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Concentration and Source of dl-PCBs in $PM_{2.5}$ in Central Hanoi, Vietnam

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Abstract

Fine particulate matter ($PM_{2.5}$) pollution is a major air quality concern in Hanoi, while information on $PM_{2.5}$ - bound dioxin - like polychlorinated biphenyls (dl-PCBs) remains limited. This study investigated the concentrations, congener profiles, and potential sources of dl-PCBs associated with $PM_{2.5}$ in central Hanoi during the dry season of 2025. Fourteen consecutive 24-h $PM_{2.5}$ samples were collected from 4 to 19 April 2025 at an urban site influenced by traffic and other anthropogenic activities. Twelve dl-PCB congeners were analyzed according to U.S. EPA Method 1668B using high resolution gas chromatography high resolution mass spectrometry (HRGC - HRMS) with isotope-dilution quantification. The 24-h $PM_{2.5}$ concentrations ranged from 32.4 to 83.1 $\mu g/m^3$, averaging 60.3 $\mu g/m^3$; 64.3% of samples exceeded the Vietnamese 24-h standard of 50 $\mu g/m^3$, while the mean concentration was approximately four times the WHO guideline value of 15 $\mu g/m^3$. Toxic equivalent concentrations of dl-PCBs ranged from 1×10^{-3} to 11×10^{-3} pgTEQ/m^3, with an average of 4×10^{-3} pgTEQ/m^3. Congener profiles were dominated by PCB-118 (36.3 - 52.9%) and PCB-105 (17.1 - 24.4%), together accounting for approximately 70% of total dl-PCBs, followed by PCB-77 (7.2 - 10.6%). This profile suggests that volatilization from PCB - containing products and materials may represent an important source of atmospheric dl-PCBs in central Hanoi, although contributions from thermal processes cannot be excluded. These findings provide baseline data on $PM_{2.5}$ - bound dl-PCBs in central Hanoi, supporting future source apportionment studies, air - quality management, and environmental health assessments.

Keywords

air pollution; dl-PCBs; Hanoi; $PM_{2.5}$.

Introduction

Air pollution, particularly fine particulate matter ($PM_{2.5}$), has become and increasingly prominent concerns due to its negative impacts on the environment and human health (Nguyen *et al.*, 2018). These particles can penetrate deeply into the lungs via the respiratory system, reach the heart, and enter the bloodstream, thereby causing severe health effects due to the physical and chemical properties of $PM_{2.5}$ (Hien *et al.*, 2022; Linh *et al.*, 2023). Long-term exposure to $PM_{2.5}$ has been linked to increased rates of respiratory and cardiovascular diseases as well as reduced life expectancy (Zhang *et al.*, 2022). According to statistics from the World Health Organization (WHO), approximately 60,000 people die annually in Vietnam due to air pollution, with economic losses estimated at 10.82 - 16.63 billion USD, equivalent to about 5% of the country's GDP (Nguyen, 2021; World Health Organization, 2024). Based on their sources, natural sources of $PM_{2.5}$ include sandstorms, volcanic eruptions, pollen, and sea spray. Meanwhile, anthropogenic sources arise from human activities, such as transportation, industrial processes, agriculture, and handicraft production. Finally, secondary sources refer to particles formed in the atmosphere through complex bio-geo-chemical and physical reactions (Gurjar *et al.*, 2010). These impacts result from the contribution of local emission sources or long-range transport of $PM_{2.5}$, depending on their transport trajectories (Hien *et al.*, 2022), the physical properties of the particles, and meteorological and topographic conditions (Bui *et al.*, 2023). The composition of $PM_{2.5}$ includes three main groups: water-soluble ions, metallic elements, and organic compounds (Bui *et al.*, 2023).

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Among these, organic aerosols dominate (30-90%), containing thousands of harmful components (Yao *et al.*, 2016). A notable group within these compounds is polychlorinated biphenyls (PCBs), which have garnered significant research attention (Chang *et al.*, 2013; Ding *et al.*, 2015). PCBs are substances that persist in the environment, are bioaccumulative, have long-range transport potential, and are highly toxic. They belong to the group of typical persistent organic pollutants (POPs), characterized by low water solubility, high lipid solubility, and, notably, the potential to bioaccumulate, with effects that progressively intensify along the food chain (Zhu *et al.*, 2017). Although banned in the 1970s and 1980s, PCBs continue to be emitted from obsolete industrial products and the combustion of chlorine-containing materials (Han *et al.*, 2010). Among the 209 types of PCBs, 12 dioxin-like PCBs (dl-PCBs) have been proven to cause endocrine disruption, irritation, and carcinogenic effects (Pham *et al.*, 2019).

Atmospheric transport is the primary means by which organic compounds spread from emission sources to distant regions (Hien *et al.*, 2022). Suspended $PM_{2.5}$ can effectively act as a carrier for transporting dl-PCBs in the environment. Common suspended particles in the atmosphere can enter the human body through various pathways (e. g., food, breath, and skin) and pose a significant threat to humans (Sun *et al.*, 2020). High-resolution gas chromatography coupled with high-resolution mass spectrometry (HRGC–HRMS) has therefore been widely applied and recognized as a reliable analytical technique for the determination of trace-level dl-PCBs in PM samples (Mila *et al.*, 2022). dl-PCBs can enter the atmosphere through emission sources and subsequently adhere to $PM_{2.5}$ particles, penetrating deep into the human body via the respiratory system (Sun *et al.*, 2020). Due to their distinct characteristics as POPs, research on dl-PCBs has been extensive worldwide, with numerous studies (Han *et al.*, 2010; Pham *et al.*, 2019; Sun *et al.*, 2020). However, comprehensive assessments of dl-PCBs in $PM_{2.5}$ in Vietnam remain scarce, highlighting the need for further research on this issue.

In this study, we collected 14 daily $PM_{2.5}$ samples during a campaign investigating air pollution levels in the dry season in the central area of Hanoi, Vietnam, and measured the concentrations of dl-PCBs in these samples. Through this, the study can provide fundamental data to support local pollution control efforts.

Materials and Methods

Sampling $PM_{2.5}$

The sampling site was established within the campus of the University of Engineering and Technology (VNU-UET), in the central area of Hanoi (105°46'58.1" E; 21°02'17.8" N) (Fig. 1). Located in the urban center of the city, this site features a very high population density and intense commercial-service activities. More importantly, the sampling station is directly influenced by major urban traffic arteries. These roads experience extremely heavy traffic volumes, leading to severe and frequent congestion, particularly during peak hours (e.g., 7-9 am. and 5-7 pm.). Therefore, this location was selected for its high representativeness of an air environment strongly impacted by anthropogenic emissions, primarily from traffic exhaust and other human activities.

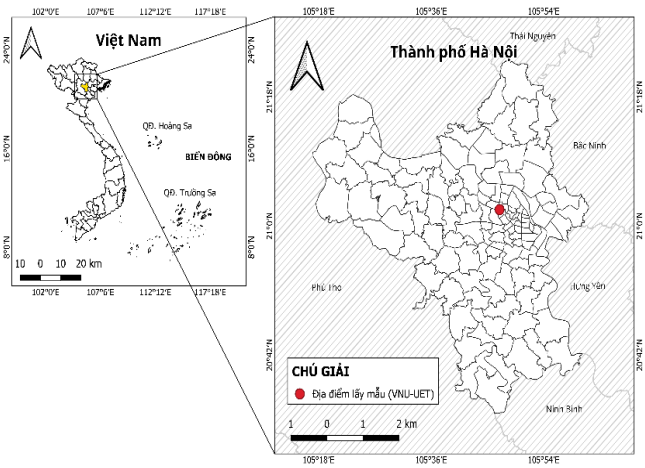

Figure 1. Sampling site

Daiy $PM_{2.5}$ samples were collected using a high-volume air sampler, TE-1000DBLX *(Tisch Environment, Inc.)*, which captures particulate and gaseous pollutants. The sampler is equipped with a 200 L/min inlet and 102 mm diameter quartz filter paper *(TE-QMA4, Tisch Environmental Inc., USA)*. $PM_{2.5}$ samples were collected daily, with each sample representing a 24 hours (06:00–06:00 the following day). After sampling, the used filter was placed back into its Petri dish and stored in an airtight bag under refrigeration. All samples were transported to the Laboratory of the Institute of Chemistry and Environment (Vietnam-Russia Tropical Centre) for determining dust concentrations and analyzing the dl-PCBs concentrations in the collected samples. Sampling was conducted from 4 to 19 April 2025, which falls within the dry season in Hanoi, typically extending from November to April of the following year.

Determine $PM_{2.5}$ Mass Concentration

The daily $PM_{2.5}$ samples were collected, transferred to the laboratory, and then the filter papers were dried at 110°C. Subsequently, they were weighed using a Mettler Toledo XS 205 analytical balance. The daily $PM_{2.5}$ concentration was then determined based on Eq. (1).

$$C = \frac{m_2 - m_1}{V} \qquad (1)$$

where:

C: $PM_{2.5}$ concentration (µg/m³)

m_1: Weight of the filter paper before sampling (µg)

m_2 : Weight of the filter paper after sampling (µg)

V: Total volume of air passing through the sampler during the sampling period (m³)

dl-PCBs Analysis

The analysis of dl-PCBs was conducted according to US EPA Method 1668B (U.S. Environmental Protection Agency, 2010). The $PM_{2.5}$ samples were extracted using a Soxhlet system with toluene as the solvent. The extract was then subjected to initial treatment with H_2SO_4 and KOH, followed by cleanup through a multi-layer silica gel column. To separate dl-PCBs from PCDD/Fs congeners, the sample was passed through an activated carbon column and subsequently further purified using an alumina column. The final extract was spiked with a 13C12-labeled dl-PCB internal standard, concentrated, and introduced into an HRGC-HRMS system (equipped with a DB-5MS column) for analysis. The quantification of dl-PCBs was performed using the isotope dilution method.

Quality Assurance (QA) and Quality Control (QC)

To ensure data quality and analytical reliability, quartz fiber filters were pre-combusted at 450°C for 6h to remove residual organic contaminants prior to sampling. After collection, $PM_{2.5}$ samples were transported to the dioxin analysis laboratory of the Joint Vietnam-Russia Tropical Science and Technology Research Center and stored at -20°C until analysis. Field-blank samples were processed and analyzed in parallel with $PM_{2.5}$ samples to control for potential contamination and assess sampling and handling reliability.

All analyses were conducted at the ISO/IEC 17025 accredited laboratory of the Joint Vietnam-Russia Tropical Science and Technology Research Center (VRTC), Hanoi (No. 856) (Bureau of Accreditation, 2015). The limit of detection (LOD) for dl-PCBs was 0.003 pg/m³, and the corresponding limit of quantification (LOQ) was 0.012 pg/m³. All measured concentrations in $PM_{2.5}$ samples exceeded the LOQ, ensuring reliable quantification. Quantification was performed using isotope dilution, with recoveries of $^{13}C_{12}$-labeled standards ranging from 40 to 135%, in compliance with US performance criteria. EPA Method 1668C. Duplicate analyses showed that concentration differences among congeners did not exceed 25%, indicating good method repeatability and analytical reliability.

Results

Concentration Level of $PM_{2.5}$

The monitoring results of the 24-hour average $PM_{2.5}$ concentrations in the Hanoi center, during the dry season are presented in Fig. 2. Within the total 14 monitored samples, 9 samples (accounting for 64.3%) exceeded the

limit value specified in the National Technical Regulation on Ambient Air Quality (QCVN 05:2023/BTNMT) for 24-hour average $PM_{2.5}$ concentration (50 µg/m³). Concentrations fluctuated significantly, ranging from 32.4 µg/m³ (KKHN-07) to 83.1 µg/m³ (KKHN-05 and KKHN-13). The average value across all 14 collected $PM_{2.5}$ samples was 60.3 µg/m³, which is 1.2 times the permissible limit set by QCVN and 4 times the World Health Organization (WHO) recommendation (15 µg/m³ for a 24-hour average) (World Health Organization, 2021). Those values reveal an alarming level of air pollution in Hanoi, Vietnam.

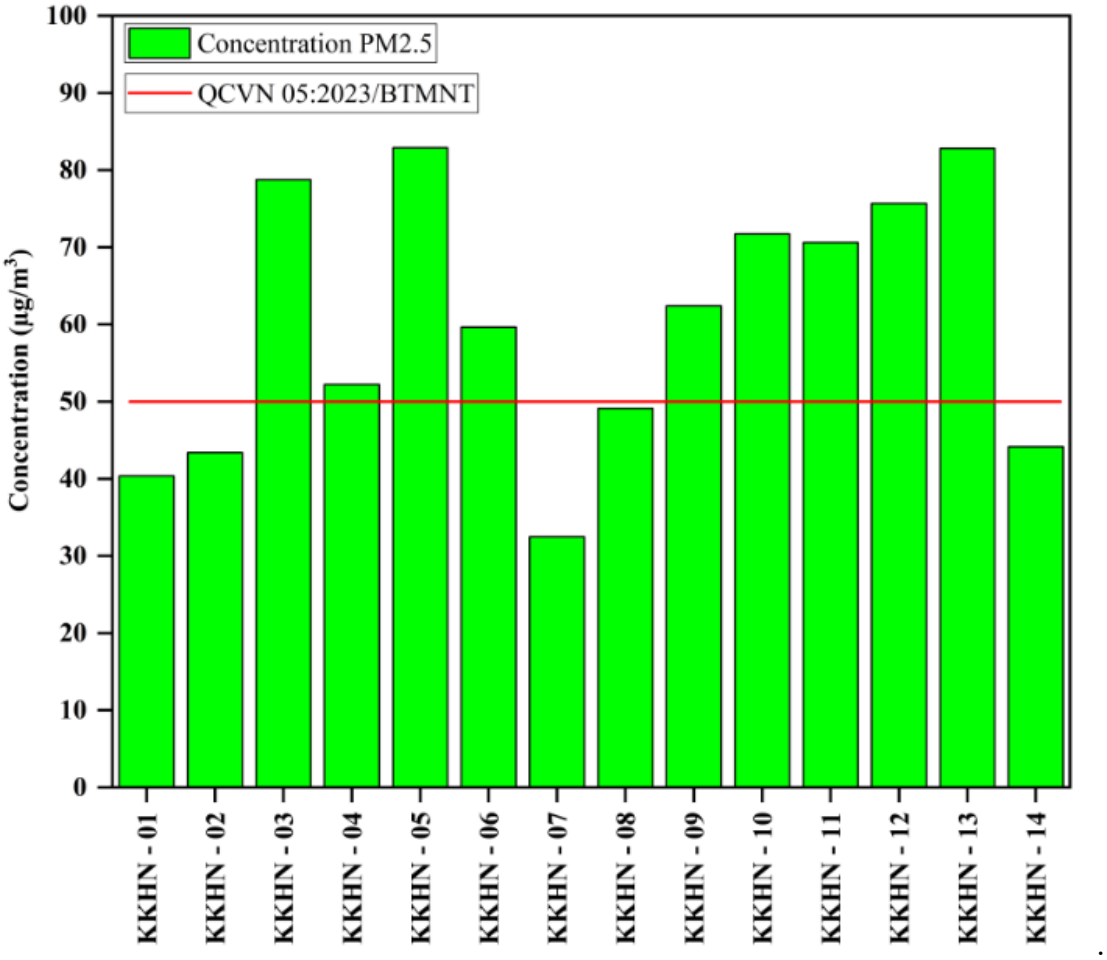

Figure 2: The $PM_{2.5}$ concentration levels

Concentration of dl-PCBs

Fig. 3 shows that the measured dl-PCBs concentrations during the dry season sampling period in Hanoi exhibit significant fluctuations, ranging from 10^{-3} pg TEQ/m³ (recorded in sample 0425HN10) to 11×10^{-3} pg TEQ/m³ (in sample 0425HN07), representing a more than tenfold difference. The trend shows considerable variability, likely reflecting localized pollution events, with markedly higher concentrations recorded in samples 0425HN06, 0425HN07, and 0425HN13, at 9×10^{-3} pg TEQ/m³, 11×10^{-3} pg TEQ/m³, and 8×10^{-3} pg TEQ/m³, respectively. In contrast, the middle period of the survey (from sample 0425HN08 to 0425HN12) recorded consistently low TEQ concentrations, indicating significant daily variations in air quality at the monitoring site. The average concentration in the study area was 4×10^{-3} pg TEQ/m³, which is comparable to values reported in other regions, such as northern Taiwan (2×10^{-3} - 5×10^{-3} pg TEQ/m³) (Chi *et al.*, 2008). This value is lower than those recorded in Ho Chi Minh City in a commercial area, which averaged 12×10^{-3} pg TEQ/m³ (Trinh *et al.*, 2018), and in China, where concentrations ranged from 7×10^{-3} - 16×10^{-3} pg TEQ/m³ (Die *et al.*, 2015).

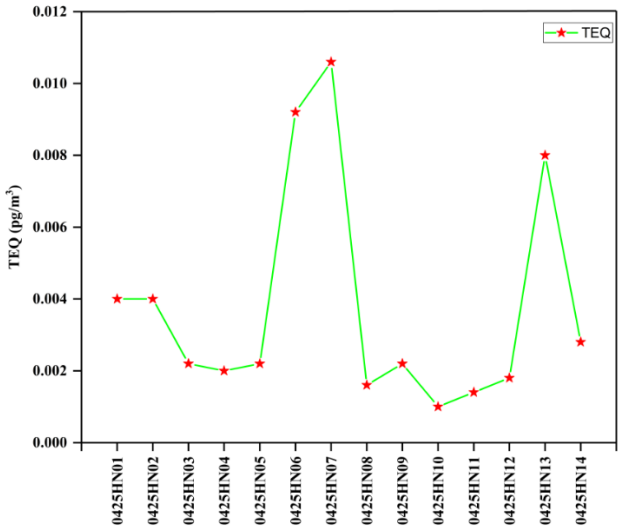

Figure 3: The concentration levels of dl – PCB

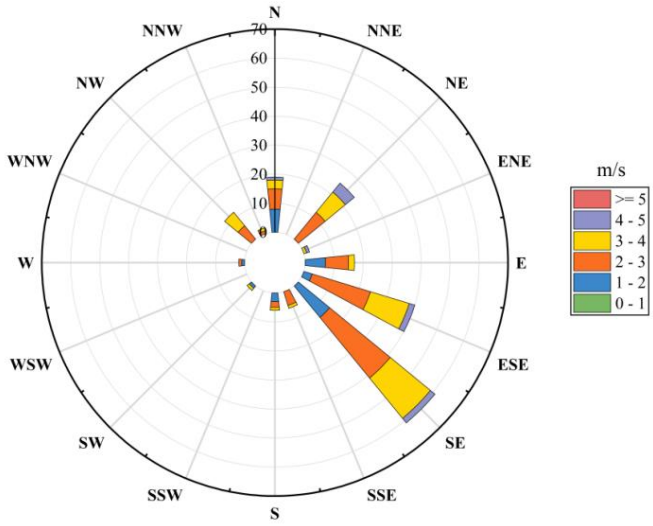

Figure 4: Windrose during sampling time

Discussion

Concentration of $PM_{2.5}$

The monitoring results showing an average $PM_{2.5}$ concentration (60.3 µg/m³) in early April 2025 indicate a particularly severe pollution situation. This value is nearly equivalent to the average (59.5 µg/m³) recorded during peak air pollution episodes in inner-city Hanoi in a recent study by Dat et al. (2024). Analysis of the wind rose diagram (Figure 3) reveals that the prevailing wind directions during the sampling period were Southeast (SE) and East-Southeast (ESE). The characteristic wind directions during the study period demonstrate a clear influence of long-range pollution transport from the SE. This aligns with previous studies, where the HYSPLIT trajectory model indicated that air masses originating from the SE/ESE direction likely carried significant amounts of pollutant precursors and transported them deep into the inner-city area of Hanoi (Cohen *et al.*, 2010; Dat *et al.*, 2024). During transport, these pollutants undergo chemical transformations, forming secondary inorganic aerosols that directly contribute to the total observed $PM_{2.5}$ concentration in Hanoi. Furthermore, local pollution sources could be a key factor contributing to high $PM_{2.5}$ levels, as pollutants accumulate when air masses stagnate over Hanoi City, which has dense traffic and construction activities (Bui & Duong, 2019).

Another issue in recent years in Hanoi City is that straw burning also contributes to air pollution (Le *et al.*, 2022; Nguyen & Nguyen, 2020). However, the sampling period did not coincide with the large-scale straw burning episodes in the Red River Delta, which typically occur in June and October each year. This further supports the conclusion that the pollution sources in the study area primarily originate from transportation, industrial, and other human activities within the urban area.

Congeners of dl-PCBs

Figure 5 shows that pentachlorinated biphenyls (PeCBs) congeners contributed the largest proportion across all monitoring days. PCB-118 was the dominant contributor, accounting for 36.3% to 52.9%, followed by PCB-105 at 17.1% to 24.4%. The tetrachlorinated congener PCB-77 ranked third, with a contribution ranging from 7.2% to 10.6%. In contrast, heavier congeners (HxCBs, HpCBs) constituted only a very small fraction. This congener profile aligns with characteristics of urban background pollution, where dl-PCBs primarily originate from two sources: volatilization from PCB-containing materials and thermal processes (Abad *et al.*, 2006). Research by Frederiksen *et al.* (2012) indicates that solder-welding activities can significantly alter the congener distribution of dl-PCBs in ambient air, with

PCB-118 and PCB-105 being the two predominant congeners, accounting for approximately 80% of total dl-PCBs. Conversely, dl-PCBs emitted from thermal processes exhibit a lower relative abundance of PCB-118 and PCB-105 compared to emissions from sealed welding activities. Studies in Taiwan have shown that PCB-118 and PCB-105, formed de novo during combustion, account for about 35-45% of total dl-PCBs. Additionally, lower-chlorinated dl-PCB congeners, such as PCB-77, PCB-126, and PCB-169, also constitute a significantly higher proportion in such scenarios (Bai *et al.*, 2017). Specifically, in this study, since PCB-118 and PCB-105 constitute about 70% of the total dl-PCBs concentration, while the combined share of PCB-77, PCB-126, and PCB-169 is relatively small (approximately 20%), the primary source of dl-PCBs in the inner-city area of Hanoi is likely volatilization from PCB-containing products. In developing countries, PCB emissions have been linked to sources such as used engine oil, transformer oil, and imported electronic waste from developed nations, as found in research findings (Kaw & Kannan, 2017). This supports the conclusion that PCB-containing products significantly influence the levels of dl-PCBs in the air of Hanoi City.

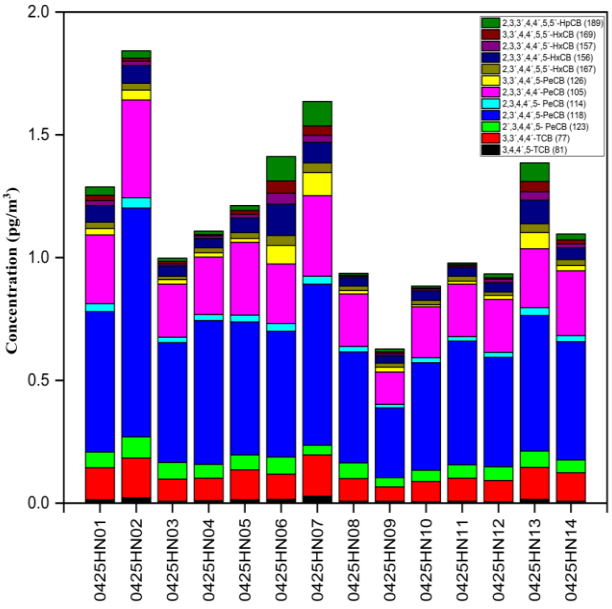

Figure 5: Concentration levels of the congeners dl-PCBs

Conclusion

The study has provided important empirical data on the characteristics of $PM_{2.5}$ pollution and the concentration of dl-PCBs in the urban atmosphere of the central area in Hanoi during the dry season of 2025. The results show that the 24-hour average $PM_{2.5}$ concentration (60.3 µg/m³) significantly exceeds the limit specified in QCVN 05:2023/BTNMT and is four times higher than the WHO recommendation. It reflects a severe and persistent fine particulate pollution situation in the study area. Regarding dl-PCBs, the measured TEQ concentrations ranged from $\times 10^{-3}$ to 11×10^{-3} pgTEQ/m³, with an average value of 4×10^{-3} pgTEQ/m³. This is comparable to urban areas in northern Taiwan but lower than Ho Chi Minh City and some industrial regions in China. The congener profile of dl-PCBs in the $PM_{2.5}$ samples revealed a clear dominance of PCB-118 and PCB- 105 (accounting for approximately 70%), while lower-chlorinated congeners such as PCB-77, PCB-126, and PCB-169 contributed a smaller proportion. Therefore, it can be preliminarily concluded that the primary source of dl-PCBs in the inner-city area of Hanoi is likely volatilization from PCB-containing products.

Overall, the results confirm that the study objectives were achieved by characterizing $PM_{2.5}$ levels and assessing the occurrence and potential sources of dl-PCBs in the urban atmosphere of Hanoi. This work provides one of the first integrated datasets combining $PM_{2.5}$ mass concentrations with dl-PCBs measurements in central Hanoi, offering valuable baseline information for air quality assessment and supporting future air quality management and environmental health evaluations.

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Data Availability Statement: *The data supporting the findings of this study are available from the corresponding author upon reasonable request.*

Author Contributions: *Bui Duy Linh: Formal Analysis, Investigation, Visualization, Writing - Original Draft;*

Hoang Anh Le: Conceptualization, Methodology, Data Curation, Visualization, Writing - Review & Editing, Supervision; Nguyen Thanh Tuan: Resources, Data Curation, Writing - Review & Editing; Nguyen Duc Thang: Resources, Data Curation; Nguyen Thi Nang: Writing - Original Draft; Nguyen Thi Thu: Formal Analysis; Tran Dinh Phien: Formal Analysis; Pham Chau Thuy: Methodology, Data Curation, Visualization; Nguyen Viet Thanh: Methodology, Data Curation, Visualization.

Statement on the Use of Generative AI: *The authors declare that AI tools were used only for language editing/formatting, and not for generating scientific content. All data, analyses, and interpretations were performed and verified by the authors, who take full responsibility for the manuscript.*

Conflicts of Interest Statement: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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