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Using low-cost sensors to investigate relationships between indoor and outdoor $PM_{2.5}$ during the COVID-19 lockdown period in urban areas of Bien Hoa city, Vietnam

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Abstract: *$PM_{2.5}$ pollution remains a pressing environmental concern in Bien Hoa city, a key industrial center within Vietnam's Southern Key Economic Zone. This research utilized low-cost sensors to measure indoor and outdoor $PM_{2.5}$ levels in five urban households from April 2021 to January 2022, with calibration performed using the DustTrak™ II Aerosol Monitor 8530. During the COVID-19 lockdown, daily average $PM_{2.5}$ concentrations ranged from 22 to 40 µg/m³, meeting Vietnam's air quality standards but exceeding the World Health Organization's guidelines. Indoor $PM_{2.5}$ levels were significantly elevated in older homes due to factors such as smoking and incense burning, while outdoor levels were primarily impacted by traffic and other local sources, with peaks observed during rush hours. Seasonal analysis revealed reduced $PM_{2.5}$ concentrations during the rainy season, underscoring the mitigating effects of rainfall and natural ventilation on indoor air pollution. The significant linear correlation between indoor and outdoor $PM_{2.5}$ concentrations underscores the need for thorough air quality evaluations. This study is the first to assess indoor-outdoor $PM_{2.5}$ relationships in Bien Hoa City households using low-cost sensors over nearly a year, including the COVID-19 control period. The study demonstrates that low-cost sensors are an effective and practical option for air quality monitoring in resource-limited settings like Vietnam.*

Keywords: *fine particulate matter, ambient, indoor, urban, low-cost sensor, coronavirus disease.*

1. Introduction

Indoor air pollution poses a significant environmental health challenge. Urban dwellers generally remain indoors for approximately 80% to 90% of their daily routines, encompassing spaces such as homes, schools, workplaces, and transportation modes like cars, buses, and subways (Dimitroulopoulou et al., 2023). Indoor air pollution contributes to approximately 3.2 million deaths worldwide each year (WHO, 2023). Fine particulate matter ($PM_{2.5}$) is a significant factor contributing to health problems associated with indoor air pollution (Nansai et al., 2021). Besides health effects, indoor $PM_{2.5}$ pollution levels also have a direct impact on learning and work performance (Li et al., 2017). Consequently, more recently, indoor $PM_{2.5}$ pollution levels have been receiving greater attention in environmental health research. On the other hand, a strong correlation exists between indoor and outdoor $PM_{2.5}$ concentrations (Xiao et al., 2018). Indoor $PM_{2.5}$ levels are affected by both outdoor $PM_{2.5}$ pollution and the effectiveness of indoor control measures (Lin et al., 2018), often resulting in considerably higher indoor $PM_{2.5}$ levels (Orru et al., 2014, Liu and Zhang, 2019, Zhang et al., 2021). This contradicts the common belief that indoor air quality is typically better and safer than outdoor air. Therefore, it is crucial to examine indoor and outdoor $PM_{2.5}$ pollution levels concurrently.

Air pollution, specifically $PM_{2.5}$ pollution, stands out as a major environmental challenge in Bien Hoa city. This class-1 provincial city, with many large industrial parks, has the highest population growth rate in Vietnam (Review, 2024). As a result, the city faces many environmental challenges, e.g., $PM_{2.5}$ pollution, due to rapid urbanization and increased industrial activity. Additionally, a study showed that the methods used to eliminate dioxin contained in Agent Orange and other herbicides at Bien Hoa Airbase have also contributed to elevated $PM_{2.5}$ levels in the city (Bui et al., 2022). Besides the local sources of $PM_{2.5}$ emissions mentioned above, the $PM_{2.5}$ pollution in Bien Hoa city could also be affected by emission sources from non-local regions, particularly Binh Duong province and Ho Chi Minh City (Bui et al., 2022). Recently, researchers have shown increased interest in assessing $PM_{2.5}$ and its heavy metal composition in Bien Hoa city (Bui et al., 2022, Linh et al., 2023, Hoang et al., 2024). However, most studies on this topic have only been carried out in specific areas such as the Bien Hoa Airbase and industrial parks. Data on $PM_{2.5}$ pollution in urban areas of Bien Hoa remains limited. Moreover, little focus has been placed on both indoor and outdoor $PM_{2.5}$ levels in this city, despite extensive research on these levels in Vietnam's two most populous cities, Ho Chi Minh City and Hanoi (Vo et al., 2020, Tran et al., 2021, Hien et al., 2022, Vo et al., 2022, Vo, 2022, Huyen et al., 2024).

The objectives of this study were to monitor indoor and outdoor $PM_{2.5}$ concentrations using low-cost sensors at the household level in the urban areas of Bien Hoa city, Vietnam, and to assess the correlations between these concentrations. Significantly, the study focused on measuring $PM_{2.5}$ levels in both indoor and outdoor environments during the unique period of the COVID-19 lockdown in Bien Hoa city. This study is the first to evaluate the indoor-outdoor $PM_{2.5}$ relationship in urban households of Bien Hoa City using low-cost sensors, including during COVID-19 control measures.

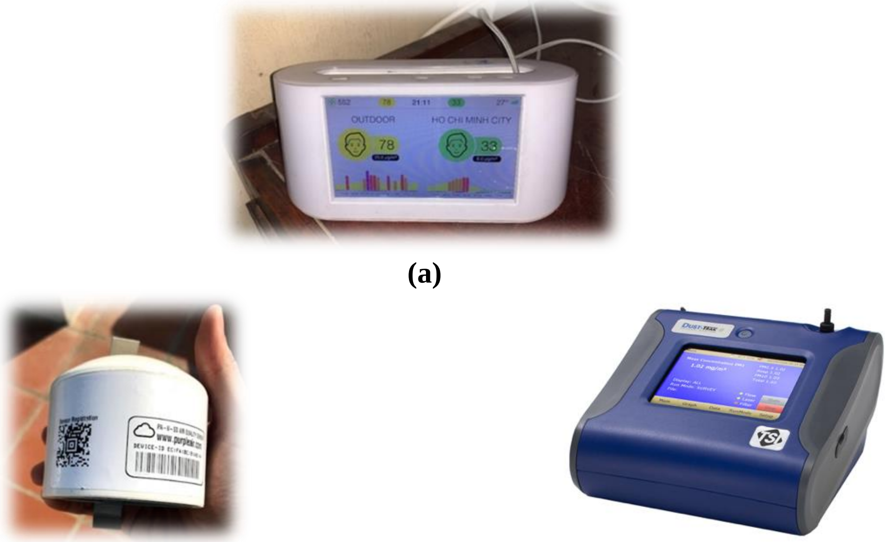
2. Methods

2.1. Data collection

2.1.1. Measuring indoor and outdoor $PM_{2.5}$ concentrations with low-cost sensors

Low-cost sensors

This study utilized two types of low-cost sensors, the AirVisual sensor and the PurpleAir sensor, to monitor indoor and outdoor $PM_{2.5}$ concentrations **(Figs. 1a, 1b)**. Both types of sensors operate based on optical principles (AirVisual, 2024, PurpleAir, 2024). The AirVisual sensors were employed for measuring indoor $PM_{2.5}$ levels, while the PurpleAir sensors were used for outdoor $PM_{2.5}$ measurements. Previous studies have indicated that both sensor types offer reliable data with good performance (Baron and Saffell, 2017, Morawska et al., 2018).



(a)

(b) **(c)**

Fig. 1. (a) AirVisual sensor used for indoor $PM_{2.5}$ measurements; (b) PurpleAir sensor used for outdoor $PM_{2.5}$ measurements; (c) Reference instrument, the DustTrak™ II Aerosol Monitor 8530

Reference instrument

In this study, the DustTrak™ II Aerosol Monitor 8530 was used to calibrate the low-cost sensors (**Fig. 1c**). The DustTrak is a real-time aerosol mass measurement device that functions based on optical principles (TSI, 2024).

Calibration strategies

The AirVisual and PurpleAir sensors were set up next to the DustTrak device (side-by-side) to simultaneously measure $PM_{2.5}$ concentrations at a residence in Binh Thanh District, Ho Chi Minh City, in April 2021. The calibration process was conducted under both indoor **(Fig. 2a)** and outdoor **(Fig. 2b)** conditions, with each condition lasting for 5 days. This setup and calibration process were described in our previous study (Tran et al., 2024).

Study Locations

After calibration, the sensors were installed in five houses in the urban areas of Bien Hoa city to measure $PM_{2.5}$ concentrations. The houses were labeled from S1 to S5 (**Table 1)**. $PM_{2.5}$ concentrations were measured in both indoor and outdoor environments at all the residences, except for house S3, due to a limited number of sensors. A total of five AirVisual sensors were used for indoor $PM_{2.5}$ measurements, and four PurpleAir sensors were used for outdoor $PM_{2.5}$ measurements.

We selected the five houses for $PM_{2.5}$ measurements following the air quality assessment guidelines for low-cost sensors outlined in the "Air Sensor Guidebook" by the United States Environmental Protection Agency, (Williams et al., 2014) as well as the World Health Organization's sampling methods for indoor air quality assessment (Organization, 2021). Additionally, we integrated insights from studies on indoor and outdoor $PM_{2.5}$ concentrations that utilized low-cost monitoring networks in the United States and China (Zhou et al., 2016, Hegde et al., 2020). All selected houses were single-story, ground-floor residences with natural ventilation and were occupied during the study period.

Monitoring strategies

Fig. 3 illustrates the indoor and outdoor environments of the five houses included in the study. Based on instructions from the Air Sensor Guidebook, the AirVisual sensors were installed in the living rooms of the houses at a height of 0.74 to 1.8 meters above the ground. The PurpleAir sensors were placed on the eaves in front of the houses, at a height of approximately 2.5 to 2.8 meters above the ground. The $PM_{2.5}$ measurement period lasted for nine months, from April 2021 to January 2022. On-site inspections were conducted weekly to ensure stable measurement conditions, and $PM_{2.5}$ data were collected weekly likewise.

(a)

(b)

Fig. 2. (a) Indoor calibration and (b) outdoor calibration settings with all AirVisual and PurpleAir sensors in a household during 10 days in April 2021

Fig. 3. Indoor and outdoor environments of five houses in Bien Hoa city, Vietnam

2.1.2. Questionnaires and time-activity logs

To gather basic information about the houses and factors affecting $PM_{2.5}$ concentrations, the study used questionnaires and time-activity logs. The questionnaire covered $PM_{2.5}$ knowledge, house conditions, daily activities, and socio-economic information. To ensure answer consistency, one member from each house completed the questionnaire at the beginning of the $PM_{2.5}$ measurement process, and another member completed it at the end. Time-activity logs tracked $PM_{2.5}$ emission sources, weather conditions, and ventilation features over time. During the first week, researchers visited each house to assist with the logs and provide instructions. Afterward, each house maintained its own logs, which were collected weekly along with the sensor data for $PM_{2.5}$.

2.2. Data analysis

2.2.1. Data calibration

Indoor and outdoor $PM_{2.5}$ concentrations from the low-cost sensors were calibrated in two stages (**Table S1**). Initially, 5-minute averages from the sensors were calibrated against those from the DustTrak device using simple linear regression. Each sensor was calibrated individually, and subsequent adjustments accounted for humidity effects based on established methods (Wu et al., 2005, Wu et al., 2022, Cong-Thanh et al., 2023).

After calibration, the data were checked for differential values, negative values, and invalid points, which were marked as "not available" (NA). Hourly and daily averages were then calculated and tested for completeness using the data recovery formula **(Formula 2.1)** (Polidori et al., 2017).

$$\text{Data recovery (\%)} = \frac{\text{N valid data}}{\text{N test period}}\ x\ 100\ (2.1)$$

Data recovery (%) represents the percentage of complete data, with $N_{valid\ data}$ *as the count of valid sensor readings and* $N_{test\ period}$ *as the total data points during the testing period.*

2.2.2. Descriptive statistics and hypothesis testing

The Shapiro-Wilk test was used to assess the normality of hourly and daily $PM_{2.5}$ concentrations, with data transformation applied when needed to approximate a normal distribution. The average daily $PM_{2.5}$ concentrations were summarized statistically and displayed in tables.

The connection between indoor and outdoor $PM_{2.5}$ concentrations was evaluated using the indoor/outdoor (I/O) ratio (Chen and Zhao, 2011), calculated with **Formula 2.2**:

$$\text{I/O ratio} = \frac{C_{in}}{C_{out}} \qquad (2.2)$$

The I/O ratio, defined as indoor (C_{in}) to outdoor (C_{out}) $PM_{2.5}$ concentrations (µg/m³), represents the relationship between the two.

A paired t-test was conducted to compare indoor and outdoor $PM_{2.5}$ concentrations for each household. ANOVA was used to investigate the differences among the five houses. The Pearson correlation coefficient was calculated to determine the correlation between indoor and outdoor $PM_{2.5}$ concentrations. Temporal variations were analyzed with the OpenAir package (version 2.8-1) in R (version 4.0.2). A 95% confidence level was applied to all tests.

2.2.3. Simple linear regression

The relationship between indoor and outdoor $PM_{2.5}$ concentrations was analyzed using a simple linear regression model with daily average data. The slope of the regression line represents the coefficient of penetration, indicating the fraction of outdoor $PM_{2.5}$ that remains suspended indoors (Chen and Zhao, 2011, Lv et al., 2017). **Formula 2.3** provides the regression equation. Analysis was conducted in R (version 4.0.2).

$$C_{in} = a + b * C_{out} \qquad (2.3)$$

Where C_{in} and C_{out} are indoor and outdoor $PM_{2.5}$ concentrations (µg/m³), a is the intercept, and b is the regression slope

3. Results and Discussion

3.1. Key Features of the Houses and Possible Sources of $PM_{2.5}$ emissions

All the houses were ground-floor structures with roof systems and natural ventilation. They had been constructed over 20 years ago, except for House S3, which was built in 2018 and was therefore relatively new compared to the others **(Table 1)**. Within a radius of about 15 meters, the five houses were located in small alleys in the inner city of Bien Hoa. In particular, besides the alleys to the houses, Houses S2 and S5 were distinct from the others due to their proximity to roads with two lanes in both directions and a speed limit of 20-30 km/h. The study also gathered information on activities within a 50-meter radius of the houses to identify potential sources of $PM_{2.5}$ emissions. The results indicated that the houses were close to markets, schools, pagodas, and street food stalls.

Houses S4 and S5 each had 3 residents, Houses S1 and S3 each had 5 residents, and House S2 had 6 residents **(Table 1)**. In all five houses, the main daily activities included smoking, burning incense, cooking, and cleaning, with gas used for cooking in each house **(Table 1)**. In comparison, Houses S2 and S3 had similar $PM_{2.5}$ emission activities, including burning incense (House S3), cooking (Houses S2 and S3), burning candles/oil lamps (House S2), and cleaning (Houses S2 and S3). In contrast, Houses S1, S4, and S5 exhibited a wider variety of daily activities and higher frequencies of these activities. Specifically, Houses S1 and S5 had the highest smoking frequency, which was not present in the other houses. Houses S1, S4, and S5 also had pets, unlike Houses S2 and S3. Additionally, House S1 burned coal in the yard for about 2 hours each morning, and House S4 burned charcoal and garbage in the yard 2-3 days a week. House S5 operated a street food stall in front of the house, where there were customers who smoked.

3.2. Indoor and outdoor $PM_{2.5}$ concentrations

3.2.1. Calibration results and data completeness

In the absence of standard reference equipment, the study used the DutsTrak device, a near-reference device (TSI, 2024), to calibrate the sensors according to the low-cost sensor calibration procedure outlined by the US EPA (Williams et al., 2014). All calibration models for the low-cost sensors were validated, with evaluation metrics falling within acceptable ranges **(Table S1)**. Following the guidelines (Williams et al., 2014), the low-cost sensors, once calibrated, are capable of effectively capturing the trend changes of $PM_{2.5}$. Furthermore, the calibration results, which were also presented in our previous studies (Tran et al., 2024), validated the reliability of the $PM_{2.5}$ measurements obtained from these low-cost sensors for subsequent analysis. In this study, indoor and outdoor $PM_{2.5}$ concentrations were recorded using low-cost sensors in five houses over a period of 295 days (from April 18, 2021, to January 20, 2022). To assess the completeness of the data, **Table 2** shows that, except for House S1, all four other houses had complete indoor and outdoor $PM_{2.5}$ data with less than 10% missing data. House S1 had only half the number of measurement days compared to the other houses due to a power supply issue. This incident occurred during the COVID-19 quarantine period, preventing timely inspection and repair by the researcher. Additionally, the percentage of complete outdoor $PM_{2.5}$ data for House S1 was only 56% because the memory card of the PurpleAir sensor failed to record sufficient data during the measurement period.

3.2.2. Variation in $PM_{2.5}$ concentrations: indoor-outdoor comparison and house-to-house differences

Indoor vs. Outdoor Concentrations

In general, the daily average outdoor $PM_{2.5}$ concentrations across the five houses varied between 26.1 and 38.2 μg/m³, while the daily average indoor $PM_{2.5}$ concentrations ranged from 21.7 to 40.6 μg/m³ **(Table 2)**. House S1 recorded the highest average indoor $PM_{2.5}$ concentration at approximately 41 μg/m³, whereas Houses S2 and S3 had the lowest at around 22 μg/m³ **(Table 2)**. This variation could be attributed to the construction age of the houses. A study showed that older houses tend to have higher $PM_{2.5}$ concentrations (Vo et al., 2022). House S1 in this study, constructed in 1990, was the oldest, whereas house S3, built in 2018, was the newest. The age of a house influenced its indoor $PM_{2.5}$ concentration for several reasons. Firstly, building materials in older homes might have emitted volatile organic compounds (VOCs) that contribute to $PM_{2.5}$ levels (Amato et al., 2014). For example, House S3, built in 2018, likely used modern materials with lower VOC emissions compared to House S1. Secondly, older homes like House S1 tended to accumulate more dirt over time due to the redeposition of dust particles (Amato et al., 2014).

The indoor and outdoor $PM_{2.5}$ concentrations measured in this study were lower than those reported in Hanoi by Tran et al (Tran et al., 2021), who found average daily concentrations of 52.1 ± 33.9 μg/m³ indoors and 54.4 ± 37.6 μg/m³ outdoors. This discrepancy may be attributed to due to two factors. First, as of 2024, Hanoi persisted as one of the most polluted cities in Vietnam (Vo et al., 2022). Second, the timing of the $PM_{2.5}$ measurements could also contribute to the differences. The authors conducted their study during a typical period in Hanoi (Tran et al., 2021), whereas this study was carried out during a period of heightened COVID-19 restrictions in Bien Hoa. During this time, restrictive measures, social distancing, and reduced traffic and socio-economic activities likely impacted $PM_{2.5}$ concentrations. In contrast, when compared to the outdoor $PM_{2.5}$ measurements (27.1 ± 11.9 μg/m³) from our previous study in Ho Chi Minh City during the COVID-19 quarantine period (2020-2021), which also utilized low-cost sensors, the outdoor $PM_{2.5}$ concentration in this study was roughly similar (Tran et al., 2024).

The study analyzed the differences in $PM_{2.5}$ concentrations between indoor and outdoor areas in each house. The findings showed a statistically significant difference in hourly $PM_{2.5}$ concentrations between indoor and outdoor environments in all houses ($p\text{-value} < 0.05$). However, when considering daily $PM_{2.5}$ concentrations, significant differences were observed in Houses S1, S2, and S5 ($p\text{-value} < 0.05$), while no notable difference was found between indoor and outdoor levels at House S4. This could be due to the lack of $PM_{2.5}$-emitting activities in the front yard of House S4, which resulted in a smaller discrepancy between indoor and outdoor $PM_{2.5}$ levels. In contrast, the other houses had several sources of $PM_{2.5}$ emissions in their front yards, where outdoor $PM_{2.5}$ was also monitored with low-cost sensors, leading to a more distinct difference between indoor and outdoor $PM_{2.5}$ levels.

House-to-House Differences

Table 2 and **Figs. 4a and 4b** display the daily average indoor and outdoor $PM_{2.5}$ concentrations across the five houses. The data indicated that the indoor and outdoor $PM_{2.5}$ concentrations in Houses S1 and S5 were higher than those in the other houses. This discrepancy was attributed to the more frequent daily activities in these houses, like smoking, cooking, cleaning, burning incense, and burning coal/charcoal. Both the daily indoor and outdoor $PM_{2.5}$ concentrations across the five houses complied with Vietnam's daily $PM_{2.5}$ standard (50 μg/m³). However, they surpassed the World Health Organization's 2020 standard (25 μg/m³) for both indoor and outdoor levels in Houses S1 and S5, and for outdoor levels in House S4 **(Fig. 4a)**. When compared to the standards of Taiwan, the United States, and Malaysia (35 μg/m³), Houses S1, S4, and S5 also exceeded the limit. In contrast, the I/O $PM_{2.5}$ ratio revealed variations in pollution sources. As shown in **Fig. 4b**, indoor $PM_{2.5}$ concentrations were higher than outdoor concentrations in Houses S1 and S5 (I/O ratio > 1), primarily due to frequent indoor activities such as incense burning and smoking. Conversely, Houses S2 and S4 had lower indoor concentrations (I/O ratio < 1), reflecting fewer indoor pollution sources and greater outdoor influence.

The study also analyzed the differences in indoor $PM_{2.5}$ concentrations across the five houses **(Table S2)**. It found that Houses S1 and S5 had similar indoor $PM_{2.5}$ levels, which were significantly higher than those in the other houses (p-value < 0.05). These houses were characterized by frequent activities contributing to higher $PM_{2.5}$, such as smoking, having pets, and burning incense. Conversely, Houses S2, S3, and S4 exhibited lower indoor $PM_{2.5}$ concentrations, with statistically significant differences compared to Houses S1 and S5 (p-value < 0.05), primarily due to fewer dust-emitting activities. Notably, Houses S2 and S3 had no smoking activities, and House S4 only had occasional incense burning.

For the differences in outdoor $PM_{2.5}$, two distinct groups were identified. Houses S1 and S5 had significantly higher outdoor $PM_{2.5}$ concentrations compared to Houses S2 and S4 (p-value < 0.05) **(Table S3)**. The elevated outdoor $PM_{2.5}$ concentrations in Houses S1 and S5 were attributed to key daily activities like coal burning and smoking in front of the yards, near the outdoor measurement sites. In contrast, House S4 experienced lower concentrations due to less frequent charcoal and garbage burning in a larger yard, while House S2 had no significant outdoor $PM_{2.5}$ sources.

3.3. Changes over time in indoor and outdoor $PM_{2.5}$ concentrations

3.3.1. Indoor $PM_{2.5}$ variations

Diurnal patterns

The indoor $PM_{2.5}$ concentrations in all five houses generally exhibited two peaks, including a primary peak around 6 a.m. and a secondary peak around 6 p.m. **(Fig. 5a)**. These peaks were notably pronounced in Houses S1 and S4, which experienced activities like incense burning and coal burning at these times. Diary records indicated that up to half of the residents in House S1 smoked regularly indoors, contributing to significantly higher $PM_{2.5}$ concentrations compared to other homes **(Fig. 5a, Table 2)**. House S5 also showed increased $PM_{2.5}$ concentrations, attributed to one-third of its residents smoking. The findings in this study, consistent with research from China and Vietnam, demonstrated that smoking and incense burning significantly contributed to indoor $PM_{2.5}$ levels. (Tran et al., 2021, Zhang et al., 2021). Conversely, House S2 had lower $PM_{2.5}$ levels despite showing the same two-peak pattern, as it lacked significant $PM_{2.5}$ emission sources. Additionally, House S5 displayed three distinct sub-peaks in the evening $PM_{2.5}$ concentrations, specifically, the first at 3 p.m., likely due to smoke from nearby eateries; the second at 6 p.m., associated with incense burning; and the third at 9 p.m., related to exhaust smoke from daily bagasse burning in front of the house.

Days of the week

Examining changes in indoor $PM_{2.5}$ concentrations by weekday, **Fig. 5b** illustrates a noticeable difference between weekdays and weekends across the five houses. Generally, the trend was consistent, specifically, $PM_{2.5}$ concentrations increased from Monday to Thursday and then began to decrease from Friday to Sunday. This weekend reduction on weekends might be due to fewer indoor activities, potentially lowering dust concentrations. However, this hypothesis remained speculative due to limited information on the weekend activity habits of the residents in all five houses.

Months

Fig. 5c displays the monthly fluctuations in indoor $PM_{2.5}$ concentrations, indicating that the peak values were observed in April and November, corresponding to the dry season. From May, concentrations decreased sharply, reaching their lowest in July and August (the rainy season), and then began to rise again starting in October. This trend emphasized the impact of local emission sources and climatic conditions on the temporal fluctuations of indoor $PM_{2.5}$ concentrations (Vo et al., 2022). All houses used natural ventilation systems. When the front door and windows were open, indicating natural ventilation conditions, outdoor $PM_{2.5}$ levels tended to decrease during the rainy months, possibly due to wet deposition from rainfall (Hoa, 2023), which could also contribute to a decrease in indoor $PM_{2.5}$ levels. In contrast, outdoor $PM_{2.5}$ concentrations typically rose during the dry months, leading to a corresponding increase in indoor $PM_{2.5}$ levels.

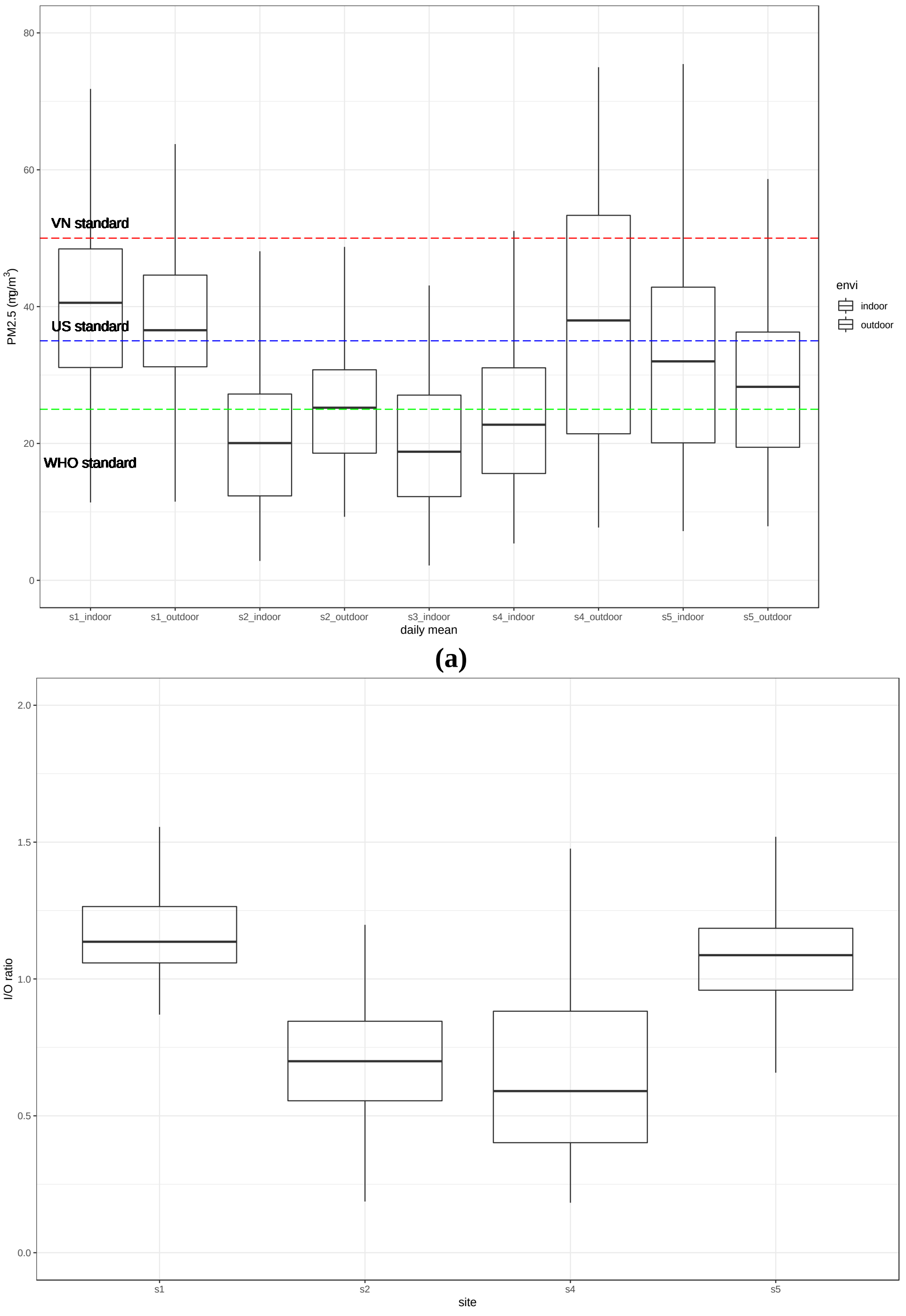
Table 1. Summary of basic characteristics of five houses in the urban areas of Bien Hoa city and their primary $PM_{2.5}$ emission activities

	House S1	**House S2**	**House S3**	**House S4**	**House S5**
Coordinates	10°57’6’’N, 106°48’46”E	10°57’57”N, 106°50’12”E	10°58’58”N, 106°51’21”E	10°55’2”N, 106°49’3”E	10°57’29”N, 106°52’26”E
Location	Quang Vinh District	Tan Phong District	Trang Dai District	Buu Hoa District	Tan Hiep District
Year of construction	1990	1998	2018	1992	1992
Area (m^2)	75	90	175	150	175
Number of residents	6	6	6	3	3
Proximity to roads	No	Yes	No	No	Yes
Surrounding environment	Restaurant	Restaurants, markets, pagodas	Residential Area	Old stone vaults, vegetation	Restaurants, markets
Pets	Yes	No	No	Yes	Yes
Smoking	Yes	No	No	No	Yes
Incense burning	2 times/day	No	1 time/day	2 times/day	1 time/day
Coal/charcoal burning	1 time/day	No	No	3-6 times/week	No
Burning garbage/bagasse	No	No	No	1-2 times/week	1 time/day
Cooking	More than 3 times/day	2 times/day	2 times/day	2 times/day	1 time/day
Candles/oil lamps burning	1-3 times/month	1 time/day	No	1 time/day	No
Cleaning	Daily	Daily	Daily	Weekly	3-6 times/week

Table 2. Statistics of daily averages of indoor and outdoor $PM_{2.5}$ concentrations and Indoor/Outdoor $PM_{2.5}$ ratios (I/O ratios) in five houses in Bien Hoa city from April 2021 to January 2022 (Unit: µg/m³)

	House S1			**House S2**			**House S3**			**House S4**			**House S5**		
	Indoor	**Outdoor**	**I/O ratio**	**Indoor**	**Outdoor**	**I/O ratio**	**Indoor**	**Outdoor**	**I/O ratio**	**Indoor**	**Outdoor**	**I/O ratio**	**Indoor**	**Outdoor**	**I/O ratio**
N (days)	177	123	123	295	278	278	253	–	–	295	278	278	294	277	277
% missing	6.8	56.1	56.1	3.1	6.1	12.6	7.5	–	–	3.1	5.0	11.5	4.4	2.9	10.9
Minimum	11.4	9.7	0.87	2.8	9.3	0.19	2.2	–	–	5.4	7.7	0.18	7.2	7.9	0.66
Maximum	85.7	63.8	1.83	122.4	56.2	1.41	81.5	–	–	81.3	86.5	3.10	106.9	58.7	1.76
Mean	40.6	37.9	1.18	21.8	26.1	0.71	21.7	–	–	25.0	38.2	0.66	33.4	28.3	1.09
SD	14.4	10.7	0.20	13.6	9.8	0.20	13.6	–	–	12.6	18.2	0.35	16.4	11.8	0.00
Median	40.7	36.6	1.14	20.1	25.2	0.70	18.8	–	–	22.9	38.2	0.59	32.5	28.3	1.09
IQR	17.6	13.4	0.21	15.0	12.2	0.29	14.9	–	–	15.5	32.1	0.48	22.8	16.8	0.23
Correlation between indoor and outdoor	**0.87***			**0.96***			**–**			**0.79***			**0.84***		

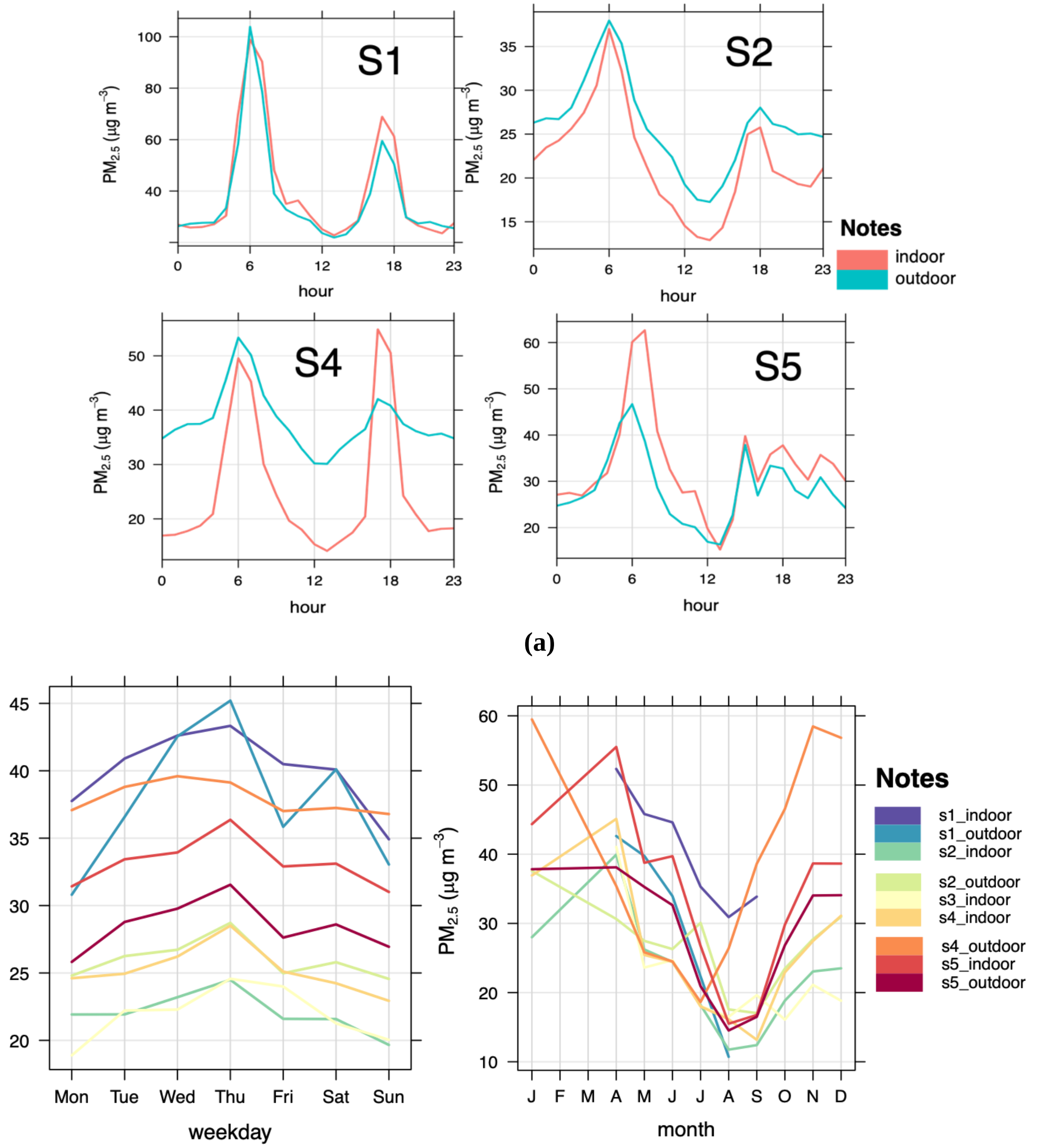
* p-value < 0.0



(a)

(b)

Fig. 4. Box plot illustrating (a) the daily average indoor and outdoor $PM_{2.5}$ concentrations, and (b) the Indoor/Outdoor ratios (I/O ratios) of daily $PM_{2.5}$ averages for five houses in Bien Hoa city, from April 2021 to January 2022



(a)

(b) **(c)**

Fig. 5. Temporal variations of indoor and outdoor $PM_{2.5}$ concentrations by (a) diurnal patterns, (b) days of the week, and (c) months in five houses in Bien Hoa city, during April 2021 to January 2022

3.3.2. Effects of the COVID-19 Lockdown on $PM_{2.5}$ Levels

Fig. 6 presents the weekly average $PM_{2.5}$ concentrations, both indoors and outdoors, for the five households between April 2021 and January 2022. As the Vietnamese government issued and adjusted COVID-19 measures on a weekly basis, the study illustrates the corresponding weekly variation in $PM_{2.5}$ levels. The COVID-19 distancing and lockdown measures were implemented by the authorities in Bien Hoa city from April to September 2021.

Outdoor $PM_{2.5}$ Concentrations

Before the lockdown, from April to June, outdoor $PM_{2.5}$ concentrations remained relatively stable, ranging from 20 to 60 µg/m³, reflecting typical pre-pandemic conditions. The period from July to September coincided with the implementation of strict lockdown measures. During this time, outdoor $PM_{2.5}$

concentrations decreased sharply to below 20 μg/m³, with a notable low of less than 10 μg/m³, representing a dramatic tenfold reduction from the peak values observed in April (**Fig. 6**). This significant drop is consistent with findings from our previous study (Tran et al., 2024) which observed similar reductions in Ho Chi Minh City during the COVID-19 period. The decrease in $PM_{2.5}$ levels during the lockdown can be attributed to various factors, such as the closure of discotheques, bars, karaoke establishments, night markets, cinemas, and the suspension of indoor sports activities. Furthermore, restrictions on gatherings and the closure of schools from 17 May 2021 likely led to a significant reduction in outdoor pollution sources. During this unique period, outdoor $PM_{2.5}$ concentrations were likely comparable to indoor $PM_{2.5}$ concentrations in all the houses, except for House S4, where cooking activities had been moved from the kitchen to the balcony at the front of the yard near the outdoor sensor, as discussed in **section 3.3.1**.

Indoor $PM_{2.5}$ Concentrations

During the COVID-19 period, the effect on indoor $PM_{2.5}$ concentrations varied depending on household activities, as people spent more time at home, potentially leading to increased indoor emissions from cooking, heating, and other daily activities. However, despite the increase in indoor activities during this period, indoor $PM_{2.5}$ concentrations also declined, underscoring the significant impact of outdoor $PM_{2.5}$ on indoor $PM_{2.5}$ concentrations. For instance, indoor $PM_{2.5}$ concentrations in Houses S2 and S3 decreased sharply to about 6 μg/m³ (**Fig. 6).**

Moreover, **Figs. S1 to S5** illustrate that the daily indoor and outdoor $PM_{2.5}$ concentrations in all five houses during the study period were above the World Health Organization's 2020 guideline for daily $PM_{2.5}$ levels (25 μg/m³), even during the COVID-19 lockdown in Bien Hoa City (July 2021 – September 2021). Specifically, in Houses S1 and S5, daily indoor and outdoor $PM_{2.5}$ concentrations exceeded the WHO standard on approximately half of the days throughout the study.

The lockdown measures were lifted in October 2021, leading to a gradual increase in $PM_{2.5}$ concentrations. This resurgence aligns with the findings of (Bui et al., 2022), who noted an increase in $PM_{2.5}$ levels in Bien Hoa city during the "new normal" conditions. The reactivation of business and industrial activities contributed to the resurgence of $PM_{2.5}$ levels, highlighting the link between economic activity and air quality.

3.4. Correlation Between Indoor and Outdoor $PM_{2.5}$ Levels

3.4.1. Indoor-to-outdoor $PM_{2.5}$ concentration ratios

The daily average $PM_{2.5}$ concentrations differed between indoor and outdoor environments across the four houses (excluding House S3), resulting in two distinct categories of indoor-to-outdoor (I/O) ratios: those below 1 and those above 1 (**Table 2, Fig. 4b**). In Houses S1 and S5, where the I/O ratios exceeded 1, activities such as smoking and incense burning were key contributors to higher indoor $PM_{2.5}$ levels. This observation is in line with a study conducted across 68 homes in four major Chinese cities, where households engaged in cooking and burning activities exhibited an average I/O ratio of 1.42 (Lv et al., 2017). On the other hand, Houses S2 and S4, where fewer dust-producing activities were reported, showed I/O ratios below 1 (**Table 2, Fig. 4b**), suggesting that outdoor $PM_{2.5}$ was more likely to enter the indoor spaces. The lower I/O ratio in House S2 may be attributed to fewer indoor sources of $PM_{2.5}$, while the low ratio of House S4 could be linked to improved air quality from nearby greenery. These findings support the idea that effective natural ventilation can reduce indoor $PM_{2.5}$ concentrations by allowing more outdoor air to enter. Nevertheless, the higher I/O ratios observed in Houses S1 and S5 underscore the need to consider various factors, including indoor emission sources, outdoor pollution levels, and ventilation, when examining the indoor-outdoor $PM_{2.5}$ relationship.

Fig. 7 presents the I/O $PM_{2.5}$ ratios for the four houses, revealing marked differences in the relationship between indoor and outdoor $PM_{2.5}$ concentrations from April 2021 to January 2022. Notably, Houses S1 and S5 displayed higher I/O ratios, particularly during certain weeks, where the ratios often exceeded 1. This indicates that indoor $PM_{2.5}$ levels were consistently higher than outdoor levels. Such elevated indoor concentrations suggest the presence of significant indoor sources of $PM_{2.5}$, including smoking, incense burning, and pets, which were previously identified as contributing factors to indoor air pollution. In contrast, Houses S2 and S4 generally showed I/O ratios below 1, where outdoor $PM_{2.5}$ concentrations surpassed indoor levels, indicating minimal indoor pollution sources. Moreover, the trend lines for most houses show that the I/O $PM_{2.5}$ ratios dropped significantly during certain periods (likely during the COVID-19 lockdown) and then gradually increased as the lockdown measures were lifted. These variations highlight the influence of both household activities and the effectiveness of ventilation systems on the I/O ratio, emphasizing the need for tailored strategies to manage indoor air quality depending on the specific conditions of each household.

3.4.2. Analysis of the Correlation and Linear Relationship Between Indoor and Outdoor $PM_{2.5}$ Concentrations

To evaluate the relationship between indoor and outdoor $PM_{2.5}$ concentrations across the four houses (excluding House S3), correlation coefficients and simple linear regression models were applied (**Table 2, Fig. 8**). The analysis revealed a robust linear correlation between indoor and outdoor $PM_{2.5}$ levels in all houses, with correlation coefficients ranging from 0.79 to 0.96, all statistically significant ($p\text{-value} < 0.05$). This indicates a strong link between $PM_{2.5}$ concentrations in the two environments. The linear regression results showed positive relationships between indoor and outdoor $PM_{2.5}$ levels in all cases (**Fig. 8**). Regression models for Houses S1, S2, and S5 demonstrated strong predictive power, with R^2 values ranging from 0.75 to 0.90 ($p\text{-value} < 0.05$), suggesting these models effectively captured the variation in indoor $PM_{2.5}$ concentrations driven by outdoor levels. The slope coefficients for these houses, ranging from 0.90 to 1.22, indicate that fluctuations in outdoor $PM_{2.5}$ levels significantly influenced indoor concentrations. In contrast, the regression model for House S4 performed poorly, with an R^2 of just 37% and a slope coefficient of 0.38, reflecting a weaker association between indoor and outdoor $PM_{2.5}$ levels. This suggests that indoor $PM_{2.5}$ concentrations in House S4 were less affected by changes in outdoor levels compared to the other houses. The differences in sensitivity to outdoor $PM_{2.5}$ among the houses may stem from varying factors such as ventilation systems, the presence of indoor emission sources, or the use of different construction materials.

The most significant scientific contribution of this study lies in being the first to evaluate the relationship between indoor and outdoor $PM_{2.5}$ levels in selected households within the urban area of Bien Hoa City, using low-cost sensors over nearly a year. Notably, the study conducted $PM_{2.5}$ monitoring in these households during the unique period of COVID-19 control measures in the city, providing valuable insights into the variations in $PM_{2.5}$ levels in urban households during this time.

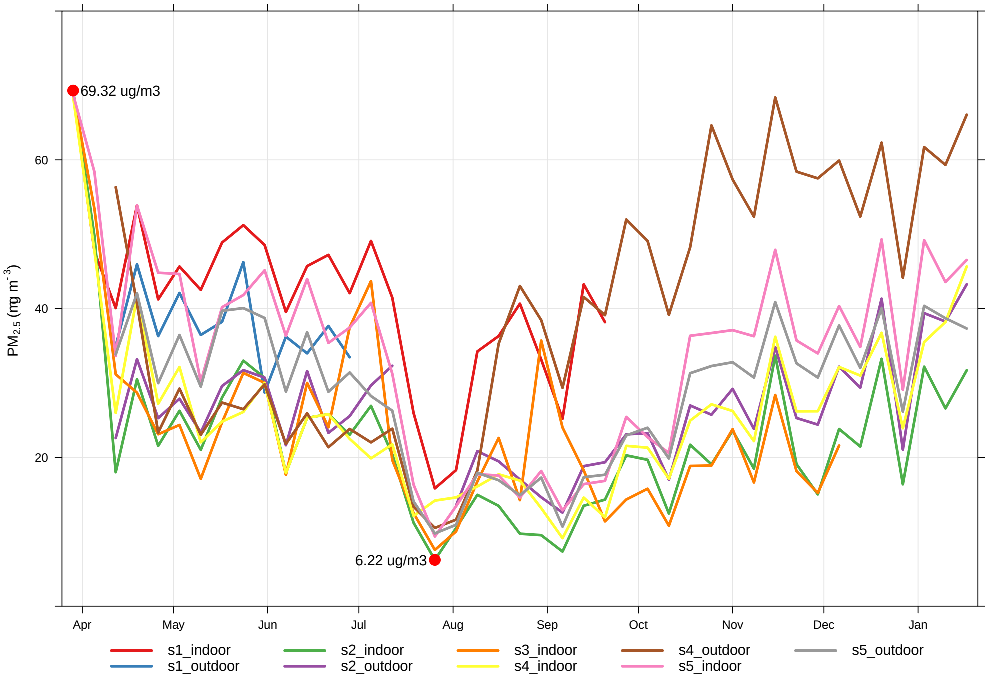


Fig. 6. Weekly averages of indoor and outdoor $PM_{2.5}$ concentrations in five houses in Bien Hoa city, during April 2021 to January 2022

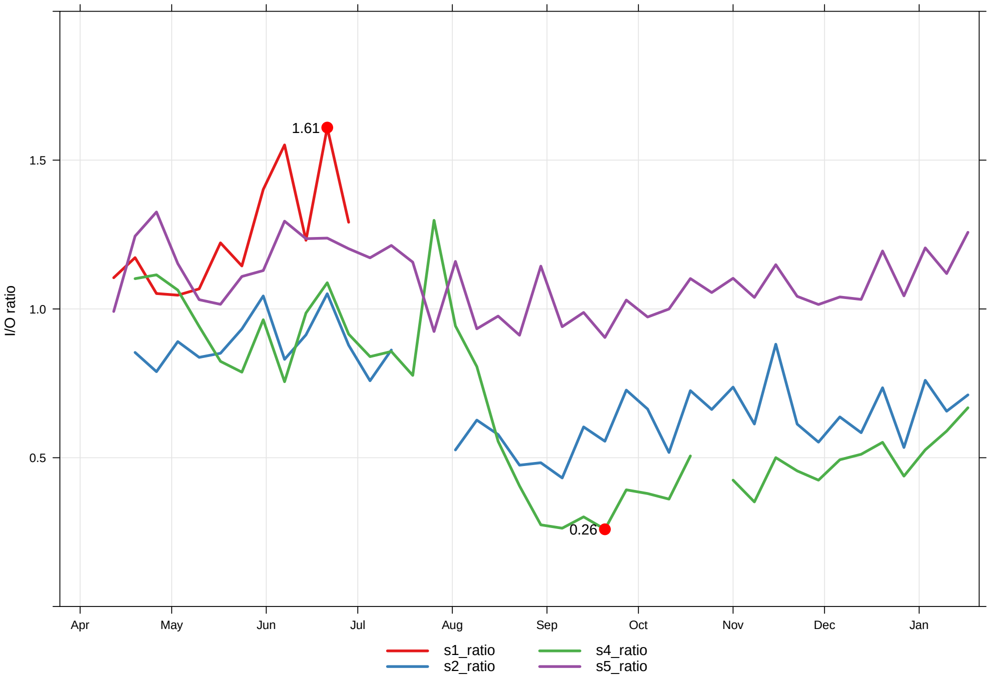


Fig. 7. Weekly averages of Indoor/Outdoor $PM_{2.5}$ ratios in four houses (excluding House S3) in Bien Hoa city, during April 2021 to January 2022

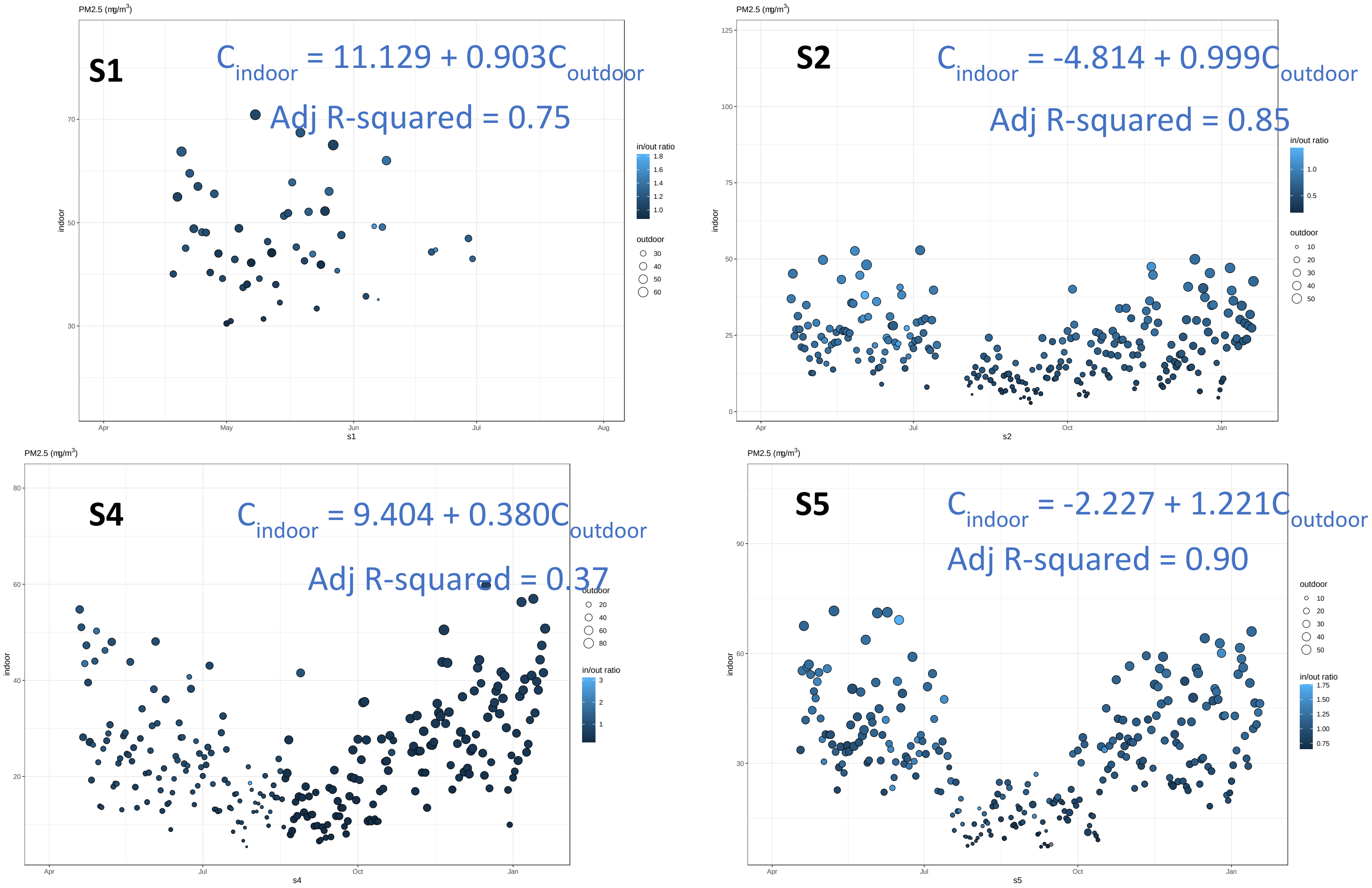


Fig. 8. Scatter plots and linear regression analyses of the daily average $PM_{2.5}$ concentrations, both indoor and outdoor, in four houses (excluding House S3) in Bien Hoa city during the period from April 2021 to January 2022

4. Conclusions

Over a nine-month period, the research examined variations in indoor and outdoor $PM_{2.5}$ concentrations across five households. Notably, this is the first investigation in Bien Hoa City to simultaneously measure $PM_{2.5}$ levels both indoors and outdoors at the household level, with a focus on the unique context of the COVID-19 lockdown. The findings uncovered distinct patterns and trends shaped by factors such as household activities, the age of house construction, and the influence of pandemic-related restrictions. The average daily $PM_{2.5}$ concentrations ranged from 21.67 to 40.55 µg/m³ indoors and 26.07 to 38.22 µg/m³ outdoors. $PM_{2.5}$ concentrations peaked around 6 a.m. and 6 p.m., particularly in homes with smoking, incense burning, coal/charcoal burning, and garbage burning. Levels were higher on weekdays and lower on weekends. Variations between homes were driven by indoor activities, local emissions, and sensor placement. Houses S1 and S5 had high indoor-to-outdoor $PM_{2.5}$ ratios, suggesting significant indoor sources of $PM_{2.5}$. In contrast, Houses S2 and S4 showed lower ratios, likely due to fewer indoor $PM_{2.5}$ emission sources and better ambient air quality from nearby vegetation. The study highlights the effectiveness of low-cost sensors for tracking $PM_{2.5}$ trends and suggests their potential for broader monitoring. Expanding their use could provide valuable data for exposure assessments and help develop improved air quality standards in Vietnam.

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