

Concentration and source of dl-PCBs in PM_{2.5} in the central Hanoi, Vietnam**Linh Bui Duy^{(1)✉}, Tuan Nguyen Thanh⁽¹⁾, Le Hoang Anh⁽²⁾, Thuy Pham Chau⁽³⁾, Thang Nguyen Duc⁽¹⁾, Phien Tran Dinh⁽¹⁾, Thu Nguyen Thi⁽¹⁾, Thanh Nguyen Viet⁽²⁾, Nang Nguyen Thi⁽¹⁾**⁽¹⁾*Institute of Tropical Environment and Chemistry, Joint Vietnam-Russia Tropical Science and Technology Research Center, Hanoi, Vietnam*⁽²⁾*University of Science, Vietnam National University, Hanoi, Vietnam*⁽³⁾*University of Engineering and Technology, Vietnam National University, Hanoi, Vietnam*✉ **Corresponding author**Email: buiduylinh1105@gmail.com

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Abstract

This study aimed to assess the concentrations of PM_{2.5} and dl-PCBs congeners in PM_{2.5} in the central area of Hanoi during the dry season of 2025. A total of 14 daily PM_{2.5} samples were collected and analyzed using the HRGC-HRMS method. The results showed that the average 24-hour PM_{2.5} concentration reached 60.3 µg/m³, with 64.3% of the samples exceeding the limit set by QCVN 05:2023/BTNMT and significantly higher than the WHO recommended level. Dl-PCBs concentrations ranged from 10⁻³ – 11 × 10⁻³ pgTEQ/m³, with an average value of 4 × 10⁻³ pgTEQ/m³, comparable to levels recorded in other urban areas in the region. PCB-118 and PCB-105 dominated the congener profile, indicating that the primary emission source is the volatilization of PCB-containing products and materials. The study's results provide important baseline data for risk assessment and the development of policies for controlling air pollution and POPs in Hanoi.

Keywords*Air pollution; dl-PCBs; Hanoi; PM_{2.5}.***Introduction**

Air pollution, particularly the issue of fine particulate matter (PM_{2.5}) pollution, has become one of the increasingly prominent concerns due to its negative impacts on the environment and human health (Nguyen *et al.*, 2018). These particles can penetrate deep into the lungs through the respiratory system, reach the heart, and enter the bloodstream, thereby causing severe health effects due to the physical and chemical characteristics 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 emissions of PM_{2.5} include

phenomena such as 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 biogeo-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). 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 with persistence in the environment, bioaccumulative properties, long-range transport potential, and high toxicity. They belong to the group of typical persistent organic pollutants (POPs), characterized by low solubility in water, high lipid solubility, and notably, they can cause bioaccumulation 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 (such as food, breath, and skin) and are considered a significant potential 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 globally, with numerous studies conducted worldwide (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 within the central area of Hanoi, Vietnam, and measured the concentrations of dl-PCBs in these PM_{2.5} 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.

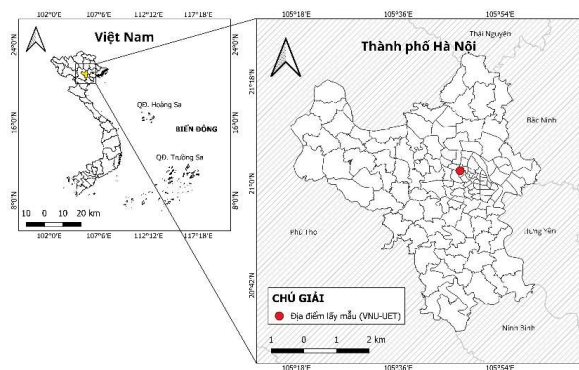


Figure 1: Sampling site.

Daily PM_{2.5} samples were collected using a high-volume air sampler, TE-1000DBLX (*Tisch Environment, Inc.*), designed to capture particulate and gaseous pollutants in the air. 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-hour period (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, 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).

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

where:

C: PM_{2.5} concentration (μg/m³)

m₁: Weight of the filter paper before sampling (μg)

m₂: 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 H₂SO₄ 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 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 ¹³C₁₂-labeled standards ranging from 40 to 135%, in compliance with the performance criteria of US.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 $\mu\text{g}/\text{m}^3$). Concentrations fluctuated significantly, ranging from a minimum of 32.4 $\mu\text{g}/\text{m}^3$ (KKHN-07) to a maximum of 83.1 $\mu\text{g}/\text{m}^3$ (KKHN-05 and KKHN-13). The average value across all 14 collected PM_{2.5} samples was 60.3 $\mu\text{g}/\text{m}^3$, which

is 1.2 times higher than the permissible limit of QCVN and 4 times higher than the recommendation of the World Health Organization (WHO) (15 $\mu\text{g}/\text{m}^3$ for a 24-hour average) (World Health Organization, 2021). Those values reveal an alarming level of air pollution in Hanoi, Vietnam.

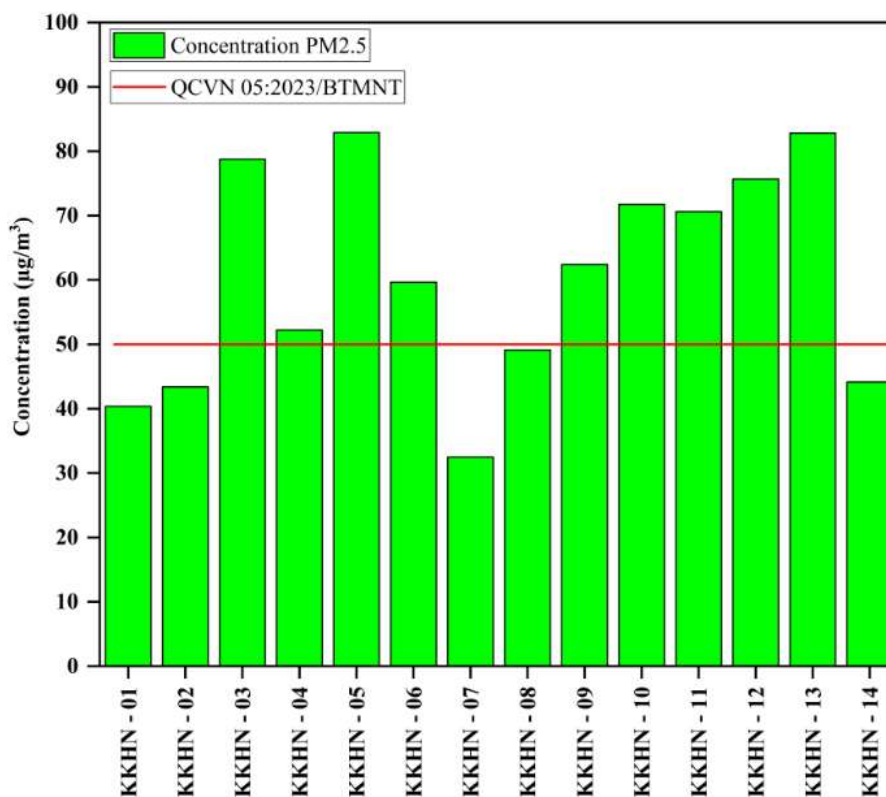


Figure 2: The PM_{2.5} concentration levels.

Concentration of dl-PCBs

Fig. 3 shows that the measured dl-PCBs concentrations during the sampling period in the dry season in Hanoi exhibit significant fluctuations, ranging from 10^{-3} pg TEQ/ m^3 (recorded in sample 0425HN10) to 11×10^{-3} pg TEQ/ m^3 (in sample 0425HN07), representing a more than tenfold difference. The trend shows considerable variability, likely reflecting the occurrence of localized pollution events, with markedly higher concentrations recorded in samples 0425HN06, 0425HN07, and 0425HN13, with values of 9×10^{-3} pg TEQ/ m^3 , 11×10^{-3} pg TEQ/ m^3 , and 8×10^{-3} pg TEQ/ m^3 ,

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/ m^3 , which is comparable to values reported in other regions, such as northern Taiwan (2×10^{-3} - 5×10^{-3} pg TEQ/ m^3) (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/ m^3 (Trinh *et al.*, 2018), and in China, where concentrations ranged from 7×10^{-3} - 16×10^{-3} pg TEQ/ m^3 (Die *et al.*, 2015).

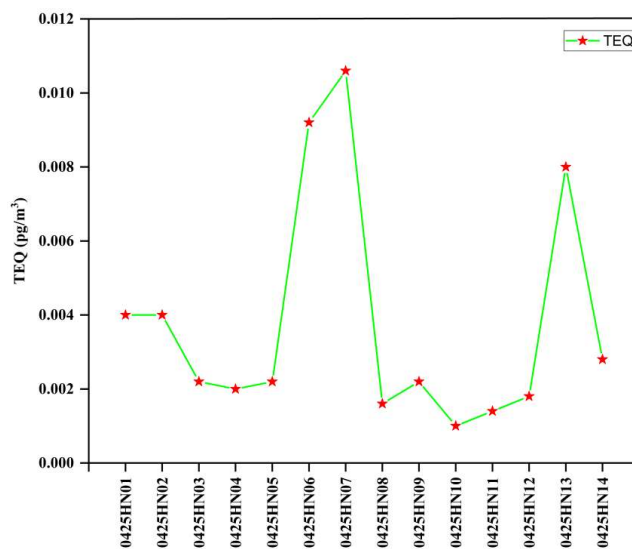


Figure 3: The concentration levels of dl-PCB.

Discussion

Concentration of PM_{2.5}

The monitoring results showing an average PM_{2.5} concentration (60.3 $\mu\text{g}/\text{m}^3$) in early April 2025 indicate a particularly severe pollution situation. This value is nearly equivalent to the average (59.5 $\mu\text{g}/\text{m}^3$) 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 causing high PM_{2.5} levels, due to the accumulation of pollutants emitted locally when air masses stagnate over Hanoi City, which has dense traffic and construction activities (Bui & Duong, 2019).

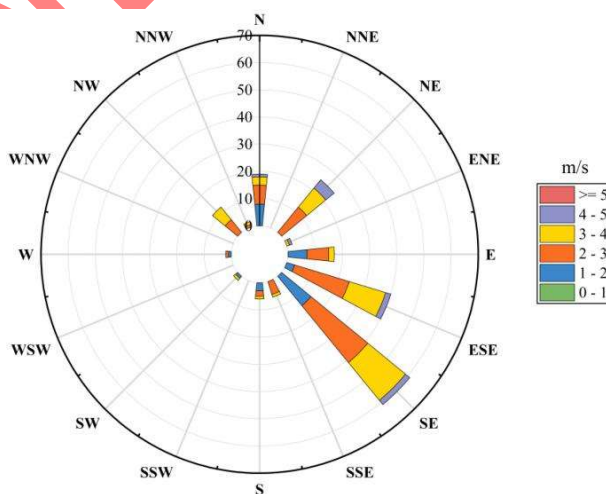


Figure 4: Windrose during sampling time.

Another issue in recent years in Hanoi City, studies have shown that straw burning also contributes to air pollution in the city (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 activities, and other human activities within the urban area itself.

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, contributing up to 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 through de novo synthesis during combustion activities, account for about 35 - 45% of total dl-PCBs. Additionally, lower-chlorinated dl-PCBs 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 have a significant influence on the levels of dl-PCBs in the air of Hanoi City.

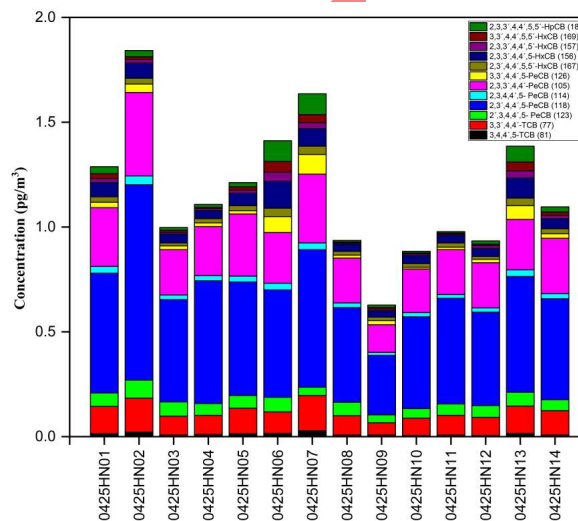


Figure 5: Concentration levels of the congeners dl-PCBs.

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 is reflecting 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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Author contributions: Bui Duy Linh: Formal analysis, numerical simulations, sensitivity analysis, investigation, visualization, writing - original draft; Hoang Anh Le: Conceptualization, methodology, data curation, visualization, writing - review & editing, response to editor and reviewers, 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, numerical simulations, sensitivity 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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