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Temporal Variation of Indoor (a residential space) and Outdoor $PM_{2.5}$ in Male', Maldives

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ABSTRACT *This study aims to assess the Indoor Air Quality (IAQ) inside a one-room apartment of about 240 square feet in the Henveiru district in Male', Maldives. Concentrations of Particulate Matter ($PM_{2.5}$), one of the most detrimental air pollutants, were measured every 15 minutes from 10-09-2021 to 18-12-2021 using low-cost PM BlueSky sensors inside the building (indoor) and simultaneously outdoor, about 300m away from the indoor sensor. The BlueSky monitors were co-located and harmonized before starting the monitoring. The mean concentrations observed indoor and outdoor for 93 days were 10.1±13.1 µg/m^3 and 6.5±4.9 µg/m^3, respectively. Both results surpass the annual average of 5 µg/m3 guideline of World Health Organization (WHO). The number of days that surpassed the 24-hour WHO limit was 9 for indoor and 7 for outdoors. The diurnal pattern of $PM_{2.5}$ shows a drastic accumulation of the pollutant inside the building when the only available ventilation (the window) was closed, which was identified at night and also during the daytime. The recorded $PM_{2.5}$ levels also aligned with household activities like cooking, cleaning, and dusting. There was a significant moderate correlation (r= 0.48) between outdoor and indoor $PM_{2.5}$. The I/O ratio was 1.95±3.01 indicating the presence of more indoor sources. This study serves as a preliminary assessment of indoor air quality in Male', Maldives. Based on its findings, efforts should be directed towards ensuring proper ventilation in residential spaces and continuously monitoring air quality in more location for longer periods to ensure healthy IAQ.*

Keywords: Indoor Air Quality, Household air pollution, $PM_{2.5}$, Male'

Introduction

Air pollution is well-known as contamination caused by chemical substances in the atmosphere that can cause detrimental effects on living organisms and the earth. There is a common misconception that air pollution is only an outdoor phenomenon. However, this problem is inevitable indoors as well. According to World Health Organization (WHO), household air pollution was responsible for around 3.2 million deaths in 2020. Exposure to household air pollutants can lead to stroke, ischemic heart disease, chronic obstructive pulmonary disease and lung cancer (WHO, 2022). Women and children under the age of 5, who spend more time at home are more vulnerable to the impacts of indoor pollution. Given that people spend an average of 87% of their time in enclosed buildings (Klepeis et al., 2001) and with increasing working-from-home jobs as a result of COVID19 pandemic, there is a need to monitor the IAQ and sources or activities that lead to poor air quality to limit exposure to indoor air pollution.

Particulate Matter, precisely $PM_{2.5}$, is collectively referred to as the particles

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suspended in air smaller than or equal to 2.5 micrometers. It is one of the most widely studied indoor and outdoor air pollutants as it is potentially toxic, carcinogenic, allergenic, and irritating and has significant health impacts. $PM_{2.5}$ can penetrate deeply into alveoli of the lungs and pass into the bloodstream. $PM_{2.5}$ can have severe health impacts such as premature death, lung cancer and several respiratory and cardiovascular diseases (Hamanaka & Mutlu, 2018; Fiordelisi et al., 2017). Primary $PM_{2.5}$ particles are emitted from anthropogenic activities such as fuel burning, transportation, biomass burning, and industrial processes. In addition to this, natural sources such as dust storms, sea spray, forest fires, and volcanic eruptions contribute to the accumulation of atmospheric $PM_{2.5}$. Secondary $PM_{2.5}$ results from the chemical reactions between particles found in the atmosphere. The sources or activities that lead to indoor and outdoor $PM_{2.5}$ production vary spatially and temporally.

Among the indoor pollutants, cooking (Aquilina and Camilleri, 2021; Diapouli et al., 2015; Shen, 2021) and cleaning indoor dust (Aquilina and Camilleri, 2021) are the major sources. Indoor dust, cleaning and personal care products, biological contaminants such pollen, mold spores, dust mites, and human skin flakes, printers, copiers and certain hobbies (Environmental Protection Agency, 2023) such as sewing can also emit $PM_{2.5}$ into the surrounding air. The ventilation condition, building type and types of indoor pollutants also affect the air quality inside buildings (Leung, 2015). These conditions can contribute to building-related illnesses known as sick building syndrome (SBS), which has symptoms like asthma, irritation of mucous membranes and eyes, gastrointestinal disturbance, and dry skin. These symptoms are very similar to that observed from acute exposure to air pollutants. It can lead to a decrease in the work efficiency of individuals (Nag, 2018). Outdoor air pollutants seep into the building and have been found to affect personal exposure significantly (Diapouli et al., 2015). The Indoor-Outdoor air quality (I/O) ratio explains the source strength of indoor air pollutants, the value of which depends on the indoor and outdoor pollutant concentration.

The ambient air quality in the small island nation of Maldives is considered good as the wind flushes out the air masses. However, in Male', the capital island, the situation is different. The most recent ambient air quality study (Budhavant et al. (2015) conducted in 2013 in Male', the annual average concentration of the island was 19 μgm^3, which is more than twice the WHO-recommended annual average of 5 $\mu g/m^3$ (WHO, 2021). Male' is one of the world's most densely populated islands with an area of about 8 square kilometers and a population of 515,122 (Maldives Bureau of Statistics, 2022). To cater to the growing population, there has been an increase in construction, land and sea transportation, municipal facilities usage (e.g electricity) and mismanaged waste, which leads to deterioration of the the ambient air quality. The size of the homes has been decreased and the height of the budlings has been increased drastically over the years, leading to congestion with lack of proper ventilation. There is the possibility of reducing air dispersion and hence trapping air pollutants within the high-rise buildings (Leung., 2015). It has also been reported that the nation's total number of non-communicable diseases, including respiratory and cardiovascular diseases has drastically increased (Ministry of Health, 2018). Since 2013, there has been no study conducted on ambient air quality and lack of literature on IAQ anywhere in the Maldives. Maldives is also yet to establish an Air Quality Index (AQI). AQI reports the level of air pollution in their urban environment. This helps people, especially vulnerable groups, such as children, older adults, pregnant women, and individuals with pre-existing respiratory and cardiovascular disease, to get information on how the air quality might affect their health.

Therefore, the main aim of this study is to assess the IAQ in a one-room apartment in the capital island of the Maldives. The study analyzes the temporal variation of $PM_{2.5}$ in indoor air compared to outdoor air. It also attempts to identify the possible indoor sources or various household activities that affect the concentration of $PM_{2.5}$. This study is the first of its kind to monitor IAQ in Male', which is highly important as most people in the capital island tend to spend more time in confined places such as homes and office buildings.

Method

Sampling Site

Indoor sampling was carried out in a one-room apartment (4.175738 ° N latitude; 73.516957 ° E longitude) of about 240 square feet (12' x 20'). The apartment was located on the second floor of a five-story building, in the east (Henveiru district) of Male' (Figure 1). Other residential buildings and shops surround it. The eastern side beach of the island is located about 300m from the apartment. The apartment has a living area, a small kitchen area, and a bedroom with an attached toilet. The sensor was kept in the living room on a shelf (Figure 2(b)), at a height of approximately 1.5 m above the floor which is about 9.5 m above the ground. The floor plan with the measurements of the apartment's spaces and the sensor's location is shown in Figure 2(c). The only natural ventilation available was through a 4'x4' sliding window in the living area which used to be opened halfway whenever the residents were home and not sleeping. The only air conditioner was attached in the room, which was on when residents slept, and the bedroom door was closed during this time. Three nonsmokers resided in the apartment. Detailed information about their routine household activities was collected for the study.

Outdoor measurement was carried out about 300m away from the Indoor sensor installed in an open space on the second floor (about 9m above the ground) of an educational institute (Latitude: 4.17645 ° N latitude and 73.51497° E longitude) in the same district (Figure 2 (a)). Residential and office buildings, shops and a nearby school surround it. The sensor faces a road that usually has moderate traffic, especially on weekdays at peak hours.

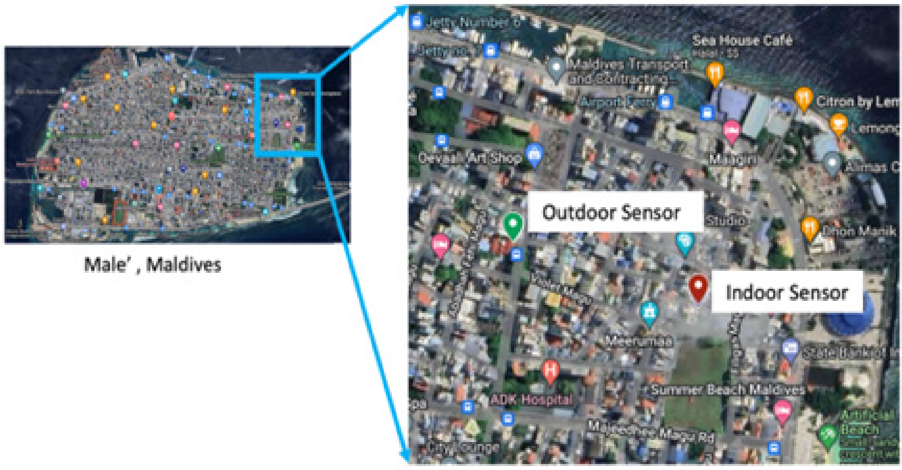

Figure 1: Location of the sensors: outdoor sensor is pinned in green and indoor sensor is pinned in red.

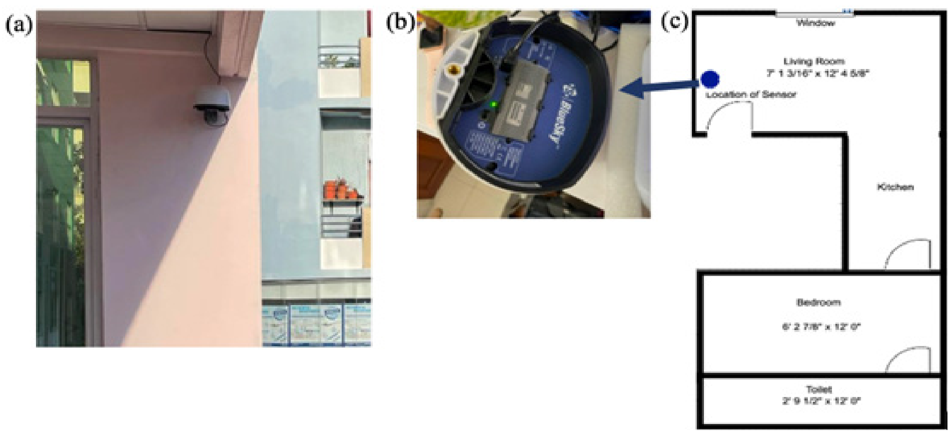

Figure 2: Sampling of $PM_{2.5}$ at (a) Outdoor Sensor located 300m away from (b) Indoor Sensor kept on a shelf in the living room and (c) The apartment floorplan.

Monitoring and Data Analysis

In recent years Low-cost sensors have become extremely useful in providing valuable information about ambient air quality, especially in developing countries (Giordano et al., 2021), where reference-grade monitors are not available. In this study $PM_{2.5}$ levels were measured from 10-09-2021 to 18-12-2021 using low-cost sensors (TSI BlueSky™ Air Quality monitor Model 8143) at both locations simultaneously. These monitors use laser-based light scattering particle sensors and are capable of measuring PM levels from 0–1000 µg/m^3 with a measurement resolution of 1 µg/m^3. The reported accuracy of the sensors has been comparable to reference grade monitors such as DustTrakTRS monitor (TSI Incorporated, 2020). These are widely used in monitoring outdoor and IAQ in various temperature and humidity settings. The sensors are capable of measuring PM levels every passing minute. The processed data from the equipment is transmitted and stored in a cloud-based and built-in data logging system (memory card) after averaging for intervals of 15 minutes.

Factory-calibrated six BlueSky monitors were co-located for harmonization for 7 days before deploying them at their monitoring sites. Linear regression over the origin was conducted for $PM_{2.5}$ concentrations from each sensor against the median of all six $PM_{2.5}$ concentrations. The regression coefficients were determined to harmonize data from individual sensors. The R^2 ranged from 0.9981 to 0.9998, indicating that the data from the low-cost sensors used in this study was highly reliable. The harmonization factor or regression coefficient was 1.06 and 0.84 for the indoor and outdoor sensor respectively. The downloaded 15-minute interval data were cleaned by removing records with TSI firmware flagged data as erroneous and records with upper limit were kept in check. The 15-minute interval data were converted to hourly data, then corrected by applying the harmonization factor. Cases with hours and days with less than 75% data completeness were removed from the data set. A total of 7 days of missing data was identified and the remaining 93 days of data were analyzed using Python libraries in Jupyter Notebook and Microsoft Excel Version 16.74.

Results and Discussions

$PM_{2.5}$ in Indoor and Outdoor Air

The mean $PM_{2.5}$ concentration measured during the sampling period inside the building was 10.1±13.1 μg/m^3 (median: 5.5 μg/m^3), which was significantly higher than that of the outdoor $PM_{2.5}$ concentration of 6.5±4.9 μg/m^3 (median: 5.2 μg/m^3). The indoor $PM_{2.5}$ concentration exhibited a larger range compared to the outdoor concentration. Both values exceed the annual WHO standard of 5 μg/m^3. The average outdoor concentration in this nearly 3 month's study is comparably lower than what was observed in a full year-round analysis conducted in 2013 (Budhavant, 2015). The study period falls into the transition period from wet to dry season. During the dry season or Northeastern monsoon, which starts in December, the ambient air quality in Male' experiences higher levels of air pollution due to transboundary air pollutants (Budhavant et al., 2015). The daily mean $PM_{2.5}$ concentrations ranged from 1.5 to 25.3 μg/m^3 in the indoor air and 2.3 to 51.7 μg/m^3 in the outdoor air (Figure 3). The highest levels for both indoor and outdoor were recorded in December. A total of 9 days out of 93 in the indoor air exceeded the 24-h WHO health guideline for $PM_{2.5}$ (15 μg/m^3), while for that of outdoor air, it was on 7 days. There were 4 days (one in November and three in December) on which indoor and outdoor air exceeded this limit.

The diurnal pattern of $PM_{2.5}$ indoors (Figure 6) varies drastically at different times of the day, unlike that of the outdoor $PM_{2.5}$ concentration. The outdoor concentration remains almost constant thought the day. This is due to the dispersion of outdoor pollutants as it is formed. However, inside the building, the source of the pollutant is closer to the sampling location, and they remain inside until outdoor air penetrates the air inside. However, in many urban cities like Jakarta, Indonesia where the outdoor $PM_{2.5}$ concentrations are generally very high, the outdoor levels vary much more than the indoor levels (Yulinawati, 2021). Yet, in some cases (Aquilina and Camilleri, 2021), the variation in both indoor and outdoor is comparable to each other.

The weekly trend (Figure 4) shows that $PM_{2.5}$ concentration remained slightly higher on Fridays (11.0 μg/m^3) compared to the remaining days of the week (ranging from 9.4 to 10.2 μg/m^3) in indoor air. Friday is the first day of the weekend and the residents reported engaging in more household activities such as dusting and cleaning on this day. There is no significant variation in the outdoor air in the days of the week. The monthly trends in $PM_{2.5}$ concentrations are shown in Figure 5. There is an increase in the concentration of $PM_{2.5}$ in indoor and outdoor air, except for indoor air between October and November, which remained constant. The months from September to November are considered as the transition period from wet to dry season. This explains the increase in the level of $PM_{2.5}$ from September to December in the outdoor air.

The mean I/O ratio was determined to see the difference in the pollution level in the indoor and outdoor air. The I/O ratio of 1.95±3.01(a value greater than 1) for this study suggests that generally, the level of pollution is greater inside the building and numerous sources of pollution originate from household activities or sources. In addition to various indoor sources, ventilation rate, outdoor air penetration factor, deposition rate (Chen and Zhao, 2011), building location and design, and different seasons (Massey et al., 2012) can also affect I/O ratio. The correlation coefficient is used to analyze how outdoor sources influence IAQ. A significant, but moderate positive correlation coefficient for daily indoor and outdoor $PM_{2.5}$ concentration was obtained (r= 0.48). This means the outdoor air has a moderate influence on IAQ. This is due to the mixing of indoor air with the outdoor air. A strong positive correlation was observed in many studies (Khumukcham, 2021; Suroto, 2019;) where higher indoor pollutant concentrations were identified than that of outdoor concentrations. Even though the mean outdoor PM concentrations exceeded the indoor concentration, Abdel-Salam (2020) reported a strong positive correlation between indoor and outdoor pollution levels. A higher positive correlation was observed between indoor and outdoor PM2.5 concentration in summer due to the frequent opening of windows for ventilation compared to that in winter when mostly the windows remained closed (Abdel-Salam, 2020). It is noteworthy that the pollutant concentration comparison and correlation and I/O exhibit huge differences from study to study in literature. This is because each study is conducted in different types of buildings (eg. schools, hospitals, etc), design of building and locations with different surrounding environment. Similarly, the results of this study might turn out to be different if the outdoor sensor was closer to or installed directly outside the building indoor measurements are being taken.

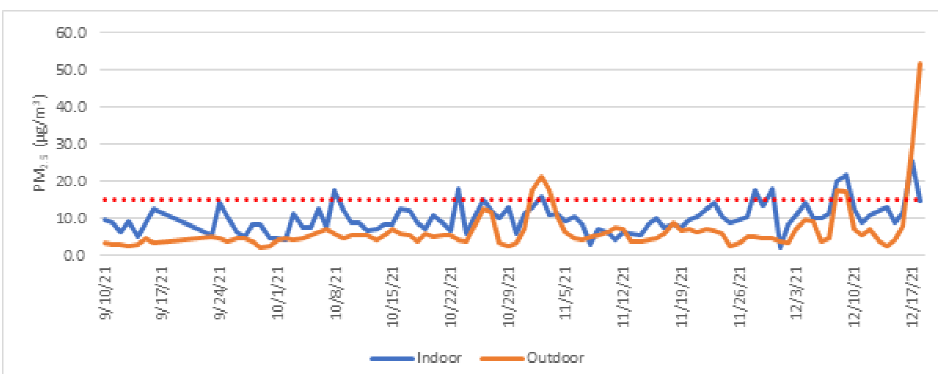

Figure 3: Daily average $PM_{2.5}$ concentrations from Indoor and Outdoor air and the dotted line denoting the mean 24-hour WHO health Guideline of 15 µg/m³.

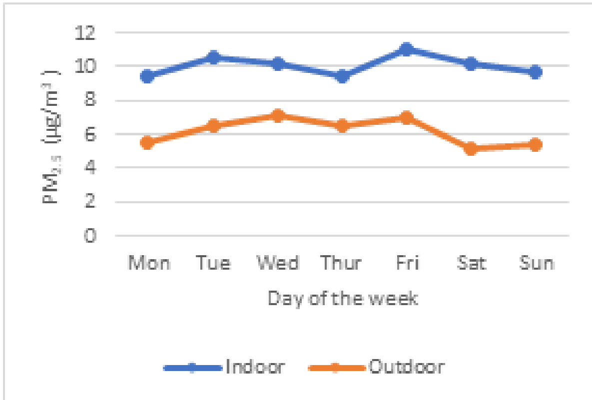

Figure 4: Average $PM_{2.5}$ from Indoor and Outdoor Air for different days of the week.

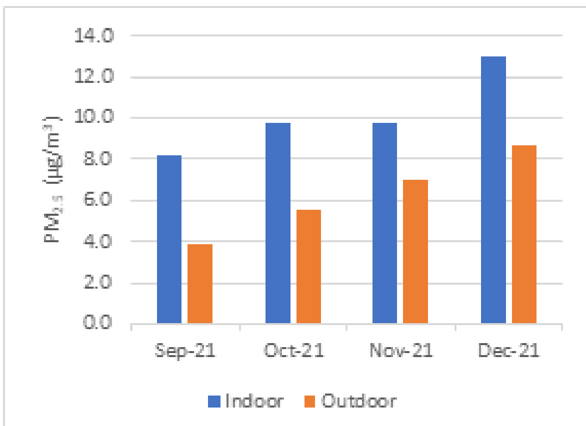

Figure 5: Monthly Average $PM_{2.5}$ from Indoor and Outdoor Air.

Figure 6: Hourly average $PM_{2.5}$ from Indoor and Outdoor and the usual household activities corresponding to the observed peaks Indoor.

Diurnal Pattern

The diurnal pattern of the $PM_{2.5}$ concentration measured indoor and outdoor is presented in Figure 6. The mean $PM_{2.5}$ concentration measured indoor shows a considerable variation across different times of the day. There is a sudden increase in the level of $PM_{2.5}$ from 12:00 to 1:00, which corresponds to the time the window was kept closed at night to sleep. The concentration of $PM_{2.5}$ kept increasing until 3:00, from where there is a slight decrease and then reaches its highest peak (21.1 µg/m3) at 6:00, the time windows are opened after waking up. One of the residents often wakes up early between 4:00-5:00 for prayer and keeps the window open during this time, which likely explains the dip before 5:00. The peak (17.0 µg/m^3) at 15:00 also represents the time during which pollutants build up since 13:00 as the window remained closed. The residents leave for work from 12:30 to 15:00. Hence the highest peaks represented building of indoor pollutants due to lack of ventilation.

Another noticeable peak (13.4 µg/m^3) occurs at 12:00, which represents the usual cooking time from 10:00-12:00, done using a gas stove with two burners. On some days only one burner was used, but on some days, two burners were also used simultaneously, the effect of which is not in the scope of this study. The overhead hood was kept on during the cooking time, and the window was kept open. The pollutant level dramatically increases if indoor sources are active and ventilation is not provided (Yang et al., 2009). However, in this case even when the window was kept open and the hood was on throughout the cooking time, the PM2.5 concentration increased and rose close to the daily health limit of WHO guideline. The concentrations of $PM_{2.5}$ can reach far above 300 µg/m3 during cooking with solid biomass fuels (Suresh et al., 2022). In addition to the type of fuel used, the method of cooking such as frying and grilling have resulted in different levels and characteristics of pollutants (Aquilina and Camilleri, 2021). Hence the effects on indoor air during cooking need to be explored in the Maldives, especially the effects on women and professionals, who spend a considerable amount of time in the kitchen.

A drastic drop in the $PM_{2.5}$ concentration was observed from 15:00 to 17:00, during which the windows were opened almost daily. On weekends the residents usually are out of the building from 17:00 to 19:00. The expected increase in concentration due to the unavailability of ventilation is not visible from the graph because it counteracts the effect of keeping the windows open for the rest of the weekdays. However, the decrease in the concentration during these hours was considerably steady. The lowest $PM_{2.5}$ concentrations attained indoors was 1.3 µg/m^3 at 23:00, which is explained by the greater penetration of outdoor air through the opened window for the longest period. The difference in the lowest level of the indoor and outdoor $PM_{2.5}$ concentration observed could possibly be due to the difference in the height of the sensors.

Conclusions and Recommendations

This study is a preliminary assessment of indoor air pollution levels in a household in Male' compared to outdoor levels by measuring $PM_{2.5}$ using low-cost sensors. The mean indoor and outdoor concentrations during the period surpass the annual WHO standard. The highest 24-hour mean levels of $PM_{2.5}$ indoors and outdoors were observed in December, which is the start of the dry season in the Maldives. The mean I/O ratio was greater than one, indicating a larger contribution from indoor sources. Cooking and possibly cleaning and dusting are identified as potential indoor sources. Cooking even with an operating overhead hood and windows kept open, affected the IAQ, but was considerably lower than what was observed in the literature. Hence it is recommended to use any means of ventilation available during cooking. Moreover, use a range hood over the stove, with the appropriate air flow rate, during cooking and leave it on after 10-20 minutes of cooking. The slight increase in the pollutant level on Friday, likely explains the effects of cleaning and dusting on IAQ. Frequent mopping, vacuuming, and wiping with a damp cloth could prevent pollutants from returning back into the air.

The positive significant correlation coefficient was obtained for indoor and outdoor concentrations, describing a moderate penetration of outdoor air into the indoor atmosphere. Thus, recognizing the need to monitor and keep the ambient outdoor air quality in check, to prevent it from affecting the IAQ. The diurnal variation of $PM_{2.5}$ concentration shows that when the windows are closed $PM_{2.5}$ accumulates inside the building. This continues until outdoor air is let in through ventilation to dilute the air inside. Therefore, an act as small as opening the windows, during this period of the year in Male', can significantly improve the IAQ. This needs to be kept in mind in the interior designing of enclosed spaces because proper ventilation is crucial in maintaining a healthy level of IAQ. This can be implied in workplaces, schools, and other educational institutes where individuals spend most of their time.

As mentioned before these pollutant variations inside buildings may vary depending on many factors. Hence, it is suggested to conduct research in different locations, types of buildings (such as workplaces and schools) and indoor settings (such as varying numbers of residents, residents with respiratory illness, smokers etc), different seasons for longer duration and apportion the sources of indoor air pollutants. This will help individuals, especially vulnerable groups of people, concerned authorities and policymakers to take measures to reduce exposure to air pollution. It will also contribute to local literature and in turn assist in determining AQI in the Maldives.

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