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# Evaluating Indoor Air Quality in Residential Environments: A Study of $PM_{2.5}$ and $CO_2$ Dynamics Using Low-Cost Sensors

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**Abstract:** Indoor air quality (IAQ) poses a significant public health concern, and exposures to high levels of fine particulate matter ($PM_{2.5}$) and carbon dioxide ($CO_2$) could have detrimental health impacts. This study focused on assessing the indoor air pollutants in a residential house located in the town of Mission, Hidalgo County, South Texas, USA. The $PM_{2.5}$ and $CO_2$ were monitored indoors: the kitchen and the bedroom. This investigation also aimed to elucidate the effects of household activities such as cooking and human occupancy on these pollutants. Low-cost sensors (LCSs) from TSI AirAssure™ were used in this study. They were deployed within the breathing zone at approximately 1.5 m above the ground. Calibration of the low-cost sensors against Federal Equivalent Method (FEM) instruments was undertaken using a multiple linear regression method (MLR) model to improve the data accuracy. The indoor $PM_{2.5}$ levels were significantly influenced by cooking activities, with the peak $PM_{2.5}$ concentrations reaching up to 118.45 $\mu g/m^3$. The $CO_2$ levels in the bedroom increased during the occupant's sleeping period, reaching as high as 1149.73 ppm. The health risk assessment was assessed through toxicity potential (TP) calculations for the $PM_{2.5}$ concentrations. TP values of 0.21 and 0.20 were obtained in the kitchen and bedroom, respectively. The TP values were below the health hazard threshold (i.e., TP < 1). These low TP values could be attributed to the use of electric stoves and efficient ventilation systems. This research highlights the effectiveness of low-cost sensors for continuous IAQ monitoring and helps promote better awareness of and necessary interventions for salubrious indoor microenvironments.

**Keywords:** indoor air quality (IAQ); fine particulate matter ($PM_{2.5}$); carbon dioxide ($CO_2$); cooking; low-cost sensor; toxicity potential



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## 1. Introduction

Indoor air pollution is a major health concern in any society and every person on this planet should have the wherewithal to live in a salubrious indoor microenvironment. Indoor air quality (IAQ) is of paramount importance, especially in developed nations, as people spend approximately 90% of their time indoors, such as in schools, offices, or homes [1–4]. The US Environmental Protection Agency (EPA)'s Science Advisory Board has ranked indoor air pollution as one of the top five environmental risks to public health [5]. Research has documented that indoor air pollutant levels may be 2 to 5 times higher than outdoor levels, and at times, these can even be 100 times higher than outdoor pollutant concentrations [1,5,6]. According to the World Health Organization [7], an estimated 3.2 million deaths in 2020 were attributed to household air pollution.

Indoor air quality (IAQ) can be influenced by various household activities, such as cooking, cleaning, vacuuming, resuspension of dust particles, second-hand tobacco smoke exposure, chemical products for cleaning, decorating, painting, furnishings, building, inadequate ventilation, excess moisture, using room air fresheners, using products for arts and crafts, and other hobbies, as well as using electrical equipment such as photocopiers [8–12]. Indoor air pollutants typically comprise $PM_{10}$ (inhalable particles, with diameters 10 µm and smaller), $PM_{2.5}$ (fine inhalable particles with diameters 2.5 µm and smaller), volatile organic compounds (VOCs), gases like carbon dioxide ($CO_2$), ozone ($O_3$), carbon monoxide (CO), and nitrogen oxide ($NO_2$), and biological particles (pollen, bacteria, and fungi), which are detrimental to human health [13–15]. Among various household activities, cooking is the most common activity that significantly impacts indoor spaces [16–18]. Specifically, cooking on gas stoves is associated with negative health outcomes as it generates $PM_{2.5}$ [19–21] and harmful gases such as $CO_2$, $NO_2$, and CO [22–24]. Inadequate ventilation systems in the indoor microenvironment can also impact the air quality [17,18,25–28].

$PM_{2.5}$ and $CO_2$ are the most common and regularly monitored household indoor air pollutants, as they have the potential to impact indoor air quality deleteriously [6,29]. $PM_{2.5}$ is one of the six criteria for air pollutants regulated by the US Environmental Protection Agency [30]. It has the potential to penetrate the respiratory tract, reach the alveoli, and even enter the bloodstream [11,31–33]. Several studies have found increases in mortality due to short-term and long-term exposures to $PM_{2.5}$ [34–37]. $PM_{2.5}$ has significant health impacts even at low concentrations [38–40]. Hence, it is paramount that a comprehensive analysis of the $PM_{2.5}$ levels in various indoor and outdoor settings is undertaken. $CO_2$ is an odorless, colorless, and mostly harmless gas, and its primary source in the indoor microenvironment is human exhalation. It is observed that occupied indoor spaces have higher $CO_2$ levels compared to the outdoor microenvironment [41–43]. High levels of $CO_2$ could be attributed to inadequate ventilation and are a marker of poor indoor air quality [27,42,44,45]. Several studies have also demonstrated that high levels of indoor $CO_2$ (500–5000 ppm) can cause headaches, drowsiness, lethargy, anxiety, and stuffiness, as well as memory loss and cognitive difficulties [42,43,45,46].

In recent years, low-cost sensors (LCSs) have gained a lot of traction in regard to indoor IAQ [6,16,47]. Low-cost sensors are very handy to use and help elucidate the spatiotemporal analysis of pollutants at a fraction of the cost compared to traditional reference monitors [48]. However, data from low-cost sensors come with some uncertainties, such as accuracy (bias) issues when compared with the Federal Reference Method (FRM) or Federal Equivalent Method (FEM). However, these issues could be overcome by subjecting the data to calibration with multiple linear regression (MLR) methods [49–51].

In this study, the IAQ was assessed for a one-month period in a residential home, in the kitchen and bedroom, using low-cost sensors. The measurements were carried out at a high school student's residence located in the city of Mission, Hidalgo County, South Texas. The main purposes of this research study were to (1) characterize the indoor levels of $PM_{2.5}$ and CO2 using LCSs; (2) calibrate the LCSs for improved accuracy using algorithm models; (3) identify potential sources of indoor pollutants; and (4) analyze the potential health hazard assessment of indoor $PM_{2.5}$. Additionally, ambient $PM_{2.5}$ data were downloaded from the nearest Texas Commission on Environmental Quality (TCEQ) Continuous Ambient Monitoring Station (CAMS), i.e., C-43 in Mission, located near the residential home. This aided in comparing the ambient air concentrations of $PM_{2.5}$ with the indoor air data collected during the study period. The RGV of South Texas is part of the U.S.–Mexico border region and is an understudied region in terms of monitoring indoor air quality. To the best of our knowledge, no study has been conducted on monitoring IAQ using low-cost sensors in this region and this research endeavor, therefore, has the potential to contribute to the growing repository of knowledge on indoor air pollution.

## 2. Materials and Methods

### *2.1. Study Design*

This study was conducted between 15 June 2024 and 16 July 2024 at a residential home in Mission, Hidalgo County, Rio Grande Valley, South Texas. This study focused on evaluating the exposure to indoor pollutants, namely, $PM_{2.5}$ ($\mu g/m^3$) and $CO_2$ (ppm), using LCSs. These were placed in the kitchen and bedroom, approximately 1.5 m from the ground level, within the "breathing zone". The primary $PM_{2.5}$ sources in the residence included cooking activities (lunch and dinner) and the influence of ambient air, whereas for $CO_2$, the primary sources included human exhalation and ventilation systems. Some of the physical features of the residence included a heating, ventilation, and air conditioning (HVAC) system and the use of electrical appliances like an electric stove for cooking purposes. A total of three people resided in this house, which was situated approximately 4.02 km miles away from E Interstate Highway 2 and 0.96 km away from N Mayberry Road. Figure 1 shows the selected residential house and the nearest TCEQ C-43, which were approximately 2.41 km from each other. The floor plan of the residence and the two microenvironments, namely, the kitchen (3.9 m × 3.6 m × 3 m) and bedroom (3.9 m × 3.9 m × 3.9 m), where the sensors were deployed, are shown in Figure 2.


**Figure 1.** Location of the study site and the nearest TCEQ C-43.

### *2.2. Instrumentation*

In this study, we used two TSI AirAssure™ IAQ Monitors (Model:8144-6, TSI Inc., Shoreview, MN, USA) to monitor the $PM_{2.5}$ and $CO_2$ (Figure 2). TSI AirAssure IAQ Monitors are designed for indoor air monitoring and are portable, lightweight, easy-to-install, low-cost sensors (17.1 cm × 8.9 cm × 3.3 cm, ~0.23 g). These LCSs have built-in light-scattering optical and non-dispersive infrared (NDIR) sensors that are capable of measuring both particulate matter and gases [52]. The time resolution for the data collection was set at an interval of 15 min.

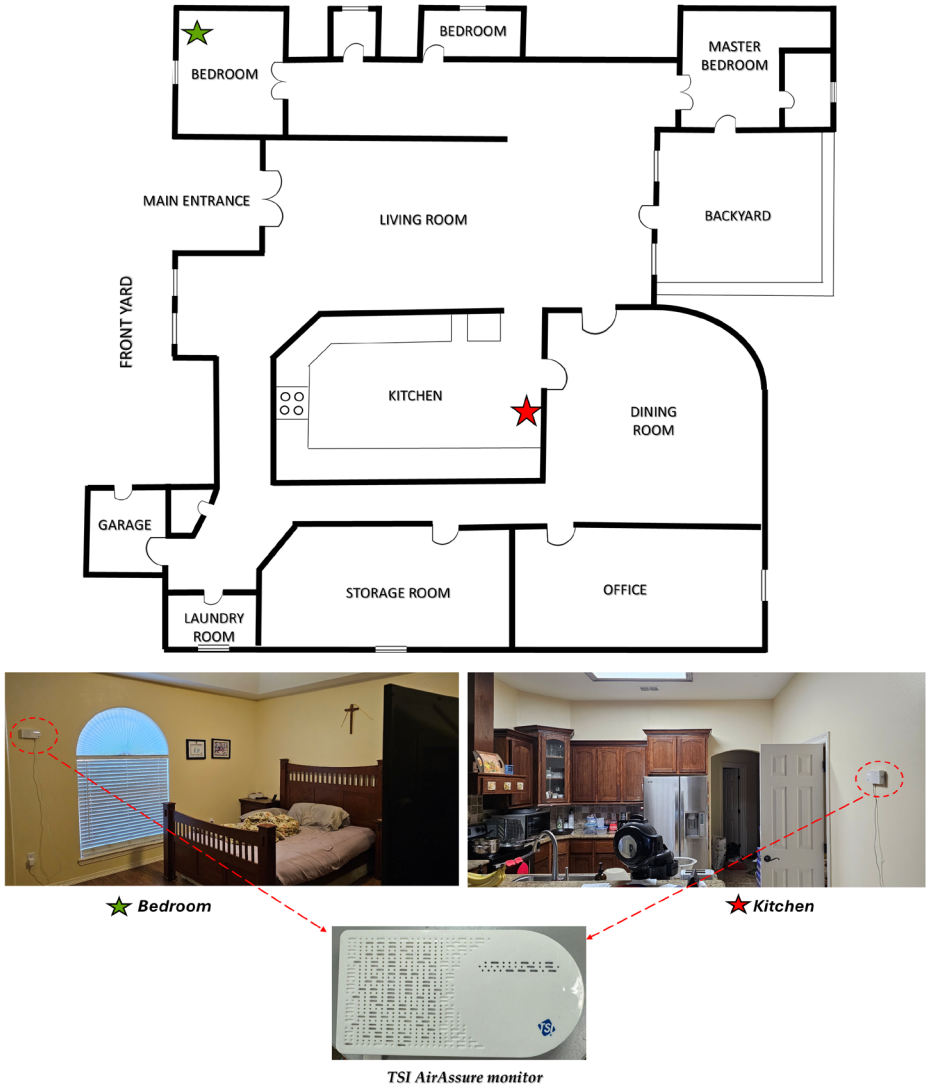


**Figure 2.** Floor plan of the residence, along with the installation of the low-cost sensors in the bedroom and kitchen.

### *2.3. Statistical Data Analysis*

For this study, Microsoft Excel (v.16.06, Microsoft Inc., Redmond, WA, USA) was used to clean the raw data and convert them into the 1 h averages. Origin Pro (Origin Lab Corporation, Northampton, MA, USA, Version 2024) was used for the graphical visualization and descriptive statistical analysis of the 1 h averaged data. The graphical visualization included hourly time series and hourly box plots. The spatial distribution of the selected residence, along with the nearest TCEQ C-43, was plotted using ArcGIS Pro (v.3.2.0, 2023).

## 3. Results and Discussion

### *3.1. Collocation Between LCSs and FEMs*

LCS measurements require correction as they come with accuracy challenges [48,49,51,53]. In order to address this issue, calibration was performed by collocating the two LCSs (TSI AirAssure monitors) with FEMs, namely, the Q-Trak™ Indoor Air Quality Monitor (Model: 7575, TSI Inc., Shoreview, MN, USA) and GRIMM Portable Aerosol Spectrometer (Model: 11-D, Grimm Aerosol Technik GmbH & Co., KG, Germany) to ensure the accuracy [50,54,55]. The Q-Trak instrument (Figure 3a) is a multi-function electrochemical sensor capable of measuring carbon dioxide ($CO_2$), carbon monoxide (CO), temperature (T), and relative humidity

(RH). The data can be recorded at multiple time resolutions: 6 s, 1 min, 5 min, 10 min,15 min, 30 min, and 1 h [56]. The Grimm 11-D instrument (Figure 3b) is designed to measure the total particle number concentrations, size distribution, and mass concentration, including $PM_1$, $PM_{2.5}$, $PM_4$, and $PM_{10}$. The data can be recorded at 6 s and 1 min intervals [57]. The two TSI AirAssure sensors were positioned approximately 0.5 m apart indoors with the Q-Trak and GRIMM instruments. The collocation period spanned seven days, after which the LCSs were deployed in the bedroom and the kitchen. All the datasets (both LCS and FEMs) were converted into 1 h averages.


**Figure 3.** FEM instruments used for the colocation with the LCSs during the calibration period: (**a**) Q-Trak™ Indoor Air Quality Monitor, Model: 7575 [56]; and (**b**) GRIMM Portable Aerosol Spectrometer, Model: 11-D [57].

To ensure a strong correlation between the performance of the two LCSs and the FEMs instruments, we developed an MLR model. MLR is an extensively researched calibration method and is widely used [58,59]. It is an extensive version of linear regression (LR) that includes more than one independent variable (such as the raw LCS measurement ($CO_2$ or $PM_{2.5}$), relative humidity, and temperature). Therefore, to predict the corrected $PM_{2.5}$, we considered the 1 h averaged TSI AirAssure raw $PM_{2.5}$ ($\mu g/m^3$), temperature (°C), and relative humidity (%) as independent variables for our MLR model [59]. Similarly, we considered the 1 h averaged TSI AirAssure raw $CO_2$, temperature, T (°C), and relative humidity, RH (%) as independent variables to predict the corrected $CO_2$ [58]. The MLR model is expressed as the following equations:

$$PM_{2.5}, \text{corrected} = \beta_0 + \beta_1 \times PM_{2.5,\,LCS} + \beta_2 \times T_{LCS} + \beta_3 \times RH_{LCS} \quad (1)$$

$$CO_2, \text{corrected} = \alpha_0 + \alpha_1 \times CO_{2,\,LCS} + \alpha_2 \times T_{LCS} + \alpha_3 \times RH_{LCS} \quad (2)$$

where $PM_{2.5}$, corrected is the corrected $PM_{2.5}$ using the MLR model; $\beta_0$ is the intercept; $\beta_1$–$\beta_3$ are the regression coefficients; and $PM_{2.5}$, LCS is the raw TSI AirAssure readings. Similarly, $CO_2$, corrected is the corrected $CO_2$ using the MLR model; $\alpha_0$ is the intercept; $\alpha_1$–$\alpha_3$ are the regression coefficients; and $CO_{2,\,LCS}$ is the raw $CO_2$ TSI AirAssure readings. $T_{LCS}$ and $RH_{LCS}$ are the temperature (°C) and relative humidity (%), respectively, measured by the TSI AirAssure monitors.

The MLR models for $PM_{2.5}$ and $CO_2$ were developed using MS Excel and Origin Pro (Table 1). This model was evaluated based on performance metrics like the root mean square error (RMSE measured in $\mu g/m^3$ for $PM_{2.5}$ and ppm for $CO_2$), coefficient of determination ($R^2$), and mean absolute error (MAE). The model showed better $R^2$, lower RMSE and an MAE with a significant improvement in accuracy (Table 1). The RMSE for $PM_{2.5}$ decreased from 2.73 $\mu g/m^3$ in the raw data to 1.57 $\mu g/m^3$ post-correction, and the MAE reduced from 2.27 to 1.05. The $R^2$ value, which indicates the correlation between the observed

and predicted values or proportion of variance by the model, increased from 0.75 to 0.79 (Figure 4a), indicating improved predictive accuracy. The correction model for $PM_{2.5}$ is expressed as follows:

$$PM_{2.5,corrected} = -13.23 + 1.48 \times PM_{2.5,LCS} + 0.06 \times T_{LCS} + 0.23 \times RH_{LCS} \quad (3)$$

where $PM_{2.5,LCS}$ represents the raw LCS $PM_{2.5}$ readings, $T_{LCS}$ is the temperature (°C) from the sensor, and $RH_{LCS}$ is the relative humidity (%).

**Table 1.** Calibration results on a 1 h average basis with the performance evaluations.

| Indoor Pollutants | Raw Data | Corrected Data (MLR) |
|---|---|---|
| *$PM_{2.5}$ ($\mu g/m^3$)* | RMSE = 2.73 $\mu g/m^3$<br>MAE = 2.27<br>$R^2$ = 0.75 | RMSE = 1.57 $\mu g/m^3$<br>MAE = 1.05<br>$R^2$ = 0.79<br>$PM_{2.5,corrected} = -13.23 + 1.48 \times PM_{2.5,\ LCS} + 0.06 \times T_{LCS} + 0.23 \times RH_{LCS}$ |
| *$CO_2$ (ppm)* | RMSE = 203.62 ppm<br>MAE = 198.02<br>$R^2$ = 0.59 | RMSE = 40.33 ppm<br>MAE = 30.98<br>$R^2$ = 0.64<br>$CO_{2,corrected} = -30.89 + 0.65 \times CO_{2,\ LCS} + 13.42 \times T_{LCS} - 4.86 \times RH_{LCS}$ |

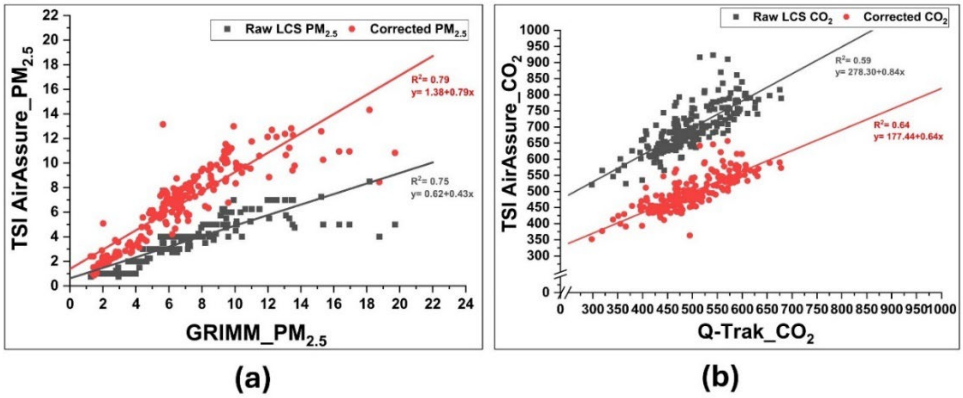


**Figure 4.** (**a**) Scatterplots showing the comparison between the 1 h $PM_{2.5}$ ($\mu g/m^3$) from GRIMM (*X*-axis) and TSI AirAssure (*Y*-axis). (**b**) Scatterplots showing the comparison between the 1 h $CO_2$ (ppm) from Q-Trak (*X*-axis) and TSI AirAssure (*Y*-axis).

The $CO_2$ data also show significant improvement after applying the MLR correction. The RMSE was reduced from 203.62 ppm in the raw data to 40.33 ppm in the corrected data, and the MAE decreased from 198.02 to 30.98. Additionally, the $R^2$ value increased from 0.59 in the raw data to 0.64 after correction (Figure 4b), indicating better model performance. The correction model for $CO_2$ is expressed as follows:

$$CO_{2,corrected} = -30.89 + 0.65 \times CO_{2,LCS} + 13.42 \times T_{LCS} - 4.86 \times RH_{LCS} \quad (4)$$

where $CO_2$, LCS represents the low-cost sensor's $CO_2$ readings, $T_{LCS}$ is the temperature (°C) from the sensor, and $RH_{LCS}$ is the relative humidity (%). This correction leads to a more accurate and reliable estimation of the $CO_2$ levels, aligning better with the reference measurements. Therefore, the MLR model demonstrated better performance during calibration for both pollutants, as shown in the time series (Figure 5). Consequently, we incorporated the MLR model to calculate the final data for analysis for the study period.

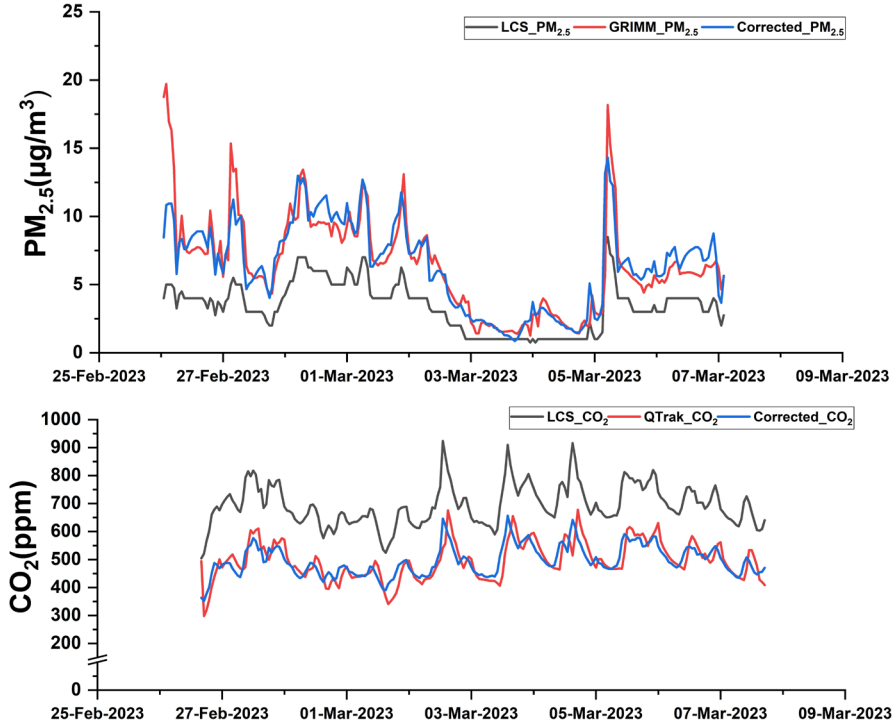


**Figure 5.** Time series of the $PM_{2.5}$ and $CO_2$ concentrations during the calibration period: comparison of LCS, FEM (GRIMM, Q-Trak), and corrected values.

### *3.2. 1 h Averaged Indoor Concentration*

This study was conducted for one summer month in a residential house occupied by three occupants. The house was fully ventilated and maintained at a constant temperature, and there were no external disturbances, with non-openable windows. This study focused on the primary sources of $PM_{2.5}$ (generated during cooking activities) and $CO_2$ (primarily from human exhalation, especially after 11:00 p.m. when all the occupants were sleeping). Figure 6 presents the time series plot of the 1 h averaged $PM_{2.5}$ and $CO_2$ concentrations in the kitchen and the bedroom. The highlighted section (Figure 6) corresponds to the period from 23 June to 29 June 2024, when the house was unoccupied. During this time, a noticeable decrease in the $PM_{2.5}$ and $CO_2$ values was observed, attributed to the absence of cooking and human activities. The lack of occupants resulted in a decline in the $PM_{2.5}$ and $CO_2$ levels, demonstrating the impact of cooking activities and human exhalation on the indoor air quality, respectively.

An increase in the $PM_{2.5}$ levels was observed in the kitchen during cooking periods, specifically from 10:00 a.m. to 11:00 a.m. and 7:00 p.m. to 8:00 p.m. (Figure 7). This corroborates the impact of meal preparation on the IAQ [28]. However, cooking activities did not significantly affect the $PM_{2.5}$ levels in the bedroom compared to the kitchen. Notably, on 15 July 2024, at around 4:00 p.m., the $PM_{2.5}$ concentrations exceeded 60 $\mu g/m^3$ in both the kitchen and the bedroom during heavy meal preparation. The mean (SD) of the 1 h $PM_{2.5}$ concentration was 3.34 (7.29) $\mu g/m^3$ in the kitchen and 3.00 (3.99) $\mu g/m^3$ in the bedroom. The 1 h averaged $PM_{2.5}$ concentrations ranged from 0.01 $\mu g/m^3$ to 118.45 $\mu g/m^3$ in the kitchen and from 0.01 $\mu g/m^3$ to 72.63 $\mu g/m^3$ in the bedroom, as shown in Table 2. Interestingly, the $PM_{2.5}$ levels also increased in the bedroom, but they were less affected by cooking activities compared to the kitchen. This suggests that the distribution of particulate matter within a home can vary depending on the proximity to the pollution source. Other studies [17,20,21] found elevated $PM_{2.5}$ levels during cooking, mainly when frying meats or cooking at high temperatures, as these activities generate higher levels of particulate emissions. Therefore, this study corroborates the findings of previous studies demonstrating that cooking activities significantly contribute to the

indoor $PM_{2.5}$ concentrations [16,17,21,60]. Similarly, an increase in the $CO_2$ concentration was observed in the bedroom, particularly during the sleeping period from 11:00 p.m. to 8:00 a.m., corresponding to the occupant's sleeping hours (Figure 7). These peaks in the $CO_2$ levels were attributed to human exhalation throughout the night and were notably higher compared to those observed in the kitchen. The mean (SD) of the 1 h $CO_2$ concentration was 606.56 (113.73) ppm in the kitchen and 644.64 (154.90) ppm in the bedroom. The 1 h averaged $CO_2$ concentrations ranged from 369.80 ppm to 826.42 ppm in the kitchen and from 381.93 ppm to 1149.73 ppm in the bedroom (Table 2). The findings indicate that human occupancy, particularly during sleeping hours, significantly contributes to increased $CO_2$ concentrations in indoor environments [61,62]. A study by Satish et al. in 2012 [42] also reported elevated indoor $CO_2$ levels associated with occupancy and limited ventilation.

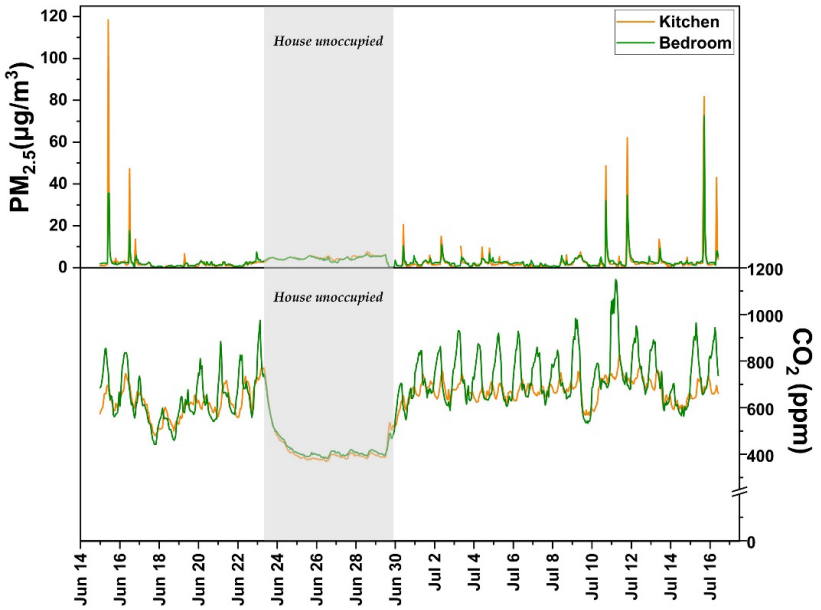


**Figure 6.** Time series showing the 1 h averaged $PM_{2.5}$ and $CO_2$ for the kitchen and bedroom obtained from the LCSs during a 1-month study period. The highlighted section represents the days when the house was unoccupied.

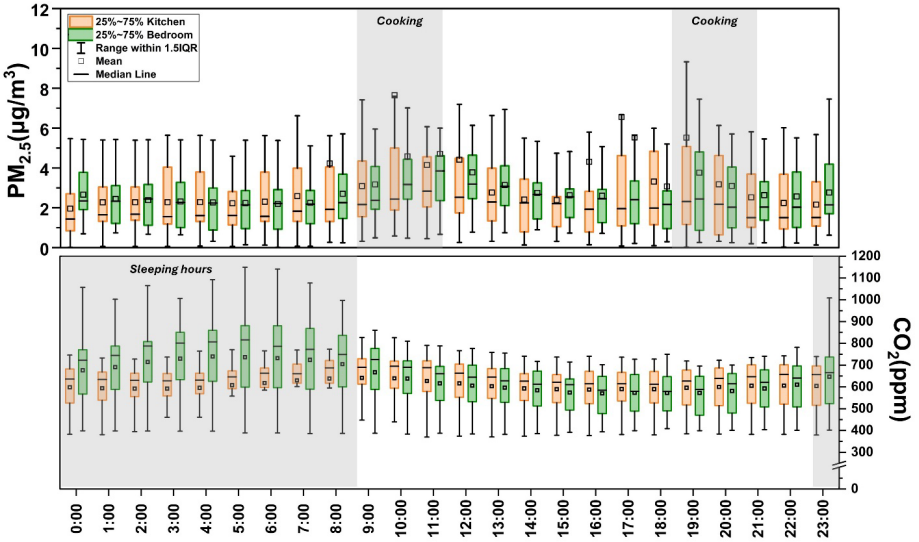


**Figure 7.** Hourly boxplots of the $PM_{2.5}$ and $CO_2$ for the kitchen and bedroom, including the primary sources during the 1-month study period.

**Table 2.** The 1 h averaged descriptive statistics of the $PM_{2.5}$ and $CO_2$ for different environments.

| Pollutant & Environment | Site | N Total | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|
| **$PM_{2.5}$ (μg/m$^3$)—Indoor** | Kitchen | 695 | 3.34 | 7.29 | 0.01 | 118.45 |
| | Bedroom | 755 | 3.00 | 3.99 | 0.01 | 72.63 |
| **$PM_{2.5}$ (μg/m$^3$)—Ambient** | Mission (C-43) | 749 | 11.91 | 6.22 | 2.10 | 39.10 |
| **$CO_2$ (ppm)—Indoor** | Kitchen | 755 | 606.56 | 113.73 | 369.80 | 826.42 |
| | Bedroom | 755 | 644.64 | 154.90 | 381.93 | 1149.73 |

SD—standard deviation, N—number of samples, min–minimum value, max–maximum value.

### *3.3. Comparison Between Indoor and Ambient PM2.5*

PM2.5 data from the TCEQ CAMS site were analyzed to explore the relationship between the ambient and indoor concentrations. The ambient data were retrieved from the TCEQ website [63] for the CAMS (C43) in Mission, the nearest federal reference monitoring station to the study site. The mean (SD) of the 1 h averaged $PM_{2.5}$ concentration at the TCEQ CAMS in Mission (C-43) was 11.91 (6.22) μg/m$^3$, with values ranging from 2.10 μg/m$^3$ to 39.10 μg/m$^3$, as shown in Table 2. However, the analysis did not reveal a strong correlation between the indoor and ambient $PM_{2.5}$ concentrations, suggesting that the house's ventilation system was effective and well-functioning. We also did not observe any identical pattern in the $PM_{2.5}$ concentration levels between indoors (kitchen and bedroom) and ambient (C-43), as shown in Figure 8. In a study by Zenissa et al. in 2020 [28], it was observed that opening windows during cooking led to higher indoor $PM_{2.5}$ levels due to outdoor $PM_{2.5}$ entering the indoor microenvironment. Therefore, proper ventilation and filtration systems help prevent outdoor air pollutants from infiltrating the building [6,27,28]. Additionally, the indoor $CO_2$ measurement could not be compared to any CAMS data, as the TCEQ CAMS does not monitor $CO_2$.

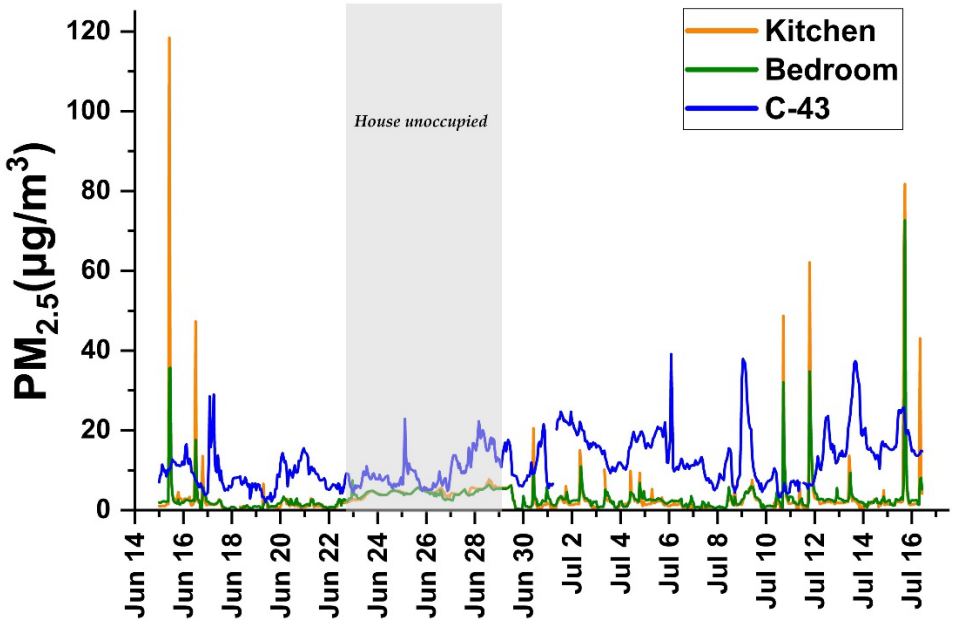


**Figure 8.** Time series showing the 1 h averaged $PM_{2.5}$ for the kitchen and bedroom during the 1-month study period, including the ambient $PM_{2.5}$ obtained from Mission C-43 (Note: C-43 does not monitor $CO_2$). The highlighted section represents the days when the house was unoccupied.

### *3.4. Health Risk Assessment of Indoor $PM_{2.5}$*

Cooking is the primary source of indoor $PM_{2.5}$. It poses a great risk to human health. The health risk associated with indoor air quality during cooking activities was evaluated by calculating the toxicity potential (TP). The TP quantifies the potential of a pollutant

released into the air to cause adverse health effects on residents within a specific area. The TP is calculated using the following formula [64,65]. The TP was calculated using Equation (5) as below:

$$\text{Toxicity potential (TP)} = (Cp/Sp) \quad (5)$$

where Cp represents the measured concentration of $PM_{2.5}$ in the indoor environment, and Sp represents the World Health Organization (WHO)'s standard for $PM_{2.5}$ (i.e., 15 $\mu g/m^3$).

A TP value exceeding 1 signifies a potential health hazard associated with the selected pollutant within a particular area. Therefore, the accepted ratio of TP is 1 [60,65]. According to the updated WHO guidelines of 2021, the standard for $PM_{2.5}$ has been revised to 15 $\mu g/m^3$ from 25 $\mu g/m^3$ for a 24 h exposure period [66].

The toxicity potential of the 24 h average $PM_{2.5}$ for the kitchen and bedroom is shown in Table 3. The TP values for $PM_{2.5}$ in the kitchen ranged from 0.03 to 0.56, while in the bedroom, they ranged from 0.04 to 0.42. It was observed that the average TP values of $PM_{2.5}$ for the kitchen (0.21) and bedroom (0.20) were much lower than 1. This indicates that $PM_{2.5}$ is not associated with potential health hazards in this residence. Akteruzzaman et al., in 2023 [60], assessed the impact of cooking in households in Bangladesh by calculating the toxicity potential in eight kitchens (gas and mud stoves) and living rooms of four selected households (with limited ventilation systems) and the value ranged between 0.82 and 8.3, whereas our study's values ranged between 0.05 and 0.6. Therefore, our results indicate that proper ventilation systems and the usage of electric stoves for cooking may help maintain a cleaner indoor environment.

**Table 3.** Toxicity potential (TP) in the kitchen and bedroom during the study period.

| Microenvironments | Mean ± SD (TP Values) | Range (TP Value) |
|---|---|---|
| Kitchen | 0.21 ± 0.14 | 0.03 to 0.56 |
| Bedroom | 0.20 ± 0.09 | 0.04 to 0.42 |

There is a caveat concerning the calculated toxicity potential obtained in this study in that it provides a health risk assessment of PM2.5 based on its mass concentrations. However, it is important to note that the actual toxicity of PM2.5 particles varies considerably depending on the chemical compositions, sizes, and sources [67]. Since we used low-cost sensors, the toxicity potential calculations rely solely on the mass concentrations, which may oversimplify the potential health risks. Therefore, future studies should also consider the chemical analysis of PM2.5 particles to determine the toxicity potential.

## 4. Limitations and Conclusions

Our study has some limitations. First, we could not evaluate the impact of the air exchange rates on the indoor air quality due to the lack of ventilation data. Secondly, the research was conducted in only one residential home, limiting the findings' applicability to other homes with different architectural designs, occupant behaviors, and environmental conditions. This study did not incorporate outdoor sensors for monitoring air quality, so we could not measure the infiltration rate of outdoor pollutants into the indoor environment. Also, the focus was limited to $PM_{2.5}$ and $CO_2$, excluding other potentially harmful indoor pollutants. This study investigated the IAQ over a one-month period, focusing on the $PM_{2.5}$ and $CO_2$ concentrations within a residential setting: the kitchen and bedroom. LCSs were used in this study. Prior to the study, these LCSs were calibrated against FEM instruments through a multiple linear regression (MLR) model to improve the data accuracy. The temporal trends indicated that cooking activities were the primary source of indoor $PM_{2.5}$, with notable peaks observed between 10:00 a.m. to 11:00 a.m. and 7:00 p.m. to 8:00 p.m. during meal preparation times, while the $CO_2$ levels in the bedroom showed increased concentrations from 11:00 p.m. to 8:00 a.m., correlating with the occupants' sleep period.

This study also found minimal correlation between the indoor and ambient $PM_{2.5}$ levels, suggesting that effective ventilation prevented the infiltration of outdoor pollutants

into the indoor microenvironment. The health risk assessment through toxicity potential (TP) calculations revealed that the indoor $PM_{2.5}$ concentrations in the kitchen and bedroom were well below the threshold for health hazards, with mean TP values of 0.21 and 0.20, respectively. These low TP values could be attributed to the use of electric stoves and efficient ventilation systems. The findings underscore the importance of maintaining proper ventilation systems to prevent the infiltration of outdoor particulate pollution in the indoor microenvironment. This study also highlights the value of calibrated LCS data in accurately assessing the IAQ. This study recommends that the indoor microenvironment, especially in residential kitchens, should be the subject of more attention due to the pollution emanating from cooking activities. In addition, increasing the public's awareness of indoor pollutants and their primary sources is necessary to understand the health risk of said pollutants.

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