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Indoor Fine Particle Pollution in High-Rise Apartments in Hanoi

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Abstract

The study focuses on clarifying the fluctuations of indoor fine particle concentrations under different conditions and identifying the main factors contributing to this exposure. The light scattering method (by using ATMOtube real-time monitor) was evaluate by comparing it with the gravimetric reference method (by using MiniVol TAS 5.0 for sampling and weighing under our Lab conditions). The two methods were first tested according to standard procedures to ensure its stability and accuracy, next implemented simultaneously for comparison, and then the light scattering method was applied to 14 apartments in Hanoi for 24 hours, recording $PM_{2.5}$ and PM_{10} concentrations. The research results show that: 1) $PM_{2.5}$ and PM_{10} concentrations are similar, proving that the indoor particulate matter is mainly $PM_{2.5}$; 2) the levels of fine particle $PM_{2.5}$ pollution in high-rise apartments in Hanoi is at alarming levels, which are much higher than the WHO recommended levels. The main influencing factors such as residential area location associated with outdoor environmental conditions (density of traffic and construction activities), living habits (opening windows, smoking, using gas stoves), and the presence of fine particle reduction equipment were carefully analysed. The study results also demonstrate the effectiveness of using air purifiers in controlling indoor fine particle, helping to maintain a more stable environment during the day and night.

Keywords: Fine particle, indoor air pollution, $PM_{2.5}$, PM_{10}, Hanoi.

1. Introduction

Particulate matter (PM) pollution has become a significant threat to both human health and the environment, especially in rapidly urbanizing areas in developing countries. Among these particles, $PM_{2.5}$ is of particular concern due to its fine size, which allows it to penetrate deep into the respiratory system, leading to a range of health issues, including cardiovascular diseases, respiratory illnesses, and even lung cancer. A study by Van Donkelaar *et al.* [1] combining satellite data, ground observations, and atmospheric models, has shown that regions such as South Asia, East Asia, and the Middle East are most severely affected by $PM_{2.5}$ and PM_{10} pollution, with concentrations far exceeding the World Health Organization (WHO) recommended levels [2].

The relationship between outdoor and indoor PM concentrations is critical, as fine particle, such as $PM_{2.5}$, from outdoor sources can easily infiltrate indoor spaces through windows, doors, ventilation systems, and structural gaps. Furthermore, indoor activities such as cooking, especially with gas stoves or at high temperatures, smoking, burning candles or incense, using coal-fired heaters, and frictional activities like sweeping or walking on carpets contribute significantly to indoor PM concentrations. Besides, household products such as paints, cleaning chemicals, or improperly maintained equipment (such as vacuum cleaners without effective filters) also contribute to the emission of fine particle. When this source combines with fine particle coming in from outside, the indoor air pollution can be serious, directly affecting the health of residents.

Recent study of Reategui-Inga *et al.* has found that indoor $PM_{2.5}$ concentrations typically ranged from 10–100 µg/m³, depending on the emission source and outdoor air quality [3]. In particular, in areas where biomass is used for cooking, $PM_{2.5}$ concentrations can exceed WHO's safety limits. In school environment, PM_{10} concentrations can reach 50–150 µg/m³, especially in the humid condition that increases the ability of particles to spread from soil and student footwear. About 80% of studies show that $PM_{2.5}$ and PM_{10} concentrations are within the WHO's recommended limits, however, in the areas of poor ventilation or high traffic sources, levels exceeding the threshold is often recorded. In Southeast Asian countries, indoor $PM_{2.5}$ concentrations frequently exceed the safety limit. Namely, in Jakarta, indoor $PM_{2.5}$ has average concentrations of 30–45 µg/m³, while in rural areas, where biomass such as firewood and honeycomb charcoal are often used for cooking, indoor $PM_{2.5}$ concentrations can rise to 60–90 µg/m³. In Bangkok, average indoor $PM_{2.5}$ concentrations are 25–35 µg/m³, higher levels are recorded in the dry season when outdoor particles easily penetrate indoors [4]. Cooking with biomass fuels is a major contributor to the increased indoor $PM_{2.5}$ concentrations in Southeast Asia, occupying up to 70–80% of total fine particle concentrations. In the

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households that use gas or electric stoves, fine particle concentrations are lower but still ranging from 15–25 µg/m³ [5, 6].

Hanoi is one of the cities facing the most serious fine particle pollution in Southeast Asia. Namely, in 2020, the average outdoor $PM_{2.5}$ concentration in the city is recorded at about 47µg/m³, nearly 9 times higher than the WHO's recommended level (5 µg/m³) [7, 8]. In the serious pollution periods, $PM_{2.5}$ concentrations can reach 150 µg/m³, seriously affect people's health. Not only outdoor pollution, but indoor pollution is also become alarming in Hanoi. From outdoors, fine size PMs easily penetrate living spaces through ventilation systems, door cracks, as well as window openings. According to a study of Nguyen Duc Luong *et al.* during the Covid-19 period, indoor $PM_{2.5}$ concentrations ranged from 16–36 µg/m³, exceeding the WHO's recommended limit for daily concentration (5 µg/m³) [9]. In particular, in low-rise apartments that are near traffic routes, $PM_{2.5}$ concentrations during rush hours can reach 123.2 µg/m³, many times higher than the WHO's recommended limit. Long-term exposure to fine particle increases the risk of respiratory diseases such as pneumonia, asthma, chronic obstructive pulmonary disease as well as cardiovascular diseases. Children and elderly people are the two most vulnerable groups. Another study also showed that every 10 µg/m³ increase in $PM_{2.5}$ concentration may increase the risk of hospitalization for respiratory diseases and cardiovascular disease by 0.7% and 0.5–4%, respectively [10, 11].

There is currently a lack of comprehensive information on indoor air quality in Vietnam, especially in high-rise buildings where fine particle exposure is a growing concern. Chronic respiratory diseases like asthma and Chronic Obstructive Pulmonary Disease (COPD) are strongly associated with long-term exposure to $PM_{2.5}$ [12]. While global solutions such as air purifiers, ventilation systems, and negative air ion technology have been explored to address indoor air pollution, their effectiveness in the context of Vietnam remains under-explored. These technologies each have their own advantages and limitations, and their suitability for local conditions needs to be further studied. In response to this research gap, this study aims to monitor and evaluate indoor PM levels, especially fine particle $PM_{2.5}$, in high-rise apartments in Hanoi. Effectively controlling indoor air quality requires both minimizing the infiltration of outdoor particles and reducing indoor sources of the particles pollution. The findings of this study will provide a foundation for developing targeted strategies to reduce indoor fine particle pollution and improve the overall quality of life for urban residents.

2. Research Method

Differences in the level of PM pollution between areas in Hanoi have been clearly indicated in the study of Nguyen T. Trung *et al.* [13], reflecting the impact of geographical location, traffic density, and regional structure. Concentrations of $PM_{2.5}$ and PM_{10} at the positions located near high traffic roads, especially areas near belt roads and intersections, were higher than ones at the positions located in urban core area.

2.1. Monitoring Sites

Based on above target, our study focuses on measuring fine particle in high-rise apartments under different conditions, mainly located in Royal City urban area, in order to reflect the pollution characteristics of middle-class high-rise residential areas in Hanoi. Royal City is next to Nguyen Trai Street and Truong Chinh Street, that often experience traffic jams (Fig. 1).

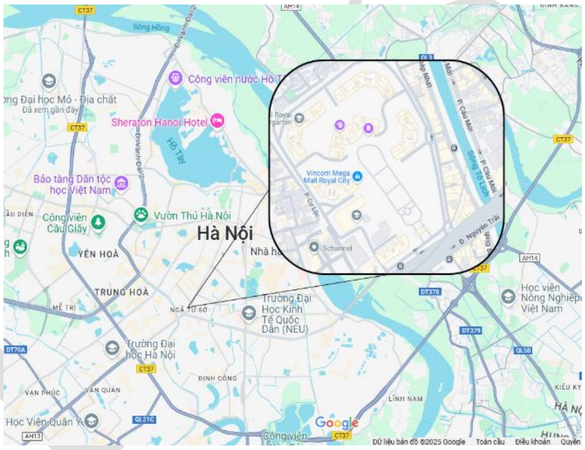

Fig.1. Location of the main research area

2.2. Monitoring Positions

In order to determine the differences in PM concentrations according to the generation sources, the research subjects were classified into two groups: group No.1 includes apartments equipped with air purifiers (denoted as N1.1, N1.2…); group No.2 includes apartments without air purifiers (denoted as N2.1, N2.2…). Each group then was divided into two subgroups: subgroup denoted by Pet includes apartments with pets (for example N1.1Pet if apartment N1.1 has pets); subgroups denoted by NPet includes apartments without pets (for example N1.2NPet if apartment N2.2 has no pets). To minimize measurement errors due to differences between research conditions, the study focused on the apartments with similar conditions in geographic location, ventilation level, and daily activities. This approach helps to ensure the accuracy and representativeness of research results, simultaneously clarify factors that affect indoor $PM_{2.5}$ and PM_{10} concentrations.

2.3. Monitoring Methods

The light scattering method (using ATMOtube real-time monitor) was applied to apartments in Hanoi for recording $PM_{2.5}$ and PM_{10} concentrations. The gravimetric method (using MiniVol TAS 5.0 sampler) was used as a reference method. Specifically, the two methods were first tested according to standard procedures to ensure its stability, then implemented simultaneously to assess ATMOtube's accuracy and adjust it's readings, if necessary, before application as follows.

- *Gravimetric method*: The SOP (standard of operation procedure) was developed based on AS/NZS 3580.9.6:2003 for PM_{10} and $PM_{2.5}$;

- *Particle light scattering method*: Real-time measurement by sensor with automatic calibration.

2.4. Equipment/Instruments

Both devices can measure indoor and ambient air quality. The MiniVol TAS 5.0 is used for 24 hour-sampling with filtered paper and weighing by a 5-digit analytical balance under our Lab conditions while the ATMOtube is convenient instrument with sensors for $PM_{2.5}$, PM_{10} at atmospheric temperature and humidity. The ATMOtube requires validation before usage with the MiniVol TAS 5.0 being the reference method.

The implementation procedure includes steps of preparation, measurement and data collection, analysis, and results evaluation (Fig. 2). Firstly, two types of PM measuring devices were tested for its' stability according to the SOP at the Environmental Monitoring and Pollution Control Center, at the Hanoi University of Science and Technology. A gravimetric method using the MiniVol TAS 5.0 being the reference method to validating the ATMOtube before usage. The difference between measurement results of the two devices was monitored. Then, the ATMOtube was applied to the apartments throughout 24 hours, recording parameters and displaying $PM_{2.5}$ and PM_{10} concentrations over time.

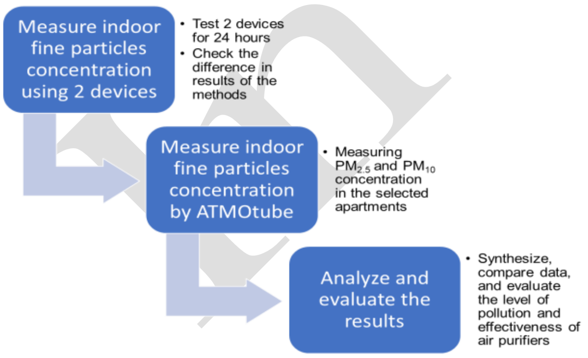

Fig. 2. Research steps

2.5. Indoor Sampling Design

The indoor monitor was placed in the center of the living (common) room of the apartment about 1.3–1.5 m above the floor which corresponds to the breathing zone. All the apartments tested with around 80 m^2 of area which is about 32 m^2 for common room, the sampler was at least 1 m away from any obstacle.

2.5.1. Indoor PM measurement method for MiniVol TAS 5.0

Filter paper preparation: 47 mm filter papers (the blank sample also prepared together for QC control). Before sampling, filter papers were placed in Petri dishes, dried at 60 °C for 4 hours (lid slightly open), and stabilized in a desiccator for 24 hours. Each filter was weighed three times using an electronic balance, with the final mass recorded once it remained stable for 10 seconds. The filters were then stored in labeled, foil-wrapped Petri boxes inside the desiccator.

Three prepared Petri boxes were packed in Ziplock bags and brought to the field; the laboratory blank (LBS) was retained. All necessary equipment was prepared, including two MiniVol TAS 5.0 samplers for $PM_{2.5}$ and PM_{10}, and tools to measure wind speed, temperature, and humidity

At the sampling site, the collectors were cleaned and coated with vaseline. A field blank sample (FBS) was collected by placing a filter in the device for 10 minutes without running the sampler. It was then wrapped, labeled, and stored.

For actual sampling, filters were inserted into the MiniVol samplers, which were adjusted to a 5 L/min flow rate. The start time was recorded, and the flow was checked every 30 minutes to ensure stability.

After sampling, the filters were dried at 60 °C for 4 hours and stabilized in the desiccator for another 24 hours. All filters (LBS, FBS, $PM_{2.5}$, PM_{10}) were reweighed using the same procedure. The data were recorded for later analysis and used to calculate PM concentrations in indoor air.

2.5.2. Indoor PM measurement method for ATMOtube

The ATMOtube device (Fig. 3) was used to monitor real-time air quality, specifically focusing on $PM_{2.5}$ and PM_{10} concentrations. The ATMOtube application was first installed on a smartphone to enable synchronization with the ATMOtube via Bluetooth. Once a stable power supply and connection were established, the device automatically began recording data. To ensure accuracy, measurements taken during the first 30 minutes were excluded, allowing the device to reach operational stability. The monitoring process continued for 24 hours, after which all data were exported for analysis. Raw data were cleaned by removing outliers and unstable values, then normalized to standard units (µg/m³) and categorized into time intervals (e.g., hourly or daily). The processed data were analyzed using tools such as Excel, SPSS, or Python to calculate descriptive statistics and assess pollution trends. Results were visualized using graphs and tables, providing insights into air

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quality variations and supporting recommendations for environmental improvement.

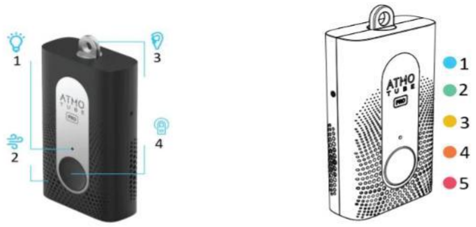

Fig. 3. ATMOtube device

Notes: (1) – Multi-coloured LEDs indicate the current Air Quality Score (AQS); (2) – Air mesh: air is directed through holes outside of the device; (3) – Carabiner button (can be used as a hanger); (4) – Start button: press the button to view the current AQS - represented by the colour of LEDs on the device. The LED light colour represents the current AQS, from Red (seriously polluted) to Blue (clean).

3. Result and Discussion

3.1. Verification of ATMOtube Measurements

As testing results for verifying the stability of the MiniVol TAS 5.0 after processing the measurement data, the average concentrations of $PM_{2.5}$ and PM_{10} were 52 µg/m³ and 54 µg/m³, respectively. The testing results for verifying the stability of the AUTOtube is shown in Fig. 4. The sampling location for stability testing is an apartment located close to roads and intersections.

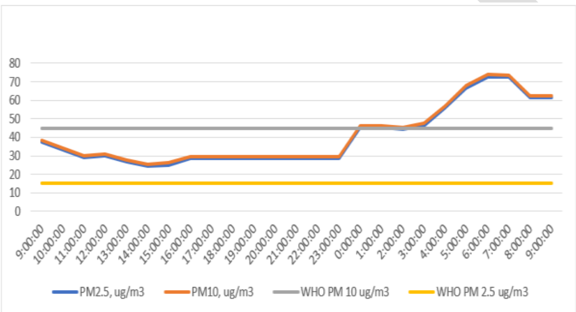

Fig. 4. Concentrations of $PM_{2.5}$ and PM_{10} measured by ATMOtube

Then, we conducted parallel measurements using both devices in certain apartments (Table 1 shows average 24-hour PM values from multiple sampling days under similar conditions), thereby determining average differences between the two measurement methods. In all the areas, compared to the MiniVol TAS 5.0, the AUTOtube always gave the lower results, for example, ranging from 10% to 20% lower in the case of $PM_{2.5}$. In the alley, for $PM_{2.5}$, the largest difference was recorded at 19.5%, showing that the MiniVol TAS 5.0 has higher sensitivity, especially in the closed spaces. When this difference was stable within a controllable range, the fine particle concentration measured by the ATMOtube would be corrected by extrapolating from the data measured by the MiniVol TAS 5.0, helping to increase the accuracy and ensure the consistency of the research results.

As seen in the table, the comparative analysis of indoor $PM_{2.5}$ and PM_{10} measurements using the ATMOtube sensor method and the gravimetric reference method shows that ATMOtube provides relatively consistent results with acceptable variability (CV ranging from 6.53% to 14.42%), meeting US EPA standards. Controlled sampling positions and distances enhance the reliability of the comparison. The similarity in concentration values indicates that ATMOtube effectively captures indoor particulate fluctuations. Although minor discrepancies exist, further calibration is needed to improve accuracy.

Table 1. Statistical comparison of MiniVol TAS 5.0 and ATMOtube measurements for $PM_{2.5}$ and PM_{10} concentrations

Measurement location		20°97'N 108°83'E (Near Bui Xuong Trach Street, in the alley)	20°98'N 105°81'E (Near Dai Tu market)	21°00'N 105°82'E (Near major roads, Truong Chinh)
$PM_{2.5}$ *(µg/m³)*	MiniVol	64.00	97.00	93.00
	ATMO	52.49	87.33	82.77
PM_{10} *(µg/m³)*	MiniVol	67.00	97.00	96.00
	ATMO	55.03	89.63	84.76
Standard deviation (*) (SD), *µg/m³*	$PM_{2.5}$	8.14	6.84	7.23
	PM_{10}	8.46	5.92	7.95
Coefficient of variation (CV), *%*	$PM_{2.5}$	13.97	7.42	8.23
	PM_{10}	17.17	8.14	10.46

(*) - SD and CV were calculated based on 24-hour average PM concentrations measured over three consecutive days for three locations, independently obtained from real-time sensing device (ATMOtube) and gravimetric sampling device (MiniVol TAS) during the same measurement campaign. The SD and CV values reflect the degree of discrepancy between the two measurement methods and provide a quantitative basis to evaluate the overall stability and agreement between sensor-based and reference-grade observations under real-life indoor conditions.

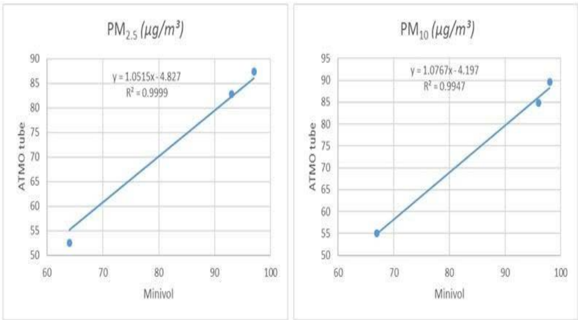

Fig. 5. Indoor $PM_{2.5}$ and PM_{10} measurement results of MiniVol TAS 5.0 and ATMOtube

In order to develop the correlation relationship between the ATMOtube and the MiniVol TAS 5.0, two key performance metrics, bias (%) and linearity (*R^2*), were used as correlation factors in accordance with the performance evaluation protocols of US EPA [14]. As resulted in Fig. 5, the slope of linear regression approaches 1 and R^2 is above 0.99 show that the ATMOtube is typically considered suitable for indicative or supplementary applications, particularly in indoor air quality monitoring.

Overall, the ATMOtube is a practical and cost-effective tool for indoor air quality monitoring but it requires further calibration and evaluation to fully meet US EPA standards. The data can be used for preliminary assessments, but it should be applied cautiously for critical decisions without supplemental quality assurance.

Explaining from the nature of the devices, the MiniVol TAS 5.0 is a specialized PM measuring device, often be used with a larger capacity for ambient air with many external impacts. This device can record higher ranges of PM due to its stronger sample collection ability. Meanwhile, the ATMOtube is designed to be suitable for measuring fine particle in indoor environments, where there is less turbulence and more stable air flow. Combined with the discussion from Fig. 3, it is seen that using the ATMOtube to determine indoor fine particle concentrations is a reasonable selection, helps to provide to residents the recommendations that are appropriate to their actual conditions.

The average results of fine particle also show that all three areas are facing alarming pollution levels. The concentrations are exceeding WHO's recommended limit by from 3 to 8 times (Table 1), indicating that strictly air quality control solutions are really needed.

In this study, because of the logistical limitations (such as limitations in monitoring instruments, accessibility to apartment, and limitations in the numbers of technicians), due to the requirement of collecting data from many apartments in high-rise buildings, the use of the MiniVol TAS 5.0 device was not feasible. Therefore, the ATMOtube was selected as the main device to measure PM concentrations in the apartments in the study area after completing the comparison assessment to ensure the reliability of the result. More in-depth research may require the use of MiniVol TAS 5.0 devices, which is originally designed for more extreme environments.

3.2. Levels of Indoor Fine Particle Pollution in the Study Area

As mentioned, the measurement of indoor PM concentration is conducted in apartments and houses near an area characterized by high air pollution due to heavy traffic and construction activities. In the first location (Fig. 4), the continuous measurement within 24 hours, from 9:00 AM October 8th to 9:00 AM October 9th, 2024, shows a clear fluctuation in fine particle concentrations over time during the day. $PM_{2.5}$ and PM_{10} concentrations tend to decrease gradually from morning to early afternoon, reaching their lowest levels between 14:00 PM–16:00 PM. This is the time when air circulation is improved and helps to reduce dust accumulation. However, at midnight and early morning (from 23:00 PM to 7:00 AM), fine particle concentrations increase, especially sharply during morning rush hours (between 6:00 AM–8:00 AM), indicating that an increase in indoor fine particle may be related to outdoor factors such as dust accumulation and traffic jams. According to WHO, the annual average and 24-hour average limits for $PM_{2.5}$ are 5 μg/m³ and 15 μg/m³ respectively [2]. Compared with the measured results, the concentrations of $PM_{2.5}$ in the surveyed spaces have been far exceeded about 3.5 times higher than the WHO's recommended limit, indicating the very high levels of pollution.

In the next three locations (Table 1), as the measurement results, the concentrations of $PM_{2.5}$ and PM_{10} in these residential private houses are similar, shows that indoor PM is mainly fine particle $PM_{2.5}$. All areas have PM concentrations far exceeding WHO's recommended limit, ranging from 230% to 800% compared to the safe level. In particular, Truong Chinh is the most polluted area where$PM_{2.5}$ concentration is from 700% to 800% higher than WHO's recommended limit. This can be explained as the large number of vehicles as well as traffic emissions and road dust cause this area seriously polluted, especially $PM_{2.5}$ which can directly affect people's respiratory and cardiovascular systems. Dai Tu, the area near a market, also has very high pollution levels where$PM_{2.5}$ concentration is from 550% to 600% higher than WHO's recommended limit. Although the pollution level is lower than that of Truong Chinh area, the fine particles are still dangerous due to activities in the market such as burning solid wastes, cooking, and having trucks coming in and coming out constantly. eanwhile, Bui Xuong Trach, the area located in an alley and far from the main road, has the lowest pollution level among the research areas, but it's $PM_{2.5}$ concentration is still from 550% to 600% higher than

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WHO's recommended limit, showing that the indoor air quality is also negatively affected.

In addition to the houses monitored above, the measurement process was carried out on 10 high-rise apartments. To clarify the impact of indoor factors such as air purifiers and pets on indoor air quality, those apartments were divided into 2 groups:

- Group 1 includes 6 apartments without air purifiers, denoted as N1.1NPet, N1.1Pet, N1.2Npet, N1.2Pet… (NPet stands for apartments without/non pets and Pet stands for apartments with pets);
- Group 2 includes 4 apartments with air purifiers, denoted as N2.1PU, N2.1NPU, N2.2PU, N2.2NPU… (PU stands for days with the air purifier turned on and NPU stands for days with the air purifier turned off/non).

The distribution of the number of the apartments also helps highlight the need for indoor air pollution reduction. The results of average daily concentrations of $PM_{2.5}$ and PM_{10} in apartments without air purifiers (Table 3) show differences according to apartment's location as well as their living habits. Fig. 6 shows the fluctuation of $PM_{2.5}$, PM_{10} concentrations during the day and night in apartments without air purifiers.

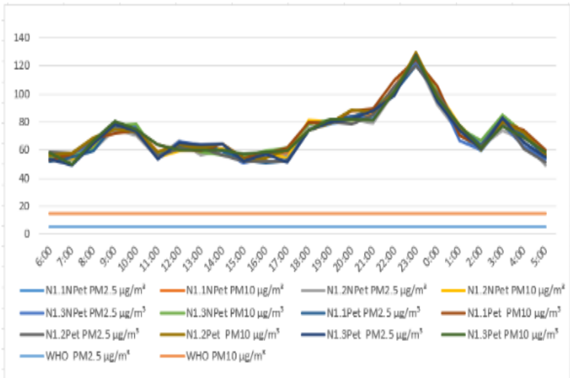

Fig. 6. Hourly fluctuation of $PM_{2.5}$ and PM_{10} concentrations in apartments without air purifiers

Fig. 6 shows that fine particle concentrations vary significantly over time. There are two notable peaks that have occurred around 8:00–9:00 AM and 11:00 PM. In the morning, the increase in fine particle concentrations may be caused by cooking, cleaning, opening windows, and influences of morning traffic. At night, the largest peak may be related to late-day peak traffic, indoor activities, and meteorological conditions that cause particles deposition in lower layers. At this time, $PM_{2.5}$ concentrations can reach 140 µg/m³, exceedingly very far the WHO's recommended limit. During midnight and early morning, fine particles accumulate in the room combined with outside pollution factors such as PM from factories on the coast blows in and swirls in the upper layer above Hanoi and then falls down at night when the temperature drops. In contrast, the lowest points appear around 7:00 AM and 15:00–17:00 PM, when fine particle concentrations drop to lowest level of the day. There are normally little activities in apartments in these times, windows are often closed, and outdoor traffic also drops sharply, causing fine particle level of between 50 – 60 µg/m³.

Table 3. Average daily PM concentration in apartments without air purifiers

Apartment	$PM_{2.5}$ *µg/m³*	PM_{10} *µg/m³*	Monitor time	Apartment condition and average PMs of Hanoi(*) at the time of monitoring
N1.1NPet	56	58	28/12 – 29/12/ 2024	Floor 23, windows were closed throughout the sampling period; $PM_{2.5}$ of Hanoi: 50 *µg/m³* PM_{10} of Hanoi: 82 *µg/m³*
N1.2NPet	61	63	29/12 – 30/12/ 2024	Floor 25, windows were opened in early morning and the evening; $PM_{2.5}$ of Hanoi: 48 *µg/m³* PM_{10} of Hanoi: 75 *µg/m³*
N1.3NPet	85	88	07/01 – 08/01/ 2025	Floor 17, near a construct. site, windows opened nearly all day; $PM_{2.5}$ of Hanoi: 53 *µg/m³* PM_{10} of Hanoi: 82 *µg/m³*
N1.1Pet	63	66	27/12 – 28/12/ 2024	Floor 21, windows were opened in the noon time; $PM_{2.5}$ of Hanoi: 42 *µg/m³* PM_{10} of Hanoi: 73 *µg/m³*
N1.2Pet	69	70	31/12 – 01/01/ 2025	Floor 17, windows were partially opened in the morning; $PM_{2.5}$ of Hanoi: 54 *µg/m³* PM_{10} of Hanoi: 79 *µg/m³*
N1.3Pet	66	68	13/01 – 14/01/ 2025	Floor 19, windows were mostly closed, slightly opened in late afternoon; $PM_{2.5}$ of Hanoi: 62 *µg/m³* PM_{10} of Hanoi: 94 *µg/m³*
N2.1NPU	59	61	12/01 – 13/01/ 2025	Floor 21, main windows facing the road, but were closed mostly; $PM_{2.5}$ of Hanoi: 54 *µg/m³* PM_{10} of Hanoi: 83 *µg/m³*
N2.2NPU	60	61	20/01 – 21/01/ 2025	Floor 24, main windows facing the road, but were closed mostly; $PM_{2.5}$ of Hanoi: 72 *µg/m³* PM_{10} of Hanoi:118 *µg/m³*
N2.3NPU	56	58	26/12 – 27/12/ 2024	Floor 23, main windows not facing the road, and were closed mostly; $PM_{2.5}$ of Hanoi: 42 *µg/m³* PM_{10} of Hanoi: 73 *µg/m³*
N2.4NPU	91	92	03/01/ 2025	Floor 22, Nui Truc str., the apartment near a construction site; $PM_{2.5}$ of Hanoi: 68 *µg/m³* PM_{10} of Hanoi: 93 *µg/m³*

(*) – Source: Hanoi Historical Air Quality Analysis, AQI Data

Thus, the overall trend shows that current situation of indoor $PM_{2.5}$ pollution is serious; the fine particle concentrations increase in the morning and evening, decrease in the afternoon and late at night. The results also emphasize that opening windows during rush hours can increase indoor $PM_{2.5}$ concentrations, especially in apartments near traffic roads. Long-term exposure to $PM_{2.5}$ at high concentrations can bring the risks of respiratory and cardiovascular diseases and affect the nervous system evenly. Therefore, the indoor pollution minimizing solutions are required to protect resident's health. In addition to limiting opening doors when the outside particles concentration is high, using air purifiers with effective technology such as High Efficiency Particulate Air (HEPA) purifier technology and/or negative ion technology is also a solution to improve indoor air quality.

Table 3 shows that the indoor PM is mainly fine particle $PM_{2.5}$, influenced by factors include apartment location related to outside polutions, traffic or construction activities, and living habits. In order to recognize which apartments would bring in higher indoor levels, we also need to see how outdoor PM levels varied from day to day. To do that, in the absence of suitable location-level data, the daily PM concentrations of Hanoi were obtained from IQAir and AQI platforms [15, 16]. AQI is a widely recognized global system that provides real-time air quality information using calibrated sensors, with data validated through comparison against official monitoring stations. As seen in the Table, apartments located near construction sites (N1.3NPet and N2.4NPU) had significantly higher PM pollution levels than others. The influence of outside pollutions was observed through slightly increased indoor PM concentrations in the apartments with opened window. Regarding indoor pets, three apartments with pets (N1.1Pet, N1.2Pet, and N1.3Pet) had slightly higher indoor PM concentration than the pet-free apartments. Scientific publications around the world have also indicated these influences [17, 18].

The data from Table 4 and Fig. 7 reflect the improvement of $PM_{2.5}$ concentrations when the air purifier in the apartments was turned on. The average $PM_{2.5}$ concentrations decreased between 25%–30% with the use of the air purifiers. In particular, this improvement helps reduce indoor fine particle concentrations to the safe levels during the hours of lower pollution levels, such as between 10:00 AM–15:00 PM when indoor activities are reduced, and the outside air is less affected by traffic or other pollution sources. During these times, the air purifier is used with most effective operating conditions, helping to maintain a cleaner and more stable indoor space.

However, during the high pollution hours, even though the air purifier operates continuously and effectively, the $PM_{2.5}$ concentrations are still higher than WHO's recommended limits, showing that air purifiers can help reduce fine particle pollution but cannot completely handle the problem without additional measures. Our further investigation of the ceiling-mounted air conditioning system in these high-rise apartments showed that a typical living room occupies about 30 m² with a ceiling height of 2.7 m, resulting in a total room space of approximately 81 m³.

Table 4. Average daily PM concentration in apartments with air purifiers

Apartment	$PM_{2.5}$ $\mu g/m^3$	PM_{10} $\mu g/m^3$	Monitor time	Apartment condition and average PMs of Hanoi(*) at the time of monitoring
N2.1NPU	59	61	12/01 – 13/01/ 2025	N2.1: floor 21, main windows facing the road, but were closed mostly; $PM_{2.5}$ of Hanoi: 54 $\mu g/m^3$ PM_{10} of Hanoi: 83 $\mu g/m^3$
N2.1PU	47	48	14/01 – 15/01	N2.1 described above; $PM_{2.5}$ of Hanoi: 63 $\mu g/m^3$ PM_{10} of Hanoi: 95 $\mu g/m^3$
N2.2NPU	60	61	20/01 – 21/01/ 2025	N2.2: floor 24, main windows facing the road, but were closed mostly; $PM_{2.5}$ of Hanoi: 72 $\mu g/m^3$ PM_{10} of Hanoi: 118 $\mu g/m^3$
N2.2PU	50	58		
N2.3NPU	56	58	26/12 – 27/12/ 2024	N2.3: floor 23, main windows not facing the road, were closed mostly; $PM_{2.5}$ of Hanoi: 42$\mu g/m^3$ PM_{10} of Hanoi: 73 $\mu g/m^3$
N2.3PU	47	48		

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N2.4NPU	91	92	03/01/ 2025	N2.4: Floor 22, Nui Truc Str., the apartment near a construction site; $PM_{2.5}$ of Hanoi: 68*μg/m³* PM_{10} of Hanoi: 93 *μg/m³*
N2.4PU	66	69	04/01/ 2025	N2.4 with air purifier using negative ion tech.; $PM_{2.5}$ of Hanoi: 45*μg/m³* PM_{10} of Hanoi: 74 *μg/m³*

(*) – Source: AQI, Hanoi Historical Air Quality Analysis [15]

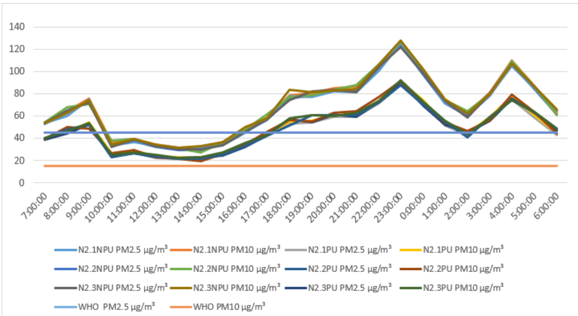

Fig. 7. Hourly fluctuation of $PM_{2.5}$ and PM_{10} concentrations in apartments with air purifiers

As the main area for daily activities, the living room is considered the primary location for deploying indoor air purification systems. Standard residential air purifiers are commonly placed adjacent to walls or wardrobes, with the air intake oriented toward the center of the room. This spatial arrangement preserves functional floor area within limited living space and ensures that the intake is situated in a zone of high ambient airflow density, where suspended particles are most likely to accumulate. By facing the room's center, the purifier can effectively capture airborne PM, particularly $PM_{2.5}$ originating from both indoor activities and outdoor air infiltration. Most purifiers in use feature air outlets positioned either at the top or on lateral sides, generating clean airflow that disperses upward toward the ceiling or laterally into the occupied zone. When positioned in an unobstructed location with at least 30–50 cm of clearance from surrounding furniture, the device facilitates a stable air circulation loop, promoting efficient distribution of purified air and enhancing the overall air exchange performance within the defined room volume. However, its effectiveness is fundamentally constrained by passive operational principles. Mechanical filters rely entirely on the movement of air through the filtration media, meaning that only particles transported into the device can be captured. As a result, filtration efficiency is directly affected by the device's clean air delivery rate, placement within the room, and the airflow circulation pattern. In the high-rise apartments under study, these factors are often suboptimal. Furniture, irregular room geometry, and user habits can disrupt air circulation, leading to stagnant zones where airborne particles persist. Additionally, the response time of mechanical filtration to sudden increases in particle concentration, such as those caused by cooking, door opening, or outdoor infiltration, is often inadequate. Another important factor affecting the effectiveness of fine particle filtration is the level of exposure to external pollution sources. As the results, apartments with main windows facing traffic roads tend to have lower reductions due to continuously affected by outside PM and smoke, even when closed. In contrast, apartments with less direct exposure to the external environment have more significant reductions suggesting that air purifiers can work best in tightly controlled air conditions. This explains why the difference of fine particle concentrations before and after turning on the air purifier varies from apartment to apartment.

To address these limitations, more spatially integrated solutions are needed. One such solution could be to integrate negative ion generators into ceiling-mounted air conditioning systems. Table 4 shows the difference in $PM_{2.5}$ concentration between apartments using conventional ceiling-mounted air purifiers and apartments using negative ion device. Specifically, before turning on the negative ion generator, concentrations of $PM_{2.5}$ in N2.4 are 89 μg/m³. After using the generator, the concentration of $PM_{2.5}$ decrease to 66 μg/m³. It is noted that, on the day the negative ion generator was used, the outdoor PM levels were more polluted.

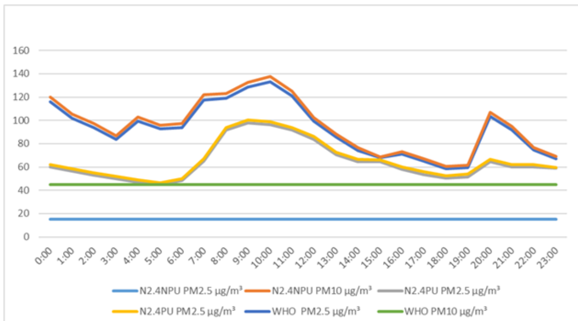

Fig. 8. Fluctuation of $PM_{2.5}$ and PM_{10} concentration in N2.4 before and after using negative ion generator

Fig. 8 shows the fluctuations of fine particle concentrations over time in apartment N2.4 before and after using the negative ion generator. The device has been turned on constantly for 6 hours, from 7:00 AM to 13:00 PM on January 4, 2025. Before turning on the device, fine particle concentrations were very high and fluctuated strongly, especially between 5:00–10:00 AM, when $PM_{2.5}$ peaked at 140 μg/m³. This apartment had

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few living activities, so it has been caused by outdoor environmental conditions such as a nearby construction site. After using the negative ion generator, the fine particle concentrations decreased significantly, and the fluctuation trend also became more stable. In particular, in the afternoon and evening, when the negative ion generator was stopped, the reduction in $PM_{2.5}$ concentration was still maintained with an average reduction of 30–50 µg/m³, showing that this device may be effective in improving indoor air quality throughout the day and night.

Unlike mechanical filters, ionization technology actively neutralizes airborne particles by imparting electrical charges that promote coagulation and subsequent deposition onto surfaces or enhanced filtration. When embedded in ceiling air conditioners, ion generators can take advantage of the system's existing airflow distribution to ensure even dispersion of ions throughout the room. Controlled experiments have demonstrated that negative ion generators can reduce $PM_{2.5}$ concentrations by up to 85% within 12 hours under enclosed conditions, with post-treatment levels falling below WHO's recommended limits [18]. Advantages could be achieved by integrating this technology into high-density urban residences. However, further investigation is warranted to assess long-term stability, maintenance requirements, and safety concerns such as potential ozone generation.

With the initial results, air purifiers in general and a negative ion generator in particular can be considered as a solution to improve air quality in living spaces. Along with regular cleaning filters solution, in order to achieve optimal efficiency, additional solutions are needed. Some housekeeping solutions include closing windows during peak pollution hours, using dust-proof curtains, placing green plants in the house also support natural air purification.

4. Conclusion

From the study results, it is affirmed that indoor PMs is mainly $PM_{2.5}$ and the indoor fine particle is a serious problem in high-rise apartment buildings in Hanoi. The $PM_{2.5}$ pollution level varies significantly depending on the location of the apartments, living habits, and the use of air purification equipment. Apartments with opened windows or located near construction sites have fine particle concentrations higher than the remaining apartments, due to the direct impact of emissions from vehicles, particles from road or construction sites. Cooking and opening windows during rush hours could be the main causes of $PM_{2.5}$ increases while pet ownership affects insignificantly. The study also indicates the effectiveness of using air purifier technologies to limit indoor $PM_{2.5}$. Using a negative ion generator combined with air filtration potentially achieve better efficiency.

Measurement results at three residential private houses showed relatively stable fine particle concentrations throughout the day. Unlike the high-rise apartments near busy roads, which experienced significant fluctuations with the sharp peaks typical of high-traffic areas. Specifically, the highest $PM_{2.5}$ concentration recorded in the residential private houses was 50 µg/m³, occurring only during brief periods in the morning and late afternoon, compared to the much higher peaks of 140 µg/m³ observed in the apartments near busy streets.

This study has a limitation in the measurement. The weighting of filters for the Minivol TAS 5.0 carried out by 5-digit balance may cause an uncertainty for the results obtained from the MiniVol TAS 5.0. Besides, for the evaluation of the ATMOtube toward the MiniVol TAS 5.0, the intercept is high even though the linearity is very good. Therefore, the PM levels have certain uncertainty and should be considered as an indicator rather than a precise concentration.

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