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# Influence of indoor environmental parameters on phthalate concentrations in bedrooms

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ABSTRACT

This study investigated the influence of three indoor environmental parameters: ventilation (expressed as air exchange rate, $h^{-1}$), temperature, and relative humidity, on phthalate concentration in dust and in estimated airborne. We monitored environmental parameters and collected dust samples in 327 bedrooms in Tianjin, China. Air exchange rates were estimated using occupants-generated $CO_2$ as a tracer gas. Six common phthalates were analyzed as components of dust: Diethyl Phthalate (DEP), Di-isobutyl Phthalate (DiBP), Di-n-Butyl Phthalate (DnBP), Benzyl Butyl Phthalate (BBzP), Di (2-Ethylhexyl) Phthalate (DEHP) and Di-isononyl Phthalate (DiNP). Phthalate concentrations were compared among environmental parameters categorized as low (below median) and high (above median) using Mann-Whitney *U* tests. Quantitative associations of phthalate concentrations with environmental parameters were further explored with exponential fittings based on a binning method. We observed a dilution effect of ventilation on low molecular weight phthalates, which was significant for DiBP, whose concentration decreased by 32 % with an increase in air exchange rate ($\Delta = 1\ h^{-1}$). We found a positive association between phthalate concentrations and indoor air temperature; the dust-phase phthalate concentration increased by 11 %, for each 1 °C increase in indoor air temperature. The results indicate that continuous ventilation may be an effective strategy to reduce concentrations of the more volatile phthalates in homes. A higher indoor temperature may lead to increased phthalate concentrations in home environments.

## 1. Introduction

Phthalates are ubiquitous pollutants in the indoor environment (Zhang et al., 2020) that have been associated with various adverse health outcomes (Bornehag et al., 2015; Chen et al., 2024; Hoppin et al., 2013). They are widely used as plasticizers and fixatives in consumer products, such as polyvinyl chloride flooring, toys, food packaging, and personal care products (Enyoh and Wang, 2024; Schettler, 2006). Phthalates are not covalently bound to any polymer matrix and are easily released into the environment from a number of sources (Fujii et al., 2003). As semi-volatile organic compounds (SVOCs), phthalates are easily adsorbed to particles, settled dust and surfaces (Weschler and Nazaroff, 2010). They partition among the gas phase, airborne particles, settled dust and available surfaces in the indoor environment (Weschler and Nazaroff, 2008). The emission and adsorption processes of phthalates are directly influenced by indoor conditions, such that phthalate concentrations vary depending on environmental factors (Wei et al., 2018).

Indoor environmental parameters, such as ventilation, temperature and relative humidity, have been investigated before (Clausen et al., 2007, 2012; Li et al., 2023; Liu et al., 2015). Theoretical analysis has suggested that increased ventilation could reduce concentrations of airborne phthalates (Liu et al., 2015; Xu et al., 2009). Controlled experimental studies have demonstrated that higher temperature would enhance phthalate emissions from indoor sources, subsequently raising airborne phthalate concentrations (Bi et al., 2015; Clausen et al., 2012;

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Liang and Xu, 2014; Zhou et al., 2021). Clausen et al. (2007) reported that the emission rate of Di (2-Ethylhexyl) Phthalate (DEHP) from vinyl flooring in a Field and Laboratory Emission Cell (FLEC) was independent of relative humidity. While these chamber experiments and/or theoretical models provide valuable insights into the impact of environmental parameters on phthalate concentrations, they may not accurately reflect the relationship in real-world living environments.

Previous field studies on the association between indoor environmental parameters and phthalate concentrations have been limited by methodology and sample size. First, critical parameters such as ventilation rates have seldom been precisely measured. For instance, Pei et al. (2018) estimated ventilation through infiltration and window opening/close status, identifying an inverse association between ventilation and phthalate concentration in dust. Sun et al. (2023) used window opening duration as a proxy for ventilation and observed a significant association between longer window opening duration and decreased concentrations of Di-n-Butyl Phthalate (DnBP) in dust. Second, some field studies have been hampered by small sample sizes. For example, Liu et al. (2020) conducted measurements in 17 homes and found no significant difference in phthalate concentrations at higher indoor air temperatures compared to those with lower indoor temperatures. Third, few studies have systematically controlled for confounding factors. In summary, previous studies yielded qualitative predictions but do not establish quantitative associations between indoor environmental parameters and phthalate concentrations.

Our study aims to investigate the influence of three major indoor environmental parameters: ventilation, air temperature, and relative humidity on phthalate concentrations in residential buildings, using sufficiently large sample sizes, precise measurements, and careful control of confounding factors. Furthermore, we seek to establish, where possible, quantitative associations between environmental parameters and phthalate concentrations. Our intent is to provide fundamental data and guidance for developing relevant standards, and to suggest effective quantitative control methods for phthalates in indoor environments.

## 2. Methods

This study is part of the China, Children, Homes, Health (CCHH) study conducted in Tianjin, China from 2013 to 2016. Detailed methodology of CCHH study has previously been reported (Hou et al., 2021; Sun et al., 2019; Zhang et al., 2020). The present paper reports on 327 bedrooms in urban Tianjin homes, that were inspected from September 2013 to January 2016. The home inspections included a dust sample collected from each child's bedroom for phthalate analysis. The indoor environmental parameters - indoor air temperature, relative humidity, and $CO_2$ concentration - were continuously monitored in the living room and bedroom(s) for at least 24 h.

This study was approved by the research office at Tianjin University. Participants provided written informed consent before participating in this study.

### 2.1. Measurement of environmental parameters and estimation of ventilation

Portable indoor air quality monitors (AZ® 7798, Instrument Corp., Taiwan, China) were placed in the living room and bedroom(s) of the inspected home to monitor indoor air temperature, relative humidity and $CO_2$ concentration. The monitors were positioned away from the sleeping person and to avoid heated radiator and room corners. Baránková's study (2004) demonstrated a sufficient mixing of metabolic $CO_2$ in the room air when excluding these non-representative sampling points. Data was collected at one-minute intervals for at least 24 h, resulting in a minimum of 1,440 data points per room for each environmental parameter. The accuracies of the sensors for temperature, relative humidity and $CO_2$ concentration measurement were ± 0.6 °C, ± 3 % RH and 50 ppm ± 5 % of reading respectively, as stated by the manufacturer. The indoor air quality monitors were calibrated according to manufacturer's instructions before home inspections.

The daily average indoor air temperature and relative humidity were calculated using data points monitored in the child's bedroom. Ventilation (expressed as air exchange rate, $h^{-1}$) in the child's bedroom at night was estimated using occupants-generated $CO_2$ as the tracer gas (Baránková, 2004; Hou et al., 2018), and known as the "$CO_2$ method". This method is based on the mass balance of $CO_2$ in an investigated indoor zone (equation (1)).

$$F + N \bullet V \bullet c_0 = V \bullet \frac{dc}{dt} + N \bullet V \bullet c \tag{1}$$

where $F$ is the emission rate of $CO_2$ ($m^3/h$) (equation (2)); $N$ is the air exchange rate ($h^{-1}$); V is the volume of the zone ($m^3$); $c_o$ is the outdoor $CO_2$ concentration ($m^3/m^3$); $t$ is the time (h); $c$ is the indoor $CO_2$ concentration ($m^3/m^3$).

The emission rate of $CO_2$ can be preliminarily estimated using equation (2) (Persily, 1997):

$$F = RQ \bullet 0.00201 \bullet H^{0.725} \bullet W^{0.425} \bullet M/(0.23 \bullet RQ + 0.77) \tag{2}$$

where $RQ$ is the respiratory quotient assumed to be 0.83; $H$ is the height of the occupant (m); $W$ is the weight of the occupant (kg); $M$ is the metabolic level in met (1 met = 58.2 $W/m^2$).

By solving equation (1), indoor $CO_2$ concentration can be expressed as in equation (3),

$$c = c_1 \exp(-N \bullet t) + \left(F \bullet 10^6/(N \bullet V) + c_0\right) \bullet (1 - \exp(-N \bullet t)) \tag{3}$$

where $c_1$ is the indoor $CO_2$ concentration in the initial measurement (ppm); $c$ and $c_0$ are expressed in ppm.

The whole home was considered as a single zone when the differences of $CO_2$ concentration in each room were less than 10 % of the volume-weighted average $CO_2$ concentration for home (equation (4)), or the $CO_2$ concentration in each room followed the same trend. In such cases, volume-weighted average $CO_2$ concentration was employed to assess air exchange rate. Otherwise, the child's bedroom was treated as a separate zone.

$$c_{aver} = (c_1 \bullet V_1 + c_2 \bullet V_2 + \cdots c_n \bullet V_n) \Big/ \sum V \tag{4}$$

where $c_{aver}$ is volume weighted average $CO_2$ concentration of the whole home; $c_n$ is the $CO_2$ concentration of room $n$; $V_n$ is the volume of room n.

We inserted the parameters - presumed air exchange rate, the initial value of measured indoor $CO_2$ concentration, the outdoor $CO_2$ concentration (assumed to be 400 ppm), the preliminarily calculated occupants' emission rate of $CO_2$, and the volume of the investigated zone - into equation (3) to estimate $CO_2$ concentrations at each time $t$. For estimation, the emission rate of $CO_2$ was constrained within a minimum defined as less height (−3 cm) and weight (−5 kg) and a metabolic rate of 0.7 met; and a maximum defined as greater height (+3 cm) and weight (+5 kg) and metabolic rate of 0.75 met. The least squares method was used to find the minimum error (sum of all individual differences between measured and estimated values (equation (5)) by changing the value of the estimated air exchange rate. The air exchange rate with minimum error was considered the optimal estimate. Meanwhile, the exact rate of $CO_2$ emission was determined.

$$Error = \sum_{i=0}^{i=m} \left(c_{i,meas} - c_{i,est}\right)^2 \tag{5}$$

where $c_{i,meas}$ is the measured $CO_2$ concentration at time $i$ (ppm); $c_{i,est}$ is the estimated $CO_2$ concentration at time $i$ (ppm).

A detailed description of the "$CO_2$ method" is provided in MethodsX, including the calculation method, practical application, validation, and sensitivity analysis.

### 2.2. Dust collection and chemical analysis of phthalates

Detailed dust collection and phthalate analysis methods have been described previously (Zhang et al., 2020; Zhao et al., 2021). Settled dust was collected using filter socks made of nylon mounted on a self-made aluminum mouthpiece connected to a household vacuum cleaner. At least 20–100 mg of settled dust was collected from moldings, window frames, shelves and other surfaces above the floor in child's bedroom. Dust from plastic surfaces was not collected to prevent artificially high concentrations from phthalate sources. Following dust collection, the filter sock with its dust sample was detached from the vacuum cleaner and wrapped in aluminum foil. Samples were stored at −20 °C until analysis.

Target phthalates were Diethyl Phthalate (DEP), Di-isobutyl Phthalate (DiBP), DnBP, Benzyl Butyl Phthalate (BBzP), DEHP and di-isononyl phthalate (DiNP). Glass vessels for chemical analysis were cleaned with chromic acid lotion to reduce background contamination. Dust was extracted with dichloromethane in a Soxhlet extractor, then concentrated and spiked with internal standard benzyl benzoate (BB). Phthalate concentrations were analyzed using an Agilent 6890 N gas chromatograph and a 5975C mass spectrometry detector. The average recoveries for DEP, DiBP, DnBP, BBzP, DEHP and DiNP as determined with spiked samples ranged from 70 % to 125 %. The internal standard method was used for quantification. Phthalate exposure levels were adjusted by subtracting average blank values from measured concentrations in dust samples. The limit of quantification (LOQ) was defined as 3 times the standard deviation of field blanks (3 × SD). Concentrations of phthalates in dust below the LOQs were assigned LOQ/2.

### 2.3. Estimation of airborne phthalate concentration

DEP is the most volatile of the targeted phthalates, and exists almost entirely in the gas phase while its presence in the particle phase can be negligible (Bekö et al., 2013). The gas-phase concentration of DEP can be estimated through its mass fraction in dust (Bekö et al., 2013).

$$C_g(DEP) = (C_d(DEP) + 0.2381)/0.0092 \quad (6)$$

where $C_g$ is the gas-phase phthalate concentration (ng/m$^3$) and $C_d$ is the mass fraction of phthalates in dust (μg/g).

For DiBP, DnBP, BBzP and DEHP, the indoor airborne concentration can be estimated by summing the gas-phase ($C_g$, ng/m$^3$) and particle-phase ($C_p$, ng/m$^3$) concentrations, as shown in equations (7) and (8) (Weschler and Nazaroff, 2010):

$$C_g = \frac{C_d}{K_d} \quad (7)$$

$$C_p = C_g \bullet K_p \bullet TSP \quad (8)$$

where $K_d$ is the dust-gas partition coefficient (m$^3$/mg); $K_p$ is the particle-gas partition coefficient (m$^3$/μg); *TSP* is the concentration of total suspended particles (μg/m$^3$), assumed to be 50 μg/m$^3$. The partition coefficients were calculated using empirical equations (Bekö et al., 2013; Weschler and Nazaroff, 2010) and adjusted according to indoor air temperature (Li et al., 2023).

For DiNP, a less volatile phthalate, the airborne concentration is negligible and therefore excluded from the subsequent analysis.

Detailed methods for estimating airborne phthalate concentration are provided in the **supplementary materials**.

### 2.4. Statistical analysis

The concentration of phthalates was not normally distributed. Their seasonal distribution, along with those of the three indoor environmental parameters, are reported as median and interquartile. Three environmental parameters measured in summer and non-summer seasons were analyzed separately to reduce their interactions. Phthalate concentrations in bedrooms with low (below median) versus high (above median) environmental parameters were compared using Mann-Whitney *U* tests. If the differences in phthalate concentrations reached significance ($P < 0.05$), the influence of indoor environmental parameters were quantitatively analyzed, with the environmental parameters divided into multiple bins, and the median phthalate concentration for each bin was calculated. These median values of phthalates were fitted to an exponential function (equation (9)) (Lunderberg et al., 2019; Sun et al., 2024), to facilitate intuitive comprehension of the variation in phthalate concentration with step changes in environmental parameters.

$$y = a \bullet b^x \quad (9)$$

where $y$ is the phthalate concentration; $x$ is the indoor environmental parameter; and $a$ and $b$ are the regression coefficients.

Additionally, sensitivity analysis was conducted to account for potential confounding factors in the multivariate regression models, and percentage change and least square geometric mean (LSGM) of phthalate concentration are reported. Sensitivity analysis was conducted using PROC GLM in SAS 9.4. Other statistical analyses were performed with SPSS 26.

## 3. Results

### 3.1. Indoor environmental parameters and phthalate concentrations

Home inspections and measurements were carried out in 65, 73, 79 and 110 bedrooms in spring, summer, fall and winter respectively in urban Tianjin. Seasonal and monthly distributions of the bedroom environmental parameters are shown in Fig. 1. The air exchange rates in the investigated bedrooms ranged from < 0.1 h$^{-1}$ to 13.0 h$^{-1}$, with the highest seasonal median levels in summer (1.1 h$^{-1}$) and lower levels in spring, autumn and winter (0.3 h$^{-1}$, 0.3 h$^{-1}$ and 0.4 h$^{-1}$, respectively). The indoor air temperatures ranged from 14.2 °C to 31.8 °C, with median values of 21.9 °C, 28.6 °C, 19.6 °C and 21.4 °C in spring, summer, autumn and winter, respectively. The relative humidity ranged from 14 % to 75 %, with the highest values in summer and lowest in winter season. The three environmental parameters were not correlated with each other (data not shown).

Dust-phase concentrations of phthalate were obtained for 284 valid dust samples. Forty-three samples were discarded due to insufficient weight or sample loss. There were no significant differences in environmental parameters between the fully inspected 327 bedrooms and the 284 bedrooms with valid dust samples (data not shown). The seasonal distribution of phthalate concentrations in bedroom dust is shown in Table 1.

Temperature data were missing in four bedrooms with valid dust samples, thus airborne phthalate concentrations were evaluated in a total of 280 bedrooms. The estimated airborne (gaseous and particle phase) concentrations of phthalates, calculated using dust concentrations, are shown in Table 2.

### 3.2. Associations between indoor environmental parameters and phthalate concentrations

The air exchange rates were categorized into low and high groups using median values as the cutoff (1.1 h$^{-1}$ at summer and 0.3 h$^{-1}$ at non-summer season) to compare the phthalate concentration distributions of the two groups, as shown in Fig. 2 (summer) and **Fig. S1** (non-summer). In summer, a negative trend was observed between night-time air exchange rate and the concentrations of three low molecular weight phthalates (DEP, DiBP and DnBP), especially for DiBP ($P < 0.05$). Subsequently, the night-time air exchange rate was binned at 0.3 h$^{-1}$ intervals, and the association between air exchange rate and DiBP

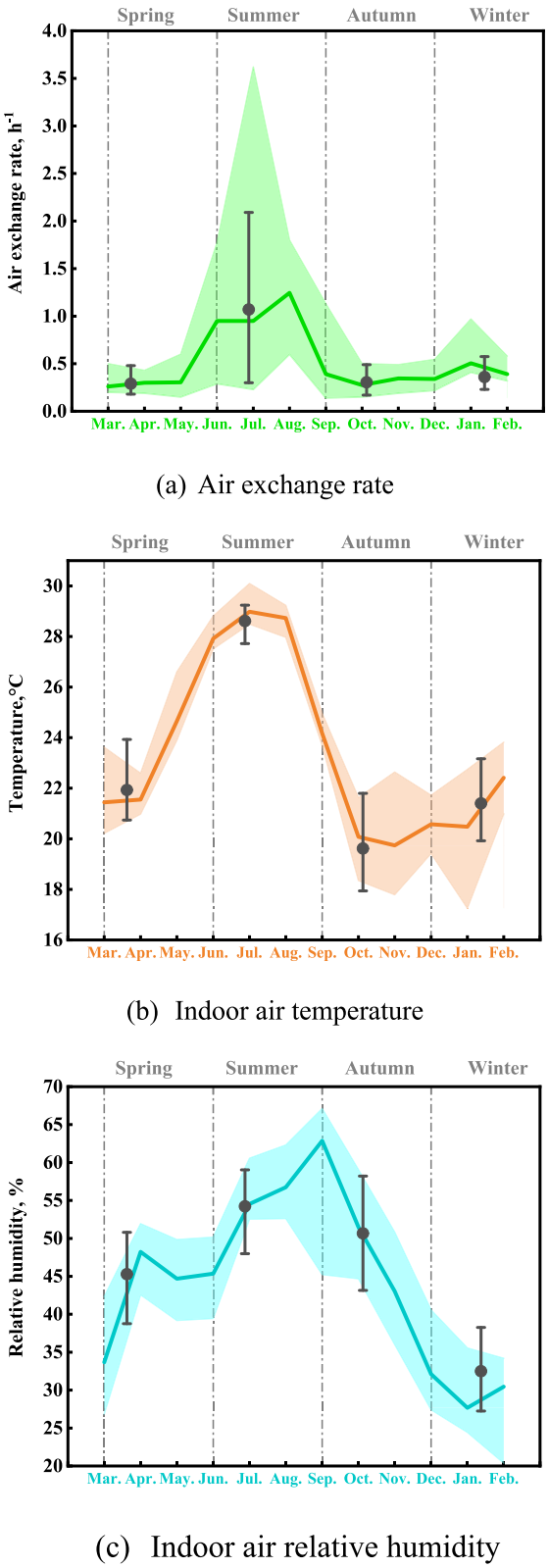


**Fig. 1.** Seasonal and monthly distributions of indoor environmental parameters in 327 children's bedrooms. (a) air exchange rate; (b) indoor air temperature; (c) indoor air relative humidity. The lines show the monthly median values, and the colored regions represent the interquartile range of the indoor environmental parameters in bedrooms. Dots show the seasonal median and bars show the interquartile range.

**Table 1**
Distribution of dust-phase phthalate concentrations in children's bedrooms in urban Tianjin (mass fractions, μg/g), n = 284.

| | | DEP | DiBP | DnBP | BBzP | DEHP | DiNP |
|---|---|---|---|---|---|---|---|
| Total | 25 % | 0.19 | 8.80 | 15.99 | 0.04 | 54.02 | 0.20 |
| | Median | 0.33 | 19.87 | 49.42 | 0.11 | 165.01 | 0.36 |
| | 75 % | 0.70 | 43.92 | 164.71 | 0.30 | 406.20 | 0.85 |
| Spring (n = 59) | 25 % | 0.19 | 8.46 | 21.60 | 0.06 | 57.48 | 0.20 |
| | Median | 0.33 | 19.95 | 43.37 | 0.15 | 133.12 | 0.36 |
| | 75 % | 0.68 | 35.26 | 237.26 | 0.38 | 299.66 | 0.91 |
| Summer (n = 64) | 25 % | 0.17 | 11.47 | 9.84 | 0.04 | 50.80 | 0.22 |
| | Median | 0.34 | 21.70 | 33.55 | 0.13 | 161.40 | 0.40 |
| | 75 % | 0.71 | 53.05 | 159.10 | 0.44 | 599.08 | 0.97 |
| Autumn (n = 68) | 25 % | 0.20 | 4.64 | 13.62 | 0.05 | 45.16 | 0.21 |
| | Median | 0.32 | 14.73 | 48.06 | 0.13 | 198.34 | 0.28 |
| | 75 % | 0.61 | 41.27 | 134.38 | 0.27 | 401.23 | 0.80 |
| Winter (n = 93) | 25 % | 0.20 | 9.42 | 19.08 | 0.03 | 61.39 | 0.20 |
| | Median | 0.35 | 22.25 | 56.04 | 0.09 | 167.82 | 0.36 |
| | 75 % | 0.73 | 56.50 | 157.00 | 0.24 | 487.94 | 0.79 |

**Table 2**
Distribution of estimated airborne phthalate concentrations in children's bedrooms in urban Tianjin (ng/m$^3$), n = 280.

| | | DEP | DiBP | DnBP | BBzP | DEHP |
|---|---|---|---|---|---|---|
| Total | 25 % | 46.53 | 110.26 | 134.43 | 0.05 | 47.93 |
| | Median | 61.75 | 305.60 | 455.82 | 0.13 | 147.96 |
| | 75 % | 101.42 | 682.68 | 1319.58 | 0.34 | 365.89 |
| Spring (n = 57) | 25 % | 46.53 | 143.49 | 191.30 | 0.08 | 51.72 |
| | Median | 61.75 | 288.89 | 436.48 | 0.18 | 120.64 |
| | 75 % | 99.79 | 460.35 | 1831.60 | 0.40 | 269.12 |
| Summer (n = 64) | 25 % | 44.36 | 308.86 | 176.37 | 0.05 | 45.81 |
| | Median | 62.84 | 572.53 | 672.18 | 0.16 | 145.75 |
| | 75 % | 102.51 | 1289.46 | 3022.37 | 0.59 | 542.19 |
| Autumn (n = 67) | 25 % | 46.53 | 55.69 | 103.05 | 0.06 | 37.73 |
| | Median | 59.58 | 152.55 | 290.37 | 0.14 | 173.17 |
| | 75 % | 90.01 | 461.41 | 983.30 | 0.29 | 367.03 |
| Winter (n = 92) | 25 % | 47.62 | 107.58 | 159.45 | 0.04 | 55.12 |
| | Median | 63.92 | 243.31 | 477.36 | 0.11 | 149.99 |
| | 75 % | 107.40 | 673.86 | 1237.40 | 0.27 | 432.61 |

concentrations was quantitatively analyzed as shown in Fig. 3. Fig. 3 shows that with an increase of 1 $h^{-1}$ in the air exchange rate, the concentration of the dust-phase DiBP decreased by 32 %, while the estimated concentration of airborne DiBP decreased by about 30 % for every 1 $h^{-1}$ increment. In non-summer seasons, no clear trend was observed between air exchange rate and phthalate concentration (**Fig. S1**).

The indoor air temperature was divided into two groups based on the median values (28.6 °C in summer and 21.1 °C in non-summer season) to investigate its association with phthalate concentrations, as shown in Fig. 4 (summer) and Fig. 5 (non-summer). Positive trends between phthalate concentrations and indoor air temperature were observed in both summer and non-summer seasons. In summer, both dust-phase and airborne concentration of DEHP ($P < 0.05$) significantly increased with higher indoor air temperature, while in the non-summer season, the significant influence of temperature extended to DEP, DiBP and DnBP. Where significant associations were identified, further quantitative analysis was performed by binning indoor air temperature into 1 °C intervals, as shown in Fig. 6. The dust-phase phthalate concentration increased by 11 %, while the estimated airborne concentration increased by 6 % – 25 %, for each 1 °C increase in indoor air temperature.

We did not find a clear association between phthalate concentrations and indoor air relative humidity (**Fig. S2 and S3**).

### 3.3. Sensitivity analysis

Confounding factors, such as utilization of air conditioning in summer, occupancy levels, and phthalate sources, were thoroughly considered for sensitivity analysis (**Tables S1-S6**). After adjusting for these

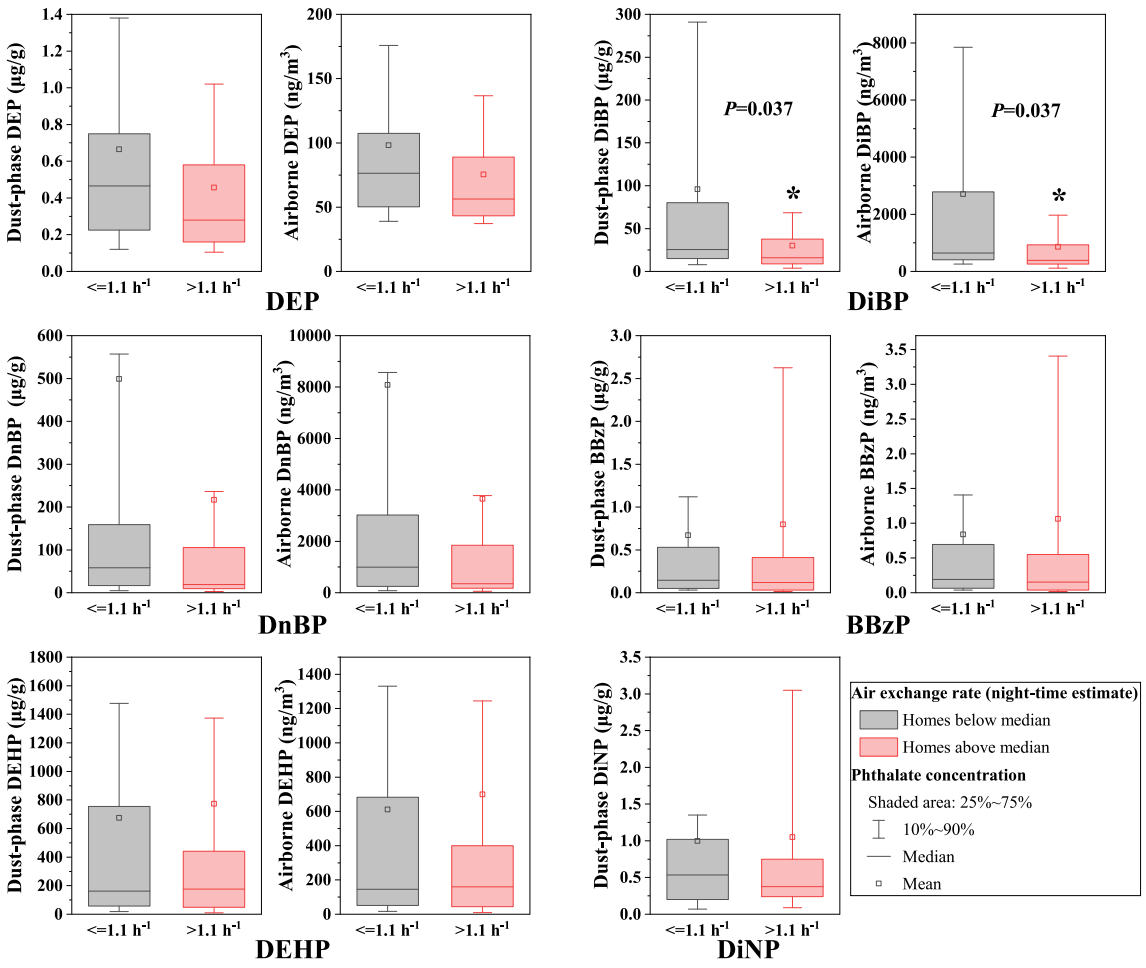


**Fig. 2.** Distribution of phthalate concentrations with low (below median, 1.1 $h^{-1}$) and high (above median) night-time air exchange rates in bedrooms sampled during the summer season (June – August, n = 62). Differences were tested using Mann-Whitney *U* test. Airborne DiNP was excluded due to its negligible concentration.

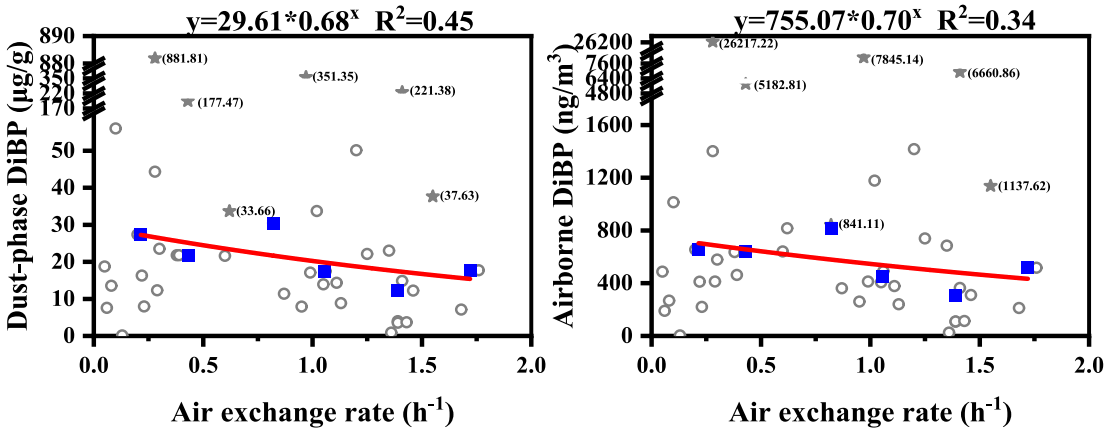


**Fig. 3.** The exponential curve (red line) estimating quantitative associations between night-time air exchange rates (Δ = 0.3 $h^{-1}$) and the median DiBP concentrations (blue points) in summer (n = 62). The grey circles are phthalate concentrations in each bedroom. The asterisks denote outliers.

factors, a consistent pattern of dilution effects of ventilation on low molecular weight phthalates was observed during the summer season (Tables S1, S2a and S3a). Positive trends between indoor air temperature and phthalate concentration were still observed in both summer and non-summer seasons (Tables S4-S6).

## 4. Discussion

We investigated associations of indoor phthalate concentrations with air exchange rate, indoor air temperature and relative humidity in 327 bedrooms in Tianjin dwellings. We observed a dilution effect of ventilation on low molecular weight phthalates. Positive associations were found between indoor air temperature and phthalate concentrations.

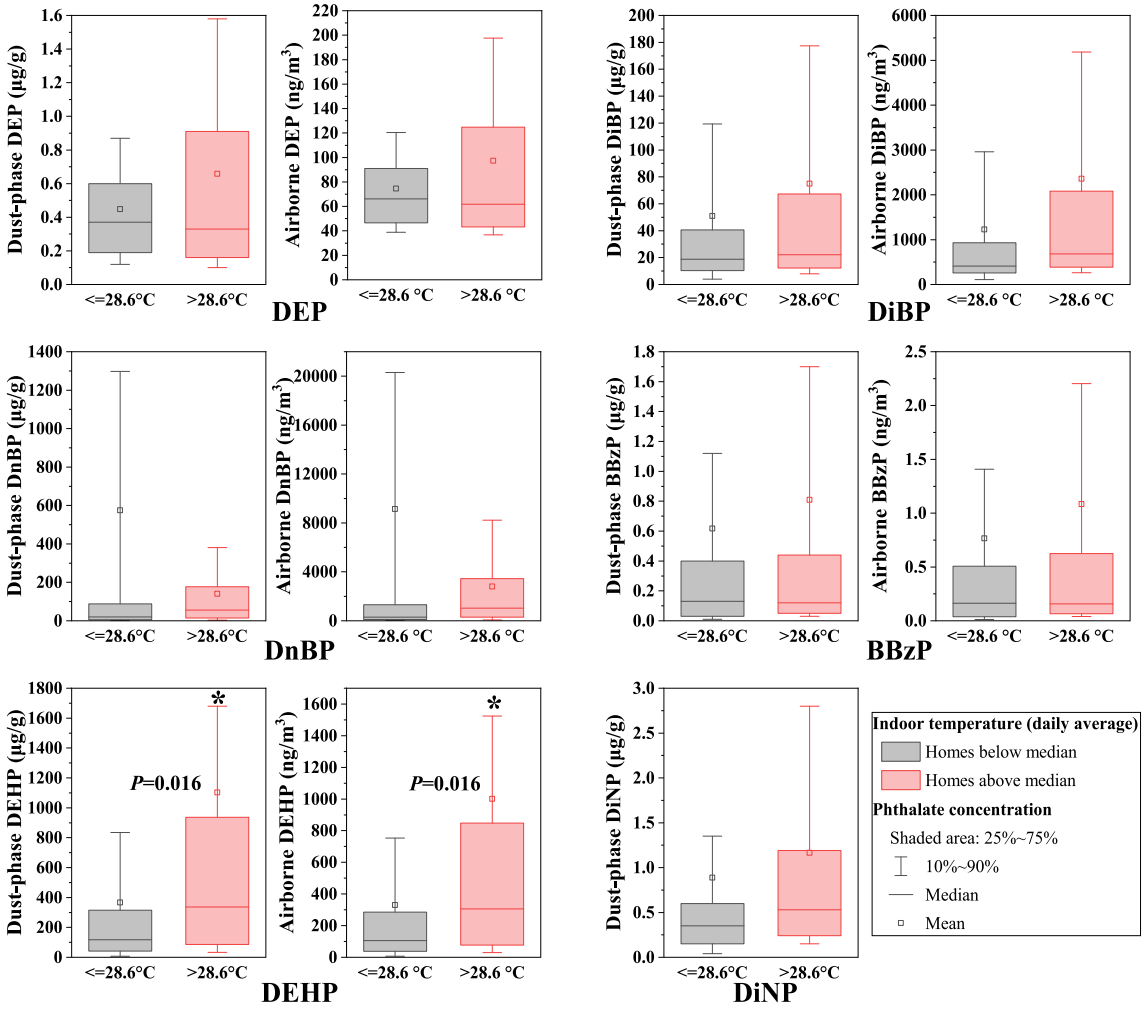


**Fig. 4.** Distribution of phthalate concentrations with low (below median, 28.6 °C) and high (above median) indoor air temperature in bedrooms sampled during the summer season (June – August, n = 64). Differences were tested using Mann-Whitney *U* test. Airborne DiNP was excluded due to its negligible concentration.

This study contributes quantitative associations between environmental parameters and phthalate concentrations. By evaluating ventilation using a more precise "$CO_2$ method" in a large study population, we were able to quantify the association between ventilation (expressed as air exchange rate, $h^{-1}$, the volumetric out-to-indoor airflow rate divided by building volume) and phthalate concentrations. Specifically, with an increase of air exchange rate ($\Delta = 1\ h^{-1}$), the concentration of the dust-phase DiBP decreased by 32 %. This quantitative association will facilitate precise regulation of phthalates in indoor environments. For example, during the summer season, a typical bedroom in our study has a median air exchange rate of 1.1 $h^{-1}$ and a median dust-phase concentration of DiBP at 21.7 μg/g. In this bedroom, an increment of 1 $h^{-1}$ in the air exchange rate would result in approximately a 10th percentile reduction of DiBP in the dust. Similarly, the quantitative association between indoor air temperature and phthalate concentrations will provide a foundation for the development of polices and standards.

The dilution effect of ventilation on phthalate concentration observed is consistent with previous theoretical analysis (Liu et al., 2015; Xu et al., 2009) and field studies (Pei et al., 2018; Sun et al., 2023). However, Li et al. (2023) found an indiscernible effect of ventilation in a simulated office environment. They observed that enhancement of air exchange rate by a factor of 3~5 for hours did not effectively reduce DiBP and DnBP concentration in the air. One possible explanation for the inconsistent findings is that longer durations of ventilation may be required to yield a discernible effect. In our summer inspections, we conducted concurrent measurement of one-week average air exchange rates by perfluorocarbon tracer (PFT) method (Dietz et al., 1986) in 8 homes. The night-time air exchange rate was strongly correlated to one-week average value, with a Spearman correlation coefficient of 0.81 ($p < 0.05$). The median values were 1.2 $h^{-1}$ (night-time) versus 0.8 $h^{-1}$ (one-week average), with means of 1.5 $h^{-1}$ and 0.9 $h^{-1}$, respectively. We assume night-time air exchange rates in summer reflect overall ventilation patterns in bedrooms. Therefore, a dilution effect of ventilation on phthalate concentration during summer was observed in our study.

In addition, we found that increasing ventilation had a greater effect on reducing concentration of low molecular weight phthalates (DEP, DiBP and DnBP) compared to high molecular weight DEHP and DiNP. Our results are consistent with the findings of Weschler and Nazaroff (2008), who noted that increased ventilation was not helpful in controlling exposures of phthalates with $logK_{oa}$ (logarithm of octanol–air partition coefficient) > 12. The $logK_{oa}$ is less than 10 for DEP, DiBP, DnBP and BBzP, while for DEHP and DiNP is larger than 12. As the values of $K_{oa}$ increase, equilibrium partitioning between the gas phase and the settled dust occurs at a decreasing rate. In indoor settings, ventilation changes diurnally, hence, the phthalate molecules may not have sufficient time to equilibrate between the adsorbed phase and the gas phase. Weschler and Nazaroff (2008) found that if the only removal mechanism is ventilation, compounds with $logK_{oa} > 10$ may persist indoors for hundreds to thousands of hours, while compounds with $logK_{oa} > 12$ may persist for years.

It is interesting that we found the dilution effect of ventilation on phthalates in bedrooms sampled during the summer season (June-

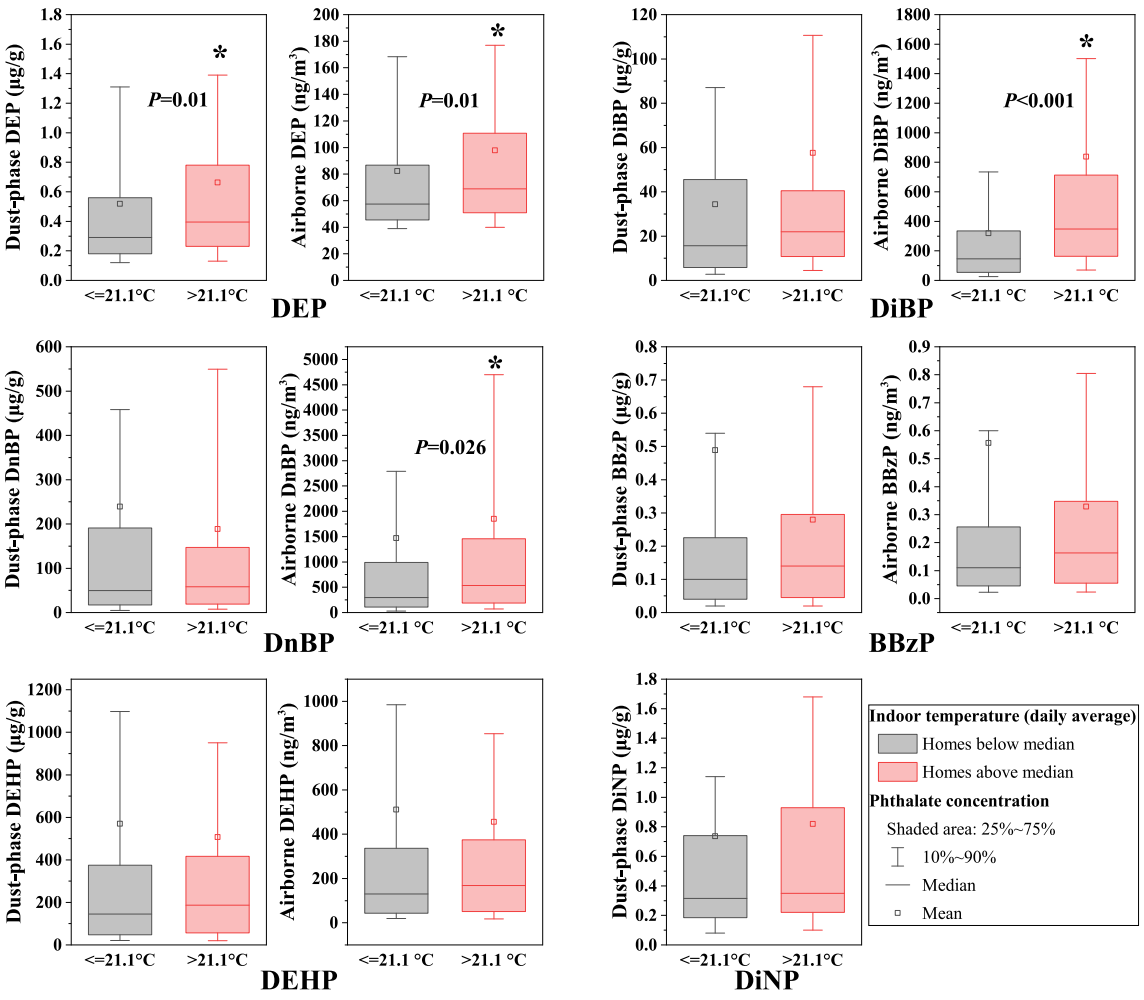


**Fig. 5.** Distribution of phthalate concentrations at low (below median, 21.1 °C) and high (above median) indoor air temperature in bedrooms sampled during the non-summer season (September – May, n = 216). Differences were tested using Mann-Whitney *U* test. Airborne DiNP was excluded due to its negligible concentration.

August) but not in the non-summer season. This observation may be attributed to the narrow variation of air exchange rates in bedrooms in the non-summer season (see Fig. 1 (a)), during which the air exchange rate was centralized at a low level (5 %-95 % quantile: 0.1–1.1 $h^{-1}$). In summer, air exchange rates varied greatly among bedrooms (5 %-95 % quantile: 0.1–5.5 $h^{-1}$), such that finding a relationship between air exchange rates and phthalate concentrations is more plausible.

We observed positive associations between indoor air temperature and airborne phthalate concentrations, which is consistent with previous experimental studies (Bi et al., 2015; Clausen et al., 2012; Zhou et al., 2021). Increase in temperature has been found to significantly contribute to the emission of phthalates (Liang and Xu, 2014), leading to higher concentrations of airborne phthalates. Additionally, we observed positive associations between dust-phase phthalate concentrations and temperature. The impact of an increase in indoor air temperature on dust-phase phthalate concentration depends on competition between the decrease in the dust-gas partition coefficient and the increase in gas-phase concentration (Bi et al., 2015). As the temperature increases, phthalates are increasingly emitted into the air from indoor sources such as building materials (for example laminated wooden flooring and PVC window frames) and /or chemical products (such as leather polish and perfume) (Zhang et al., 2020). It has been reported that when the indoor air temperature in the home increased from 25 to 35 °C, the gas-phase concentration of phthalates could increase by a factor of more than 10 times (Liang and Xu, 2014), as the corresponding dust-gas partition coefficient becomes 0.2–0.3 times of the original value (according to equation S6 in **supplementary material**). Therefore, a possible explanation for the observed increase in dust-phase phthalate concentration is that the effect of the rising gas-phase concentration with increased temperature exceeds the decrease in the dust-gas partition coefficient.

Interestingly, we found more significant associations between phthalate concentrations and indoor air temperature in non-summer season compared to summer. Wider indoor air temperature variation in non-summer season than in summer (see Fig. 1 (b)) may account for this finding. Another explanation may be that in cooler weather, more phthalates accumulate in dust, so that there is more to be released when the temperature increases.

In our study, we did not observe a clear association between relative humidity and phthalate concentration. A previous study has also reported that the emission of phthalates remains unaffected by changes in relative humidity (Clausen et al., 2007). In contrast, the degradation of phthalates in dust has been observed when the relative humidity exceeded 80 % (Bope et al. 2019). The lack of significant associations in our study may be due to the fact that the relative humidity range (14 %-75 %) did not reach the critical threshold required to initiate substantial phthalate degradation. Future studies are recommended to investigate this hypothesis further.

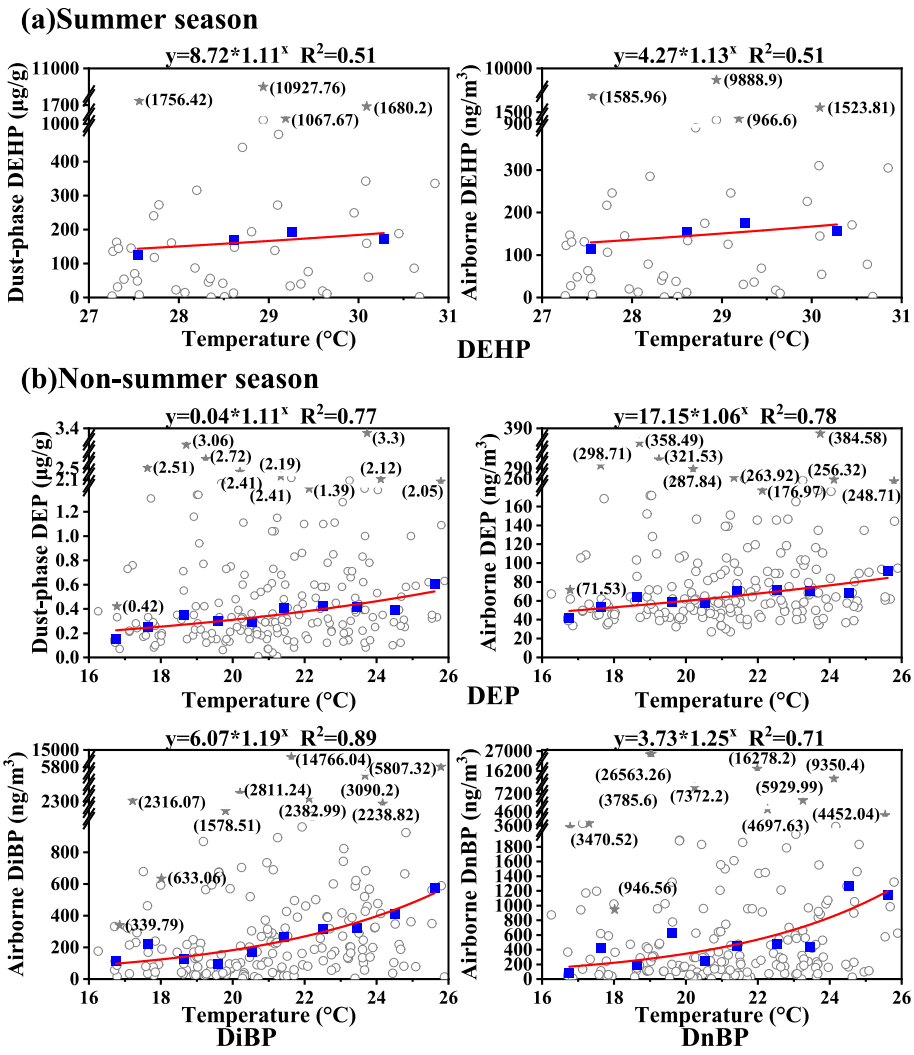


**Fig. 6.** The exponential curve (red line) estimating quantitative associations between indoor air temperature (Δ = 1 °C) and the median phthalate concentrations (blue points) in summer (a) (n = 64) and non-summer season (b) (n = 216). The grey circles are phthalate concentrations in each bedroom. The asterisks denote outliers.

### *4.1. Strengths and limitations*

This study has several strengths. The main strength is dust collection and extensive measurements of three environmental parameters of a large study population. Therefore, the effects of environmental parameters on phthalate concentrations could be analyzed quantitatively. Furthermore, potential confounding factors were collected and fully considered.

We acknowledge potential biases and limitations in this study. One limitation is that we assumed a fixed concentration of TSP when we estimated airborne concentrations of phthalates, which does not capture the variability of particle levels in different bedrooms. Also, we did not consider the influence of cleaning frequency on the exposure to phthalates (Li et al., 2023; Zhou et al., 2024). Although this may have caused underestimated concentrations of airborne phthalates, it does not change the significance of their associations with air exchange rate and temperature.

## 5. Conclusions

We observed that ventilation reduces the concentration of low molecular weight phthalates significantly for DiBP. With an increase (Δ = 1 $h^{-1}$) in air exchange rate, the concentration of dust-phase DiBP decreased by 32 %. Furthermore, we identified a positive association between phthalate concentrations and indoor air temperature. The dust-phase phthalate concentration increased by 11 %, for each 1 °C increase in indoor air temperature. Our results indicate that continuous ventilation may be an effective strategy to reduce concentrations of the more volatile phthalates in residential environments. A higher indoor air temperature may lead to increased phthalate concentrations in home environments.

## CRediT authorship contribution statement

**Yuxuan Zhao:** Writing – original draft, Software, Methodology, Formal analysis. **Anna-Sofia Preece:** Writing – review & editing. **Mengfang Wan:** Formal analysis. **Jing Hou:** Methodology, Investigation. **Yatai Li:** Writing – review & editing. **Qihong Deng:** Writing – review & editing. **Yuexia Sun:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

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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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109447.

## Data availability

The authors do not have permission to share data.

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