conducted from June to December 2018 because of seasonal variation (summer to winter) based on the selections made against set criteria for IAQ evaluation. A comparison of environmental relationship was enabled between monitored and simulated data. Primarily, the field monitoring was conducted in middle portion of each floor of dwellings to record week-long IAQ data. Environmental Data loggers and Laser Non-Contact Thermometers were positioned at midpoint of two different heights which were between the floor's 750 mm (working plane height) to 3050 mm (minimum ceiling height). The indoor environment was monitored using a Temptop LKC-1000S+ Air Quality detector with $PM_{2.5}$/PM_{10}/AQI/Particles data logger. The outdoor temperature and humidity data were collected from the local weather station provided by the Met Office, Bangladesh. The approved index according to the Department of Environment (DoE), Bangladesh has been given below [6] (Table 1):

Table 1. Approved AQI for Bangladesh

Air quality index (AQI) Range	Category In English	Color
0-50	Good	Green
51-100	Moderate	Yellow Green
101-150	Caution	Yellow
151-200	Unhealthy	Orange
201-300	Very Unhealthy	Red
301-500	Extremely Unhealthy	Purple

Table 2. Description of surveyed dwelling typologies

Type	Floor	Construction Materials
Apartment 1	Six-storey	Brick walls and roof from the reinforced concrete slab
Apartment 2	Six-storey	Brick walls and roof from the reinforced concrete slab
Apartment 3	Ten-storey	Walls brick and glass combination and roof from the reinforced concrete slab
Apartment 4	Ten-storey	Walls brick and glass combination and roof from the reinforced concrete slab
Apartment 5	Twelve-storey	Walls brick and glass combination and roof from the reinforced concrete slab
Pucca	Three-storey	Brick walls and roof from the reinforced concrete slab
Semi Pucca	One-storey	Wall and roof constructed from temporary materials such as corrugated sheet, bamboo etc.

A better undesrstanding can be achieved through a qualitative approach that includes occupants' indoor environmental quality experiences in the residences. It can also be useful for developing a housing design guideline for better IAQ. A questionnaire survey was conducted among around 200 users based on their socio-demographic and health symptoms scenario in this approach. These questions (checklist) were developed on the topic of IAQ based on international guidelines, including 'closed' and 'open' questions [7]. For instance, closed queries comprised "*Do you have any health conditions or symptoms that may raise susceptibility to environmental problems?*" and open questions included "*In which room or rooms do these symptoms usually occur and why?*" Questions have also been asked to expand knowledge about the occupants' behavior, such as "*Do you frequently dry clean clothing or household furnishings?*" and "*Do home occupants have hobbies that create dust?*" Users were also asked about their economic status and income level, level of education, family member, monthly

expenditure, age, gender, sex, etc. In these questionnaires, no one was required to mention their name or identity to provide information without hesitation.

In conclusion, occupants were allowed to suggest design or change strategies that would improve their dwelling conditions. The survey was conducted in Bengali among the focus groups. Also, notes were taken accordingly for coding and analysis. It may be noted that for data collection, any kind of influence was not formulated. User's age and sex also had a unique role in data collection. In that case, anyone under 18 years was not allowed to fill the question papers. Complete freedom has been given to all users for answering the questions. However, in particular cases, only a few ideas about the issues related to the households were given so that users could answer correctly. The question paper has been divided into two categories.

In the first part, the questions were raised about the socio-demographic scenario for household users. In this case, the questions of age, sex, marital status, employment, and workplace have been asked to the users. Later, users were asked to answer their educational qualifications, number of family members and monthly income. Since no one was required to write their names on the question paper, everyone could provide their information correctly without any hesitation. Even users have been asked about the current status of the house they live in, the house-changing information, the type of house, construction materials, the period of construction and how long they have been living in that house (Table 2). The lowest four answer typologies were given to the users as multiple choice in response to each question. So, everyone provided the appropriate answer to them. In this study, the middle and upper middle class income group were the priority. According to the socio-economic aspect of Bangladesh [8], household users of these income groups have been considered as a probable focus for buying a city-based apartment or staying in a rented houses.

In the second part of the questionnaire, the household users were asked about their health symptoms due to the environmental conditions of their dwellings. Example of the types of questions are described below.

The first question was about the type of health symptoms that have been occurred due to environmental reasons. Such as cold, weakness, hair loss, allergies, diabetes, respiratory problems, headache, blood pressure, eye problems, etc. If they face any of the issues mentioned above, they were usually asked 'which places', such as in the bedroom, drawing room, kitchen, etc. It was also asked the users where they typically stay for the longest period of the day in their houses. In the next part, the question was asked to find out about the location's surroundings or the building. Is there is any garbage or car parking area attached to the residence? Whether there is a pet in the house or if someone living in the house has some symptoms that can damage indoor environment. It has also been asked if any furniture has been changed in last three months in this living place. It has been asked which type of oven is being used in the kitchen area, how much cooking time is required and whether there is any system to release the indoor air from the kitchen to outside. If aerosol is often used in the house, what about ventilation system of the rooms and what is their locations. Also, it was asked if there is any environmental comfort feeling such as hot or cold in the house. In that case, ASHRAE 6 scale comfort code has been considered [9].

Moreover, they were also asked whether any odor is felt in their houses or if there is any leakage on the roof. Mold growth scenario has also been emphasized. Finally, they were asked about their preference for changes in their dwellings. All the things in this question paper might not be included, so their suggestions have been given priority.

3. Household Pattern in Bangladesh

Bangladesh is known as one of the most densely populated countries of the world. Although poverty is widespread and bottomless here, population growth has been reduced in recent years and improved health and education. According to the Bangladesh Bureau of Statistics (BBS), the per capita income in Bangladesh has risen from $1,190 to $1,314 in 2015 [10]. The literacy rate of Bangladesh has been raised. According to UNESCO Bangladesh, the adult literacy rate of Bangladesh is about 72.76% where the literacy rate for males is about 75.62%, and for females, it is 69.9%. About 44% of the country's urban population lives particularly in Dhaka city. In cities, they generally live in

apartments. As per the Consumer Association of Bangladesh (CAB), the living cost for the residents of Dhaka city is continuously increasing since past ten years where around 35% to 50% or more of the total income of a person is spent to pay the house rent. Dhaka is the most populated city in Bangladesh and one of the most populated cities of the world. In 2016, The estimated population of Greater Dhaka was over 18 million, whereas the city itself has 8.5 million of people. It has been noted that about 44% of the total population of Bangladesh lives in the megacities due to having a vast range of work opportunities. According to the calculation, every day, about 3.5 million people move only to Dhaka city in any way for daily work. The middle-income group prefers to live in the typical apartments with average quality of standard.

Generally, the size of the urban families is getting smaller day by day. In such a family, there are 6-7 people including husband-wife with their parents and two children. This number is associated with the monthly income and expenditure of the family. However, in most cities, family members are no more than 4-5 nos. In addition, their residences contain one master bedroom, one childbed and one guest bed in the house they live.

The whole house is divided into three parts: Public, semi-public and private zones. One attached toilet with the master bedroom and a common bathroom genially serves their requirements. In many cases, they need to arrange a single bed temporarily in their drawing room's corner to solve the space problem. The kitchen is usually attached to the dining space.

Figure 1. Household activities in a typical apartment building

There is a window for air circulation on the west or east side of the kitchen. Shortage of daylight is often faced in the dining space. These types of houses are usually sized between 850-1250 square feet (area). According to the Consumer Association, Bangladesh (CAB) [11], these households have the highest monthly expenditure on food (about 47.69%) and the cost of living (house rent) which is approximately 12.43% of their total income. Except for health, clothing and medical care, about 10% of their total income is spent on home management and home-based activities. The estimated minimum cost for a middle-income family varies between 15,000-22,000 BDT. Therefore, they can't switch into an air-conditioning system or any other significant changes in their houses at any time.

4. Results and Discussions

4.1 Socio-Demographic analysis

This survey has been conducted among 200 households families, located in the urban areas of different cities in Bangladesh. Almost all the surveyed participants age between 25 and 40. The ratio of female and male participants in the survey was about 60% and 40%. It has been found that participants having an education up to college level, have a higher monthly income and expenditures (Fig. 1 and Fig. 2) which is more than others. In that case, their monthly income is up to 60,000-70,000 BDT and up to 85% of them live in an apartment in the city center. According to their information, they do not want any significant changes in their houses for a better indoor environment. About 55% of them have their apartments. Due to this reason, their monthly expenditure is lower than those who live in rented houses.

On the other hand, the survey shows that people with a monthly income range between 30,000-40,000BDT usually spend 20,000-25,000 BDT as their monthly expenditure. About 40% of them live in flats/apartments and the rest reside in detached and semi-detached houses in the city (Fig. 3). It has been identified that reduction of the monthly expenditure is the main reason for living there. On the other hand, 80% of the people with monthly income below 20,000 BDT live in an isolated house called `Chapra.' In that case, they are choosing to live outside the city rather than the main town. They prioritized the places with easy accessibility to the city's heart with minimum expenditure. The educational qualification of these families is up to school level. The survey identified that around 90% of the living homesteads are aged between 10-20 and the users has been living there for approximately 5-6 years. According to the survey, about 70% of the participants reported that their family members are 4-5.

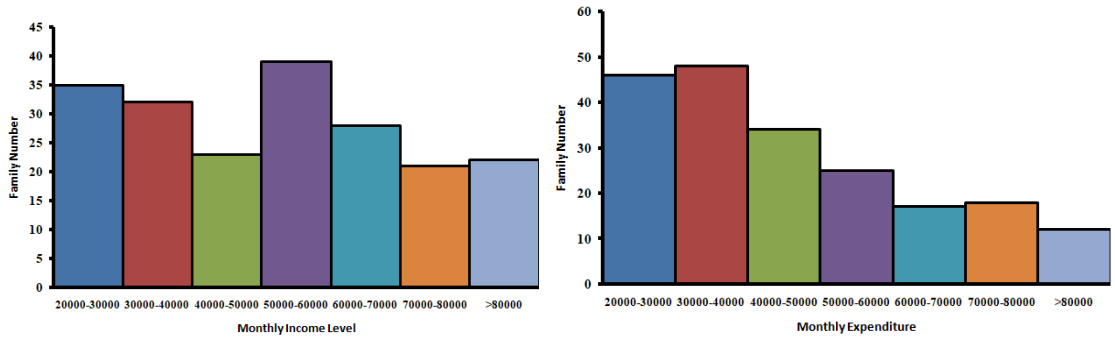

Figure 2. Comparison of monthly income and expenditure

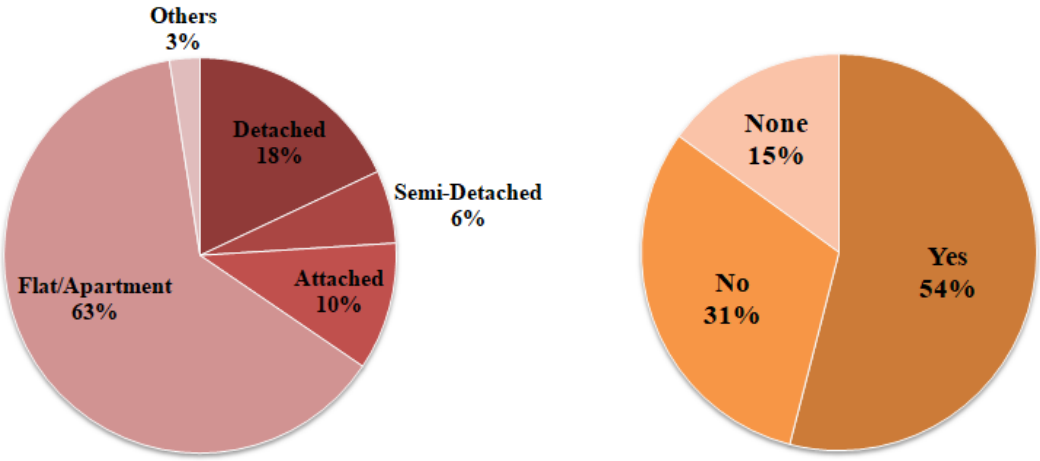

Figure 3. Comparison of building typologies and additional space requirement scenario

4.2 Health symptoms analysis

The survey found that 50 out of two hundred users suffer from nausea diseases, cold and cough (Fig. 4). The data suggest the major part of the population living in these houses suffer from eye irritation caused by lack of sunlight throughout the day. Weakness, headache, increased blood pressure and even hair loss are the frequent health symptoms for the dwellers. In most cases, these problems are act severe at night time. Of all the surveyed people, 36% mentioned that their health problems are usually more noticeable in the bedroom (Fig. 4). 26% of user data provided the information about their health problems in the kitchen.

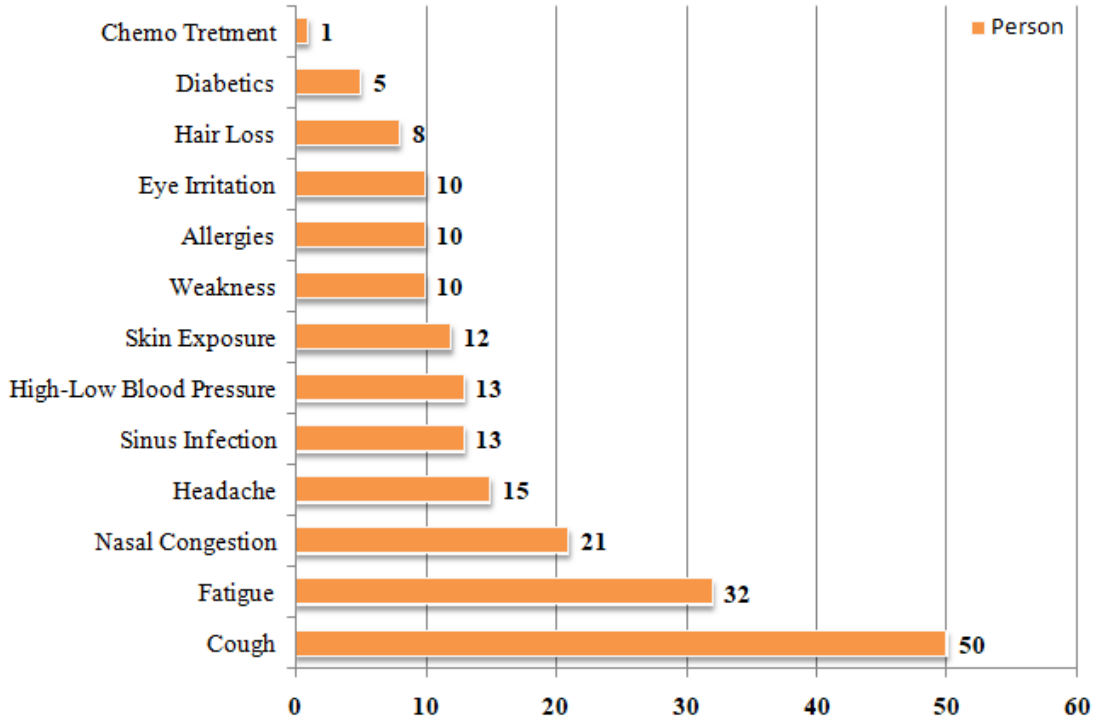

Figure 4. Health symptom scenario

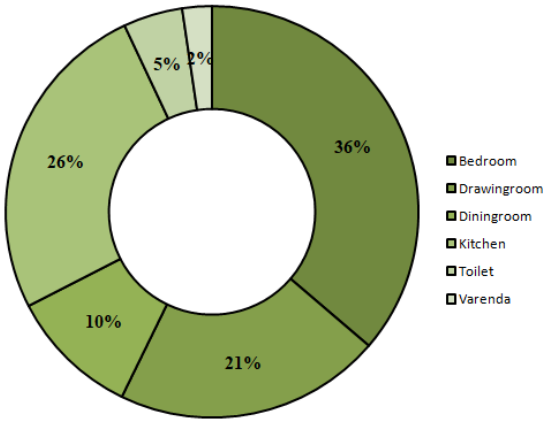

Figure 5. Health symptom occurs scenario

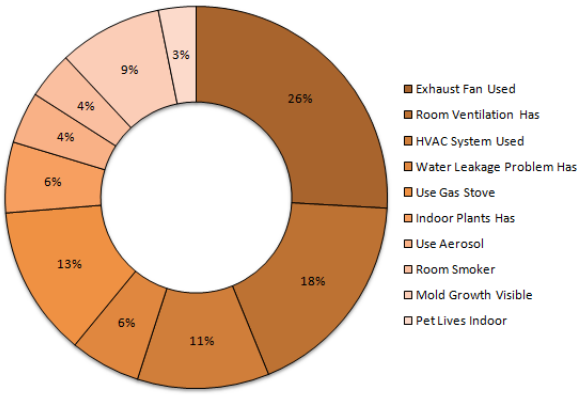

Figure 6. Comparison of indoor conditions

It was found that about 11% of the families use air-conditioning systems in their bedrooms to control the indoor air quality. About 26% of them use exhaust fans every day in their kitchen and 18% of the families have planned room ventilation. Those who use gas stoves for cooking (about 13%)

mentioned that they require adequate room ventilation during their cooking. Otherwise, the house gets covered with smoke that causes difficulty in breathing (Fig. 5-6).

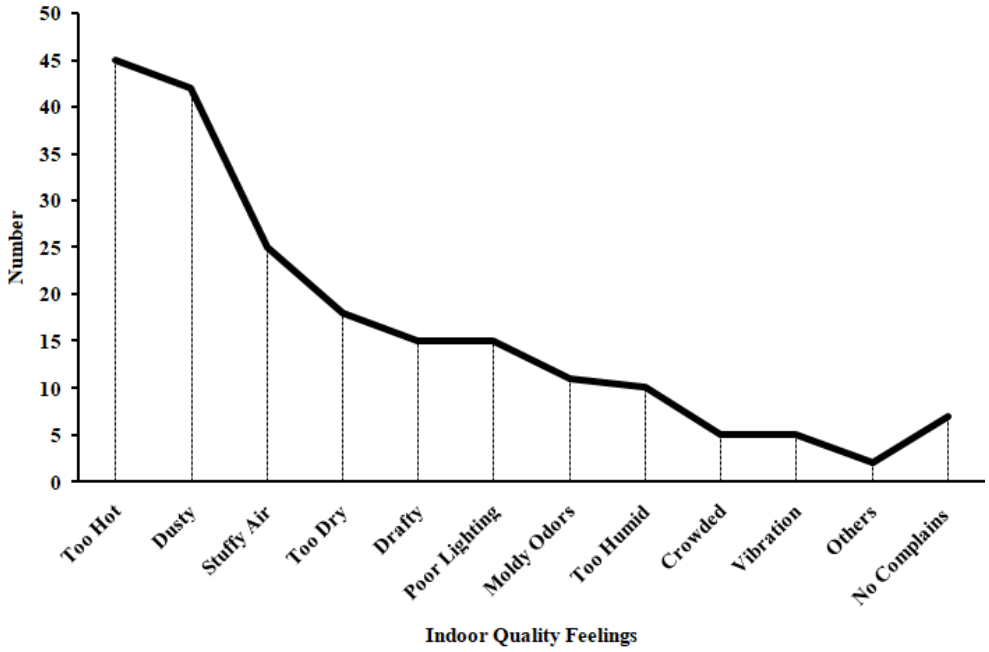

Figure 7. Comparison of indoor quality feelings of dwellers

Common phenomenon observed from the questionnaire survey are dusty and stuffy air, dryness and low daylight, which most users know (Fig. 7). About 40-45% of users informed that it is hot and dusty inside their houses. According to their information, those who smoke in the room, dry clean or have pets tend to suffer more due to allergic problems. In this case, about 12% of users mentioned about their skin problems throughout the year. But in their opinion, they have different kinds of health issues during the summer season in their houses.

5. Monitored Indoor Air Quality

In this study, TEMTOP LKC-1000S+ air quality detector has been used for measuring $PM_{2.5}$/PM_{10} as well as air quality index (AQI). Through the data monitoring of a single-family urban dwelling for a week, it was observed that AQI fractions on average indoor are considerably higher (almost 3-4 times) than the usual range as per the Department of Environment (DoE), Bangladesh (Fig. 8).

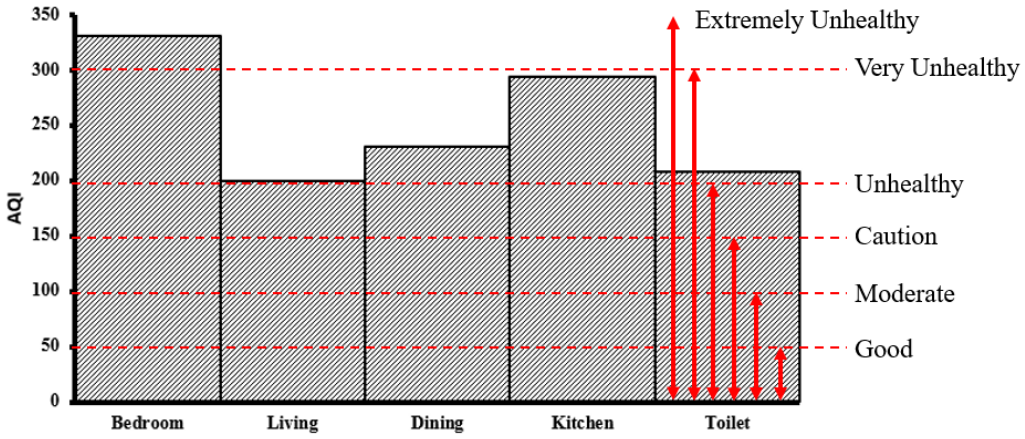

Figure 8. AQI comparison of different spaces

This analysis has monitored the highest IAQ range for the bedroom, about AQI>330, which indicated 'Extremely Unhealthy' condition for the dwellers. In that case, respiratory illness can be caused to the people with continued exposure. The effect can be severely distinct among the people with a lung condition or heart disease. It was also observed that while cooking, the indoor air quality in the kitchen noticeably decreased within 15-20 min. The data monitoring average range observed for the cooking period AQI>250 showed a 'Very Unhealthy' environment for the occupants. It can result into several health impacts such as discomfort in breathing on extended exposure and distress in heart disease. As the dining space was attached to the kitchen, AQI>200 was found which may cause discomfort in breathing. People with asthma, lung and heart disease, children and older adults are likely to be affected more.

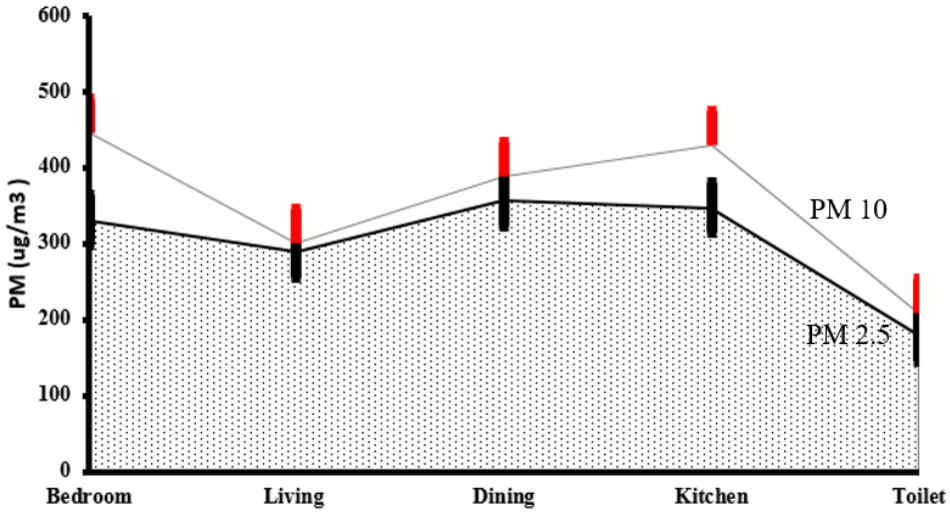

Figure 9. PM comparison of different spaces

The findings from the air particle (PM) that has been collected from diverse locations of the particular dwelling, shows that (Fig. 9) around 60-75% of the $PM_{2.5}$ and PM_{10} mass (based on house location) remained considerably higher than the Bangladesh National Ambient Air Quality Standard (BNAAQS). The Bangladesh National Ambient Air Quality Standard (BNAAQS) for annual average $PM_{2.5}$ is 15 µg/m^3 whereas the 24 hr standard is65µg/m^{3}and from the data monitor found max 350µg/m^3. On the other hand, PM_{10} is 50 µg/m^3 where the 24 hr standard was min 150µg/m^3 and found max 430µg/m^3 from the monitoring. Both $PM_{2.5}$ and PM_{10} fractions are observed to be significantly higher (almost 3-4 times) than the BNAAQS values [12] due to outside dust, kitchen smoke, lack of proper ventilation, indoor materials, etc.

6. Whole Year Prediction

EnergyPlus (Version 8.1.0), a dynamic computer simulation program developed by the U.S. Department of Energy [13]. for the whole year parametric study, integrated with Google Sketch-Up (version 8), the Open Studio Plug-in 1.3.0 have been used. For further accuracy, the simulated energy model of the dwelling is modeled as per one of the surveyed dwellings. The simulated result could be easily compared to the existing condition prior to the predicted simulations.

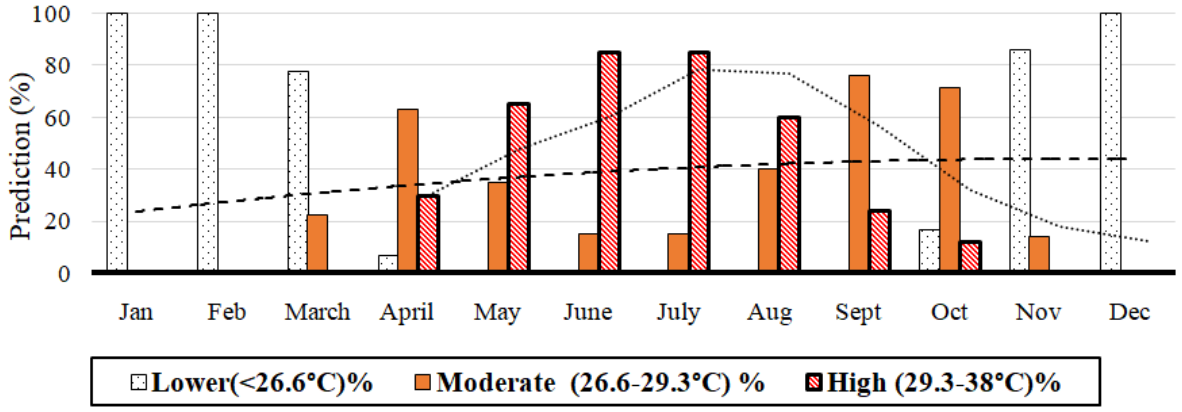

Figure 10. Whole year prediction of IAQ

From the analysis and annual simulations of indoor AT (°C) along with the risk factor criteria, the observed high risk value remained around 80% in higher conditions. The riskiest indoor environment was observed during the summer (June-July) with an average of 34-36°C where the lower level was approximately 18°C in December-February (winter). From the prediction, it has also been discovered that an average of 35-40% indoor times became extremely high during April to July (nearly 38°C), leading to a very high-risk factor level for the dwellers. Moreover, from the annual analysis, nearly 36-40% condition appeared as the moderate state and minimum 22-25% condition was characterized as very high-risk level for dwellers in the particular dwelling (Fig. 10).

7. Design Requirement

At the end of the survey, it was asked what modifications they required to improve their houses with a better IEQ. According to their data (Fig. 11), about 85% of people think proper cross-ventilation in houses may solve most problems. It will ensure continuous air circulation that will help the houses to remain cool and fresh.

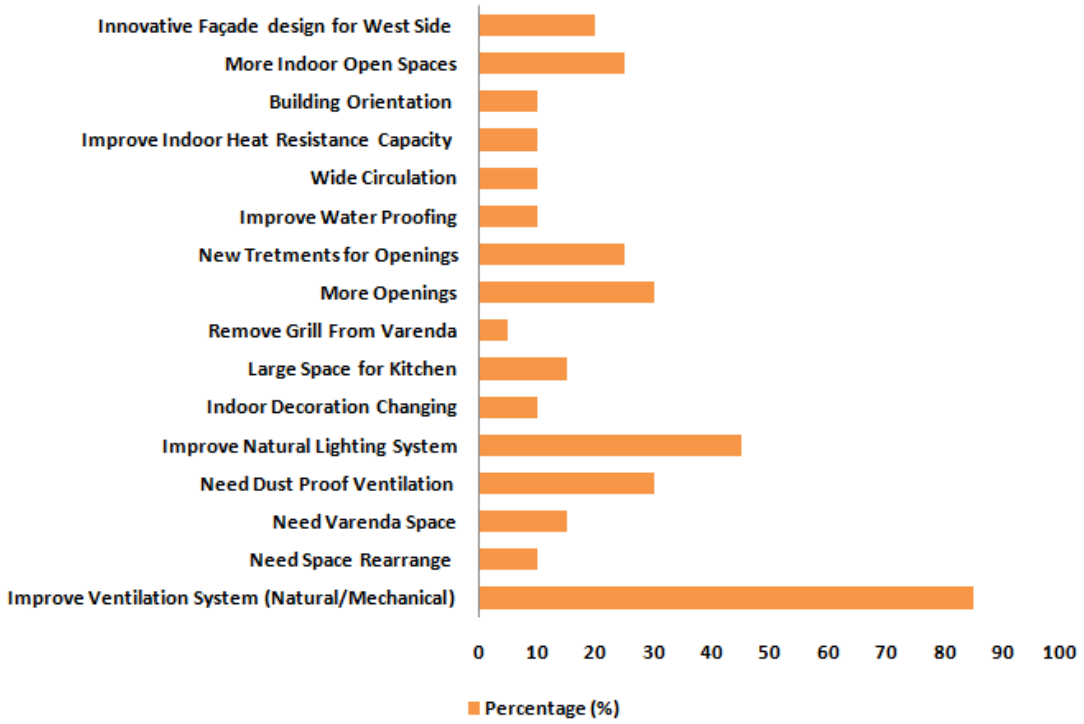

Figure 11. Design requirement comparison

Natural ventilation may be the best option to get. If it is impossible to get ventilation by natural means, it can be done in artificial ways. About 35% of people think about dust-proof natural ventilation systems where the external dust cannot come in. In addition, 48% of users believe that proper daylight is essential for good IEQ. About 30-40% of users feel that it is better if there are open or large windows in the house. Many users think that designers should think carefully about building's outer façade of the west side where the sunlight directly hits during daytime.

8. Conclusion

This study aimed to collect evidence of the IAQ of urban typical households in Bangladesh through environmental monitoring, questionnaire survey and prediction by simulations carried out among the focus groups. The key findings have been given below:

a) The survey found that most of the household's users suffer from various health symptoms like cold, cough, nausea, etc., throughout the whole year. In most cases, these problems are more significant at night time and these problems are usually more noticeable in the bedroom.
b) Average indoor AQI fractions were found, 3-4 times higher (>300) than the normal range and the highest AQI range was found in the bedroom within the scope of 300-400, which indicated as 'Extremely Unhealthy' condition for the dwellers. It was also observed that in the kitchen, IAQ became very unhealthy within 15-20 min, which indicated AQI>250-300 in range. It might result into respiratory illness and heart diseases to the dwellers on continued exposure.
c) It has also been found that about 60-75% of the $PM_{2.5}$ and PM_{10} mass was remained considerably higher than the BNAAQS standard.
d) The prediction identified that 35-40% IAQ became very high (near about 38^{o}C) from April to July, leading to a high level of health risk factors for the dwellers.
e) It has been identified that the lack of proper natural dust-free cross ventilation is the main problem for poor IAQ.

Some of the dwellers' characteristics include several variables and design parameters that has not been completely captured. Outdoor air quality, indoor climate parameters, insulations factors, HVAC system, and energy consumption have the probability of affecting IAQ concentrations and reducing health risk. [14-16]. The understanding of experimental investigations and data monitoring for IAQ of typical urban dwellings concerning AQI, $PM_{2.5}$, PM_{10}, AT and RH has been needed for further analysis to significantly improve occupants' comfort and health risks by residing in typical dwellings in Bangladesh.

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