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Influence of outdoor phthalates on indoor phthalate concentrations and exposures in Chinese residences: A modeling study and its implications

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ABSTRACT

Indoor exposure to phthalates poses significant health risks, making accurate exposure assessment critical for developing effective control strategies. While studies often neglect outdoor phthalate concentrations due to dominant indoor sources, field data of high outdoor levels indicate potential outdoor contributions. However, the extent to which outdoor-derived phthalates contribute to indoor exposure remains insufficiently understood. This study employs an integrated modeling approach to quantify the impact of outdoor phthalates on indoor concentrations and associated exposures within a typical residential setting in China. Simulation results show that increasing the dimensionless outdoor gas-phase concentration ($C_{g,out}$*, the ratio of outdoor gas-phase concentration to indoor source emission parameter y_0) from 0 to 0.05 results in 50 % and 10 % increase in indoor airborne di(n-butyl) phthalate (DnBP) and di(2-ethylhexyl) phthalate (DEHP) levels, respectively. Children's exposure would increase by >20 % when $C_{g,out}$* reaches 0.02 for DnBP and 0.05 for DEHP, respectively. When long-term outdoor monitoring data were incorporated, models revealed that excluding outdoor contributions could underestimate children's total phthalate exposure indoors by as much as 40 % in selected urban Chinese cities. Moreover, the penetration of outdoor phthalates would diminish the effectiveness of air purifiers by limiting dust-phase phthalate removal. The findings elucidate how outdoor phthalates influence indoor concentration and provide a framework for assessing the need to incorporate this influence. This study highlights the need to reconsider the role of outdoor phthalates when modeling indoor phthalate exposure and offer mechanistic insights critical for designing advanced air cleaning systems that effectively address indoor phthalate pollution.

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Nomenclature

Symbol	Description	Unit
C_g	Indoor gas-phase phthalate concentration	μg/m^3
C_p	Indoor particle concentration	μg/m^3
C_{p_out}	Outdoor particle concentration	μg/m^3
C_{sp}	Indoor particle-phase phthalate concentration	μg/m^3
C_{surf}	Phthalate concentration adsorbed on indoor surface	μg/m^2
X_d	Indoor dust-phase phthalate concentration	μg/μg
C_{g_out}	Outdoor gas-phase phthalate concentration	μg/m^3
C_{sp_out}	Outdoor particle-phase phthalate concentration	μg/m^3
C_g*	Normalized indoor gas-phase phthalate concentration (equals to C_g/y_0)	–
C_{sp}*	Normalized indoor particle-phase phthalate concentration (equals to C_{sp}/y_0)	–
X_d*	Normalized dust-phase phthalate concentration (equals to X_d/y_0)	m^3/μg
C_{g_out}*	Normalized outdoor gas-phase phthalate concentration (equals to C_{g_out}/y_0)	–
C_{sp_out}*	Normalized outdoor particle-phase phthalate concentration (equals to C_{sp_out}/y_0)	–
C_{surf}*	Normalized surface-sorbed phthalate concentration (equals to C_{surf}/y_0)	m
y_0	Gas-phase phthalate concentration immediately adjacent to source surface	μg/m^3
V	Room volume	m^3
A_e	Surface area of indoor emission sources	m^2
A_{surf}	Total indoor sink surface area	m^2
A_f	Floor area	m^2
A_{sp}	Surface area-to-volume ratio of suspended particles	m^{-1}
h_m	Convective mass transfer coefficient above source/sink surface	m/s
h_{mp}	Mass transfer coefficient between particles and air	m/s
α_n	Natural air exchange rate	s^{-1}
α_{inf}	Air infiltration rate	s^{-1}
α_c	Equivalent air exchange rate for air cleaner	s^{-1}
K_{surf}	Partition coefficient between indoor surface and air	m
K_p	Indoor particle-air partitioning coefficient	m^3/μg
K_{p_out}	Outdoor particle-air partitioning coefficient	m^3/μg
K_d	Indoor dust-air partitioning coefficient	m^3/μg
P	Particle penetration factor	–
v_d	Particle deposition rate constant	s^{-1}
v_{df}	Particle deposition rate onto floor surface	m/s
R	Dust resuspension rate	s^{-1}
ρ_p	Density of suspended particles	μg/m^3
ρ_d	Density of settled dust	μg/m^3
M	Mass of settled dust per unit floor area	μg/m^2
DI_{total}	Total normalized daily intake under baseline scenario (without outdoor contribution)	m^3/kg/day
DI_{total}'	Total normalized daily intake under outdoor-involved scenario (with outdoor contribution)	m^3/kg/day
DI_{inh}	Normalized daily intake via inhalation	m^3/kg/day
DI_{ing}	Normalized daily intake via dust ingestion	m^3/kg/day
DI_{derm}	Normalized daily intake via dermal absorption	m^3/kg/day
IR_{inh}	Inhalation rate	m^3/day
IR_{ing}	Dust ingestion rate	μg/day
BW	Body weight	kg
$k_{p,g}$	Transdermal permeation coefficient for gas-phase phthalates	m/day
SA	Skin surface area	m^2
f_s	Fraction of skin exposed to indoor air	–
RD	Relative difference in total exposure	%
η_g	Removal efficiency of gas-phase phthalates by air cleaner	–
η_p	Removal efficiency of particle-phase phthalates by air cleaner	–

1. Introduction

Phthalates, commonly referred to as plasticizers, have been widely utilized since the 1920s to improve the flexibility, durability, and overall performance of synthetic materials, particularly polyvinyl chloride (PVC) [1]. These chemicals can constitute up to 50 % of the weight of PVC materials, making them indispensable in the production of a broad range of everyday products [2], such as soft PVC items, children's toys, food packaging, medical products, and various synthetic materials [3,4]. Moreover, lower-molecular-weight phthalates are used as solvents or carriers in cosmetics and personal care products [5]. Due to their widespread use and lack of chemical bonding within products, phthalates are readily released into the indoor environments, resulting in their ubiquitous presence.

Most of the phthalates are classified as semi-volatile organic compounds (SVOCs), characterized by their low vapor pressure that facilitates their adsorption onto airborne particles, settled dust, and indoor surfaces [6]. Consequently, human exposure occurs through multiple indoor pathways, including inhalation, ingestion of settled dust, dermal absorption from the gas-phase [7,8], and direct contact with phthalate-laden surfaces [9,10]. These exposures are associated with severe health risks, including endocrine disruption [11,12] and reproductive toxicity [13,14], neurodevelopmental disorders [15,16] and chronic diseases such as asthma [17] and diabetes [18]. Notably, China is the world's largest consumer of phthalates, accounting for 45 % of global usage, approximately

5.5 million tonnes annually [1]. Previous studies pointed out that di(isobutyl) phthalate (DiBP), di(n-butyl) phthalate (DnBP) and di (2-ethylhexyl) phthalate (DEHP) were the most abundant phthalates in indoor environments, with national dust phase concentration ranging from 39.6 to 1394.7 μg/g. Indoor phthalate exposure in China resulted in 3.32 million disability-adjusted life years (DALYs) in 2017 [19]. Among these, residences, offices, and schools were identified as the primary exposure microenvironments, collectively accounting for over 60 % of the total indoor exposure [20]. Therefore, there is an urgent need to assess and manage phthalate exposure in Chinese indoor environments.

The fate of indoor phthalates is closely linked to several dynamic processes, including emission from source materials, partitioning into the gas-phase, sorption onto airborne particles, settled dust and interior surfaces, and exchange between indoor and outdoor air [21–23]. Previously, studies assessing phthalate dynamics indoors have largely excluded outdoor contributions, assuming their impacts to be minimal due to significantly lower concentrations than those detected indoors [6,24,25]. For example, Wang et al. [26] reported mean indoor/outdoor (I/O) ratios of 16.7 and 18.1 for airborne di(isobutyl) phthalate (DiBP) and di(n-butyl) phthalate (DnBP), respectively, while Chen et al. [27] observed I/O ratios of 3.7–12.2, and 2.2–5.0 for $PM_{2.5}$-bound DnBP and di(2-ethylhexyl) phthalate (DEHP) in Beijing. However, this assumption is valid under strong indoor source and low ventilation conditions. During heavy air pollution episodes, outdoor phthalate concentrations may equal or exceed those typically found indoors. For example, DEHP bound to ambient $PM_{2.5}$ reached 0.14 μg/m^3 when outdoor $PM_{2.5}$ exceeded 200 μg/m^3 in Shanghai [28], and phthalate concentrations under moderate pollution conditions reached 0.45–0.7 μg/m^3 [29]. Similarly, Lu et al. [30] reported ambient levels of 0.19–1.1 μg/m^3 for DiBP, DnBP and DEHP in Hangzhou-levels comparable to average indoor concentrations reported in Chinese indoor environments [20]. These findings raise critical issues about the validity of excluding outdoor phthalate contributions in exposure models, especially in buildings with minimal indoor sources and/or elevated ventilation rates.

Accurate modelling of indoor phthalate behavior is essential not only for exposure assessment but also for designing effective air cleaning strategies to mitigate indoor human exposure [31]. Predictive models have been developed to evaluate air purifier performance under typical indoor conditions, but these models often fail to account for outdoor phthalate contributions [32,33]. In scenarios involving significant outdoor air pollution, this omission could lead to an overestimation of air cleaning efficiency and underestimation of actual exposure risks. To address these knowledge gaps, this study focuses on residential buildings as examples, and the objectives were therefore to: (1) develop a mass balance model that incorporates the influence of outdoor phthalates to mechanistically describe their fate indoors; (2) quantify the role of outdoor phthalates in indoor concentrations and associated exposures, and obtain critical conditions requiring consideration of outdoor inputs; and (3) to reveal the impact of outdoor phthalates using real-world outdoor measuring data from selected Chinese cities as case studies, and further evaluate its impact on indoor air cleaning efficacy. This study provided a novel contribution for understanding the indoor-outdoor dynamics of phthalates and offer insights for optimizing air purification strategies, ultimately aiming to reduce human health risks associated with indoor exposure.

2. Methodology

2.1. Model development

As illustrated in Fig. 1, a traditional model for indoor SVOCs transport [34] was utilized to characterize the behavior and fate of multi-phase phthalates within a naturally ventilated environment. The model accounts for key physical and chemical processes, including source emission, ventilation, particle aerodynamics, partitioning between the gas- and particle/dust-phase, and sorption of the vapor phase onto indoor surfaces. The model also assumes: (i) well-mixed indoor air (uniform concentration distribution), which is reasonable for naturally ventilated rooms with moderate air mixing; and (ii) constant window/door conditions (air exchange rates) during the simulation period. The mass balance equation governing the indoor concentration of gas-phase phthalates is expressed as follows:

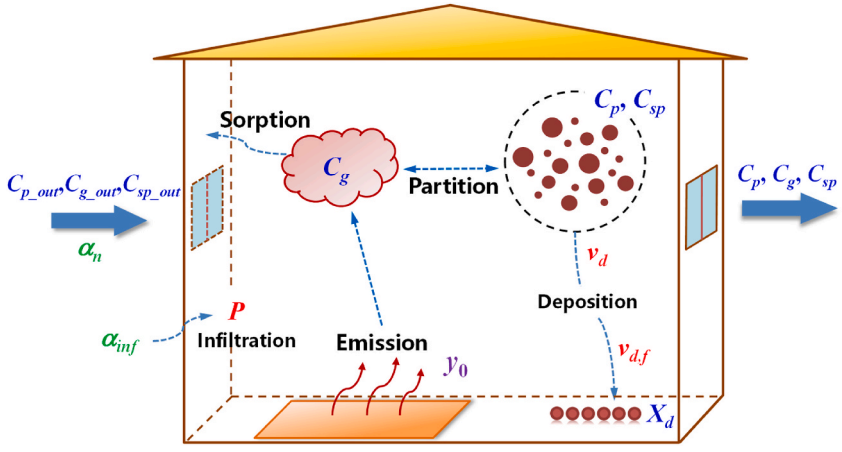

Fig. 1. Schematic of the fate of phthalates in naturally ventilated room.

$$\frac{dC_g}{dt}=\frac{A_e h_m}{V}\left(y_0-C_g\right)-\left(\alpha_n+\alpha_{inf}\right)\left(C_g-C_{g\_out}\right)-\frac{A_{surf}h_m}{V}\left(C_g-\frac{C_{surf}}{K_{surf}}\right)$$
$$-\sum_i\frac{A_{sp,i}C_{p,i}h_{mp,i}}{\rho_p}\left(C_g-\frac{C_{sp,i}}{C_{p,i}K_p}\right)-\sum_i\frac{A_f}{V}h_m A_{sp,i}\frac{M_i}{\rho_d}\left(C_g-\frac{X_{d,i}}{K_d}\right) \quad (1)$$

where C_g (μg/m^3) is the gas-phase concentration in the room; A_e (m^2) is the surface area of source material; h_m (m/s) is the convective mass-transfer coefficient above the source/sink surface; V (m^3) is the room volume; y_0 (μg/m^3) is the gas-phase phthalate concentration immediately adjacent to source surface; α_n (s^{-1}) is the natural air exchange rate; α_{inf} (s^{-1}) is the air infiltration rate; C_{g_out} (μg/m^3) is the gas-phase phthalate concentration in the ambient air; A_{surf} (m^2) is the total area of indoor surfaces that sorb the gas-phase phthalate; C_{surf} (μg/m^2) is the concentration of absorbed phthalate on indoor surface; K_{surf} (m) is the partitioning coefficient of phthalate between indoor surface and room air; A_{sp} (m^{-1}) is the ratio between the surface area and the volume of a single suspended or dust particle (the subscript "i" refers to the ith particle size bin); C_p (μg/m^3) is the indoor particle concentration; h_{mp} (m/s) is the mass-transfer coefficient of phthalate between particles and room air; C_{sp} (μg/m^3) is the indoor particle-phase phthalate concentration; ρ_p (μg/m^3) is the density of suspended particles; K_p (m^3/μg) is the partitioning coefficient between indoor particle- and gas-phase phthalate; A_f (m^2) is the floor area; M (μg/m^2) is the amount of settled dust per unit floor area; ρ_d (μg/m^3) is the density of settled dust; X_d (μg/μg) is the dust-phase phthalate concentration; K_d (m^3/μg) is the partitioning coefficient between the dust- and gas-phase phthalate; and t (s) is the time. The items on the right-side of the mass balance equation represent, respectively, the emission rate of phthalate from source materials, the exchange rate of gas-phase phthalate between indoor and outdoor air via ventilation, and the sorption of the gas-phase onto indoor surfaces, suspended particles, and settled floor dust. Note that for generalization, the sorption term in Eq. (1) can be extended to a summation over different indoor surfaces (e.g., walls, furniture, ceiling) with distinct partitioning coefficients ($K_{surf,j}$) and surface areas ($A_{surf,j}$). In this study, we assume a lumped surface approach for simplicity due to the lack of surface-specific K_{surf} data.

The mass balance of particle-phase phthalates for size bin i is as follows:

$$\frac{dC_{sp,i}}{dt}=\alpha_n\left(C_{sp\_out,i}-C_{sp,i}\right)+\alpha_{inf}\left(P_i C_{sp\_out,i}-C_{sp,i}\right)+\frac{A_{sp,i}C_{p,i}h_{mp,i}}{\rho_p}\left(C_g-\frac{C_{sp,i}}{C_{p,i}K_p}\right)$$
$$-\nu_{d,i}C_{sp,i}+\frac{A_f}{V}R_i M_i X_{d,i} \quad (2)$$

where C_{sp_out} (μg/m^3) is the particle-phase phthalate concentration in the ambient air; P (−) is the particle penetration factor; ν_d (s^{-1}) is the particle deposition rate constant; R (s^{-1}) is the particle resuspension rate. The items on the right-side represent, respectively, the exchange rate of particle-phase phthalate between indoor and ambient air, the sorption rate of the gas-phase by suspended particles, the deposition rate of the particle-phase phthalate, and the resuspension rate of dust-phase phthalate into the air.

The accumulation of phthalates in the floor dust can be described by the following mass balance equation:

$$\frac{d\left(M_i X_{d,i}\right)}{dt}=h_m A_{sp,i}\frac{M_i}{\rho_d}\left(C_g-\frac{X_{d,i}}{K_d}\right)+\nu_{df,i}C_{sp,i}-R_i M_i X_{d,i} \quad (3)$$

where ν_{df} (m/s) is the particle deposition rate on floor surface. The items on the right-side represent the sorption rate of gas-phase phthalate by floor dust, the deposition rate of the particle-phase phthalate on the floor, and the resuspension rate of dust-phase phthalate, respectively. To better simulate real residential environments, we assume that indoor floor dust is cleaned at regular intervals.

Phthalate sorbed on indoor surface (C_{surf}) is governed by the following mass balance equation:

$$\frac{dC_{surf}}{dt}=h_m\left(C_g-\frac{C_{surf}}{K_{surf}}\right) \quad (4)$$

Indoor particle concentration (C_p) and dust concentration on floor surface (M) can be obtained as follows:

$$\frac{dC_{p,i}}{dt}=\alpha_n\left(C_{p\_out,i}-C_{p,i}\right)+\alpha_{inf}\left(P_i C_{p\_out,i}-C_{p,i}\right)-\nu_{d,i}C_{p,i}+\frac{A_f}{V}R_i M_i \quad (5)$$

$$\frac{dM_i}{dt}=\nu_{df,i}C_{p,i}-R_i M_i \quad (6)$$

In Eq. (5), the items on the right-side represent the indoor-outdoor exchange rate of suspended particles, the deposition of indoor particles onto the surfaces, and the dust resuspension, respectively. In Eq. (6), the right-side items correspond to the deposition rate of particle-bound phthalates onto floor surface and the resuspension rate of phthalate-laden dust into the indoor air, respectively.

2.2. Model normalization

As anticipated, the influence of outdoor airborne phthalates on indoor phthalate concentrations is closely linked to indoor source emission parameter, denoted as y_0. It is noticeable that y_0 for emission sources may vary substantially across different indoor

environments. When the emission strength of indoor sources is significantly greater than the indoor-outdoor exchange rate of airborne phthalates, the impact of outdoor concentrations becomes relatively negligible. Conversely, when indoor emissions are weak or comparable to exchange rates, outdoor contributions become more prominent. Affected by indoor environmental parameters (such as room temperature), the y_0 value may continuously change over a period of time. Therefore, we normalized the multi-phase concentration by y_0 to minimize the influence of source emission strengths and obtain a generalized solution across different settings, leading to the introduction of the following new parameters:

$$C_g^* = \frac{C_g}{y_0}, C_{sp}^* = \frac{C_{sp}}{y_0}, C_{surf}^* = \frac{C_{surf}}{y_0}, X_d^* = \frac{X_d}{y_0}, C_{g\_out}^* = \frac{C_{g\_out}}{y_0}, C_{sp\_out}^* = \frac{C_{sp\_out}}{y_0}.$$

Eqs. (1)–(4) can be rewritten as:

$$\frac{dC_g^*}{dt} = \frac{A_e h_m}{V}\left(1 - C_g^*\right) - \left(\alpha_n + \alpha_{inf}\right)\left(C_g^* - C_{g\_out}^*\right) - \frac{A_{surf} h_m}{V}\left(C_g^* - \frac{C_{surf}^*}{K_{surf}}\right) - \sum_i \frac{A_{sp,i} C_{p,i} h_{mp,i}}{\rho_p}\left(C_g^* - \frac{C_{sp,i}^*}{C_{p,i} K_p}\right) - \sum_i \frac{A_f}{V} h_m A_{sp,i} \frac{M_i}{\rho_d}\left(C_g^* - \frac{X_{d,i}^*}{K_d}\right) \tag{7}$$

$$\frac{dC_{sp,i}^*}{dt} = \alpha_n\left(C_{sp\_out,i}^* - C_{sp,i}^*\right) + \alpha_{inf}\left(P_i C_{sp\_out,i}^* - C_{sp,i}^*\right) + \frac{A_{sp,i} C_{p,i} h_{mp,i}}{\rho_p}\left(C_g^* - \frac{C_{sp,i}^*}{C_{p,i} K_p}\right) - \nu_{d,i} C_{sp,i}^* + \frac{A_f}{V} R_i M_i X_{d,i}^* \tag{8}$$

$$\frac{d\left(M_i X_{d,i}^*\right)}{dt} = h_m A_{sp,i} \frac{M_i}{\rho_d}\left(C_g^* - \frac{X_{d,i}^*}{K_d}\right) + \nu_{df,i} C_{sp,i}^* - R_i M_i X_{d,i}^* \tag{9}$$

$$\frac{dC_{surf}^*}{dt} = h_m\left(C_g^* - \frac{C_{surf}^*}{K_{surf}}\right) \tag{10}$$

By combining Eqs. (5)–(10), the normalized indoor phthalate concentrations can be quantitatively predicted. In this study, DnBP and DEHP were selected as the representative target compounds due to their predominance in both the Chinese plasticizer market and indoor environments [20]. Furthermore, DnBP and DEHP serve as representative compounds for low-molecular-weight and high-molecular-weight phthalates, respectively, allowing for a more comprehensive analysis of phthalate behavior across molecular classes.

2.3. Parameterization

In the present study, PM_{10} was used as a representative metric for suspended particles, and was further divided into two size bins, i.e., $PM_{2.5}$ and $PM_{2.5\text{-}10}$. The ambient $PM_{2.5}$ concentration was set at 54 μg/m^3, reflecting the average (24-h averaged) value measured across six major Chinese cities [35]. The ratio of ambient $PM_{2.5}$ and PM_{10} was assumed to be 0.74 [28]. To evaluate the influence of outdoor phthalates, the proposed model considered two distinct scenarios for characterizing indoor phthalate transport: baseline scenario (i.e., $C_{g\_out} + C_{sp\_out} = 0$) and outdoor-involved scenario (i.e., $C_{g\_out} + C_{sp\_out} > 0$). For the outdoor-involved scenario, a linear partitioning relationship between gas- and particle-phase phthalate concentrations in the outdoor air was applied:

$$C_{sp\_out} = C_{p\_out} K_{p\_out} C_{g\_out} \tag{11}$$

where K_{p_out} (m^3/μg) is the particle-gas partitioning coefficient for airborne phthalate in the ambient air, set as $10^{-2.3}$ m^3/μg [36] and $10^{-2.2}$ m^3/μg [26] for DnBP and DEHP, respectively (Note that the effect of particle size on particle-air portioning coefficients was not considered). According to previous field measurements, the ratios between $PM_{2.5}$-bound and PM_{10}-bound DnBP and DEHP concentrations in the ambient air were set to be 0.68 and 0.77, respectively [37]. Detailed information about input parameters is introduced in the Supplementary Information (SI) Section S1.

Eqs. (5)–(10) were numerically solved to obtain time-resolved indoor multi-phase phthalate concentrations using the Runge-Kutta method implemented in MATLAB R2017b. The computational time step (Δt) was set to 300 s, which was verified to be sufficiently small to ensure a solution stability and insensitivity to further reductions in time step size. This temporal resolution allowed for accurate simulation of phthalate transport and transformation processes under both baseline and outdoor-involved scenarios. The model was evaluated by comparing modeled results with those measured in real Chinese residences (as detailed in SI Section S2).

2.4. Exposure assessment

In residential environments, the primary exposure pathways to phthalates include inhalation of airborne compounds, dust ingestion and dermal absorption from the gas-phase. To quantify the contribution of each route, normalized route-specific daily intakes were calculated using the following expressions:

$$DI_{inh} = \frac{(C_g^* + C_{sp}^*) \times IR_{inh}}{BW} \quad (12)$$

$$DI_{ing} = \frac{X_d^* \times IR_{ing}}{BW} \quad (13)$$

$$DI_{derm} = \frac{C_g^* \times k_{p\_g} \times SA \times f_s}{BW} \quad (14)$$

where DI_{inh} (m^3/kg/day) is the normalized daily intake via inhalation; IR_{inh} (m^3/day) is the inhalation rate; BW (kg) is the body weight; DI_{ing} (m^3/kg/day) is the normalized daily intake via dust ingestion; IR_{ing} (μg/day) is the daily dust ingestion rate; DI_{derm} (m^3/kg/day) is the normalized daily intake via dermal absorption; k_{p_g} (m/day) is the transdermal permeation coefficient; SA (m^2) is the skin surface area; f_s (−) is the faction of skin directly exposed to indoor air. The mean values of modeled multi-phase concentrations were used as inputs for the exposure assessment. In this study, Chinese pre-school children (aged 1–5 years) were selected as the target population due their high vulnerability and the considerable amount of time they typical spend at home. Detailed exposure parameters, including physiological and behavioral characteristics, are provided in SI Table S2.

To evaluate the influence of ambient air on indoor phthalate exposure, a comparative analysis was conducted between the normalized total daily intakes (the sum of exposures via three pathways) under two scenarios: baseline scenario (DI_{total}, m^3/kg/day) and outdoor-involved scenario (DI_{total}', m^3/kg/day). The relative difference (RD, %) in total exposure due to the inclusion of outdoor was calculated using the following equation:

$$RD = \frac{DI_{total}' - DI_{total}}{DI_{total}'} \times 100\% \quad (15)$$

In addition, a general criterion was proposed to guide the inclusion of ambient phthalates in indoor exposure assessments. Specifically, when the $RD \geq 20$ %, the impact of ambient air is considered non-negligible, and outdoor phthalate concentrations should be included in the assessment. The outdoor phthalate level corresponding to this threshold serves as a practical benchmark for determining the necessity of accounting for ambient contributions in modeling indoor phthalate exposure and associated health risks.

Table 1
Measured outdoor phthalate concentrations in Chinese urban areas.

Reference	City	Sampling duration	DnBP			DEHP		
			C_{g_out} (μg/m^3)	C_{sp_out} (μg/m^3)	$C_{g\_out}^*$ (−)[e]	C_{g_out} (μg/m^3)	C_{sp_out} (μg/m^3)	$C_{g\_out}^*$ (−)[e]
Li et al. [29] [a,d]	Shanghai	<24 h Dec 5–15, 2016	0.051	0.019 (TSP)	0.02	0.066	0.024 (TSP)	0.06
Ma et al. [28] [b]	Shanghai	24 h Oct 2011–Aug 2012	–	–	–	0.11	0.11 (PM_{10})	0.09
Chen et al. [27] [b,d]	Beijing	72 h Dec 2014–Feb 2016	0.16	0.044 ($PM_{2.5}$)	0.07	0.11	0.039 ($PM_{2.5}$)	0.09
Wang et al. [40] [b,d]	Beijing (Spring)	24~48 h Mar 5–20, 2016	0.67	0.18 ($PM_{2.5}$)	0.28	0.65	0.22 ($PM_{2.5}$)	0.54
Wang et al. [26] [c]	Beijing	24 h May–Jul 2012	0.055	0.066 (PM_{10})	0.02	0.056	0.093 (PM_{10})	0.05
Lu et al. [30] [c]	Hangzhou	12 h Mar 2018–Apr 2019	0.17	0.021 ($PM_{2.5}$)	0.07	1.05	0.083 ($PM_{2.5}$)	0.88
Zhang et al. [38] [b]	Harbin	24 h Nov 2015–Aug 2016	–	–	–	0.19	0.094 ($PM_{2.5}$)	0.16
Wang et al. [41] [b,d]	Xi'an	24h May 16–30, 2012	0.70	0.19 ($PM_{2.5}$)	0.29	0.70	0.24 ($PM_{2.5}$)	0.58
Zhang et al. [38] [b]	Guangzhou	24 h Jan 2016–Mar 2017	–	–	–	0.12	0.043 ($PM_{2.5}$)	0.10

[a] Total airborne concentrations (sum of gas-phase and particle-phase) were reported.
[b] Both outdoor particle and particle-phase concentrations were reported.
[c] Both outdoor gas- and particle-phase concentrations were reported.
[d] Outdoor $PM_{2.5}$ level was assumed to be 54 μg/m^3 for phase-specific concentration estimation.
[e] C_{g_out} was normalized by y_0 values of 2.39 and 1.2 μg/m^3 for DnBP and DEHP, respectively (see SI Section S1 for details).

3. Results and discussion

3.1. Influence of outdoor phthalates on indoor concentrations

As shown in Table 1, the average values of C_{g_out}* derived from previous studies often exceed 0.05. In particular, recent studies have reported normalized outdoor gas-phase DEHP concentration (C_{g_out}*) exceeding 0.5 in urban China, pointing to a severe burden of ambient DEHP pollution. Here, C_{g_out}* ranged from 0 to 0.15 to represent typical scenarios in urban China. The simulation results presented in Sections 3.1~3.3 employed fixed outdoor concentrations (both airborne particles and phthalates) to quantitatively assess the influence of outdoor air on indoor phthalate levels and human exposure. For real-world scenarios (see Section 3.4), these values were determined based on field measurement data and exhibited temporal variations.

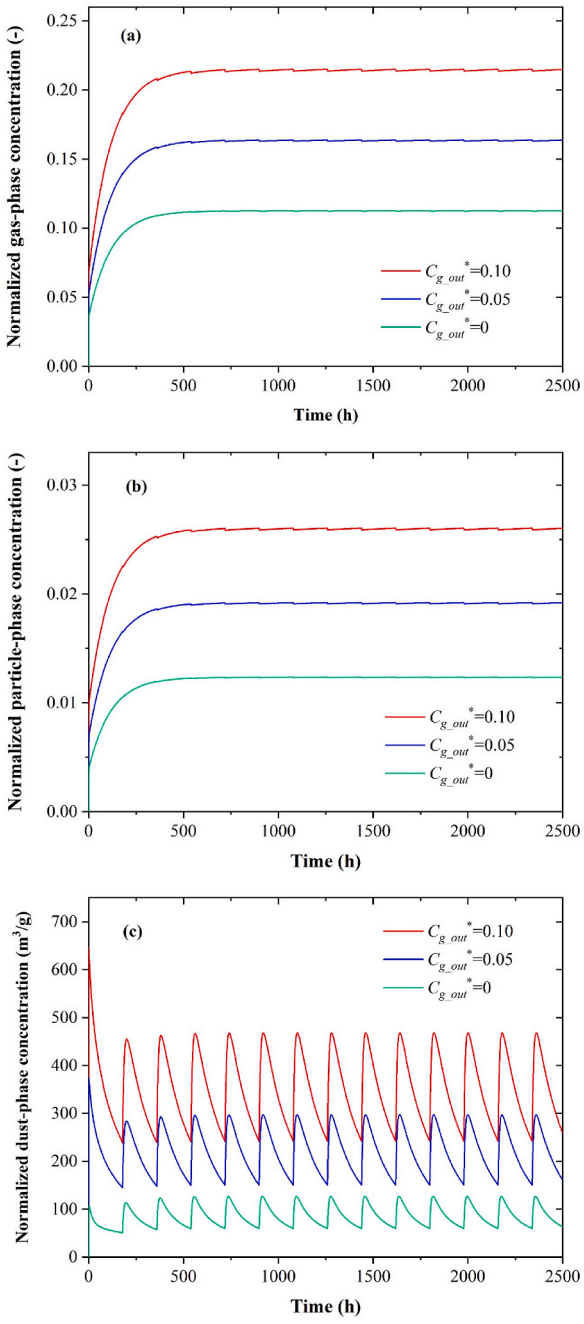

Fig. 2. Modeled normalized indoor DnBP concentrations. (a) Gas-phase; (b) Particle-phase; (c) Dust-phase.

Figs. 2–3 illustrate the temporal changes of normalized indoor concentrations of DnBP and DHEP over a period of 2500 h, with typical C_{g_out}* values set as 0, 0.05 and 0.10. For DnBP, airborne phase concentrations-primarily in the vapor phase-increased sharply following the introduction of indoor source materials and gradually approached a steady state after approximately 400 h. In contrast, the dust-phase concentrations of DnBP initially spiked rapidly due to a higher initial phthalate deposition rate compared to dust accumulation. However, this trend reverse overtime, leading to a decline in dust-phase concentration. Notably, after 180 h (the first room cleaning event), dust-phase concentrations began to rise again. This marked the onset of a "periodic steady state" driven by the regularity of cleaning activities that intermittently removed and allowed the re-accumulation of phthalates in dust.

For DEHP, a compound with lower volatility, the indoor concentrations increased continuously throughout the simulation. This is attributed to the difficulty of reaching equilibrium under typical indoor conditions, where mass transfer processes are much slower for less volatile compounds. Furthermore, the results indicate that indoor multi-phase concentrations are positively influenced by outdoor phthalate levels. For example, the normalized steady state airborne concentrations (C_g*+C_{sp}*) of DnBP increased from 0.12 to 0.23 as the outdoor vapor-phase concentrations C_{g_out}* rosed from 0 to 0.1. Similarly, for DEHP, the final airborne concentration increased from 0.33 to 0.41. These findings underscore the significance of outdoor air as a contributing source to indoor phthalate exposure,

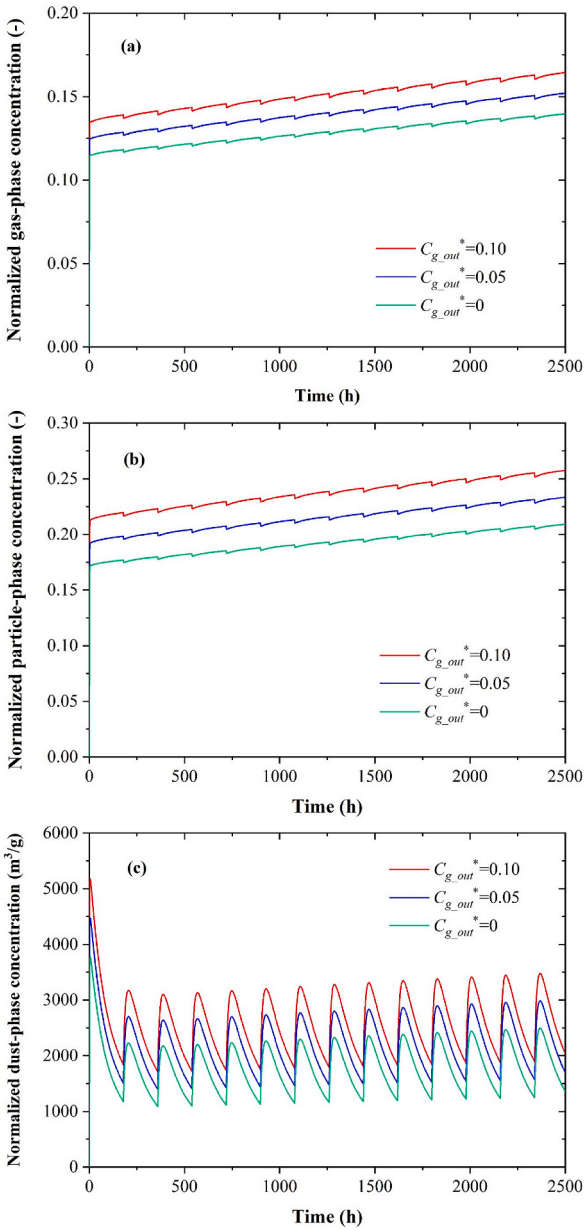

Fig. 3. Modeled normalized indoor DEHP concentrations. (a) Gas-phase; (b) Particle-phase; (c) Dust-phase.

especially in scenarios where ventilation systems facilitate indoor-outdoor exchange.

Fig. 4 presents the modeled average indoor concentrations as a function of varying outdoor phthalate concentrations. The results demonstrate that outdoor air can be a significant contributor to indoor phthalate levels, particularly for more volatile compounds such as DnBP. When $C_{g\,out}$* increases from 0 to 0.05, the average indoor airborne DnBP level rises by approximately 50 % (from 0.12 to 0.18), while the dust-phase concentration increases by 158 % (from 85 to 219 m^3/g). The effects become even more pronounced with higher outdoor concentrations. When $C_{g\,out}$* increases from 0 to 0.15, the average airborne and dust-phase concentrations of DnBP rise by 142 % and 471 %, respectively, highlighting the strong influence of ambient air on indoor phthalate accumulation. In contrast, for DEHP, the indoor concentrations respond moderately to changes in outdoor levels. As $C_{g\,out}$* increases from 0 to 0.15, the modeled average vapor-phase concentration (C_g*) increases by 23 % (from 0.13 to 0.16), the particle-phase concentration (C_{sp}*) by 37 % (from 0.19 to 0.26), and the dust-phase (X_d*) by 68 % (from 1789 to 3011 m^3/g). Although these percentage increases are lower than those observed for DnBP, they still indicate a clear upward trend, emphasizing that even low-volatility phthalates are susceptible to outdoor influence under extended exposure durations. These findings underscore the need to consider outdoor air quality as a significant determinant of indoor exposure. The magnitude of increase across different phases and compounds also demonstrates the importance of compound-specific volatility in determining the extent of indoor contamination resulting from outdoor air.

Our results suggested that the contribution of phthalates in the ambient air should not be always overlooked when estimating indoor phthalate concentrations. Taking DnBP as an example, when the normalized outdoor gas-phase concentration ($C_{g\,out}$*) reaches 0.05 (i.e., the outdoor gas-phase level accounting for 5 % of indoor source strength (y_0)), neglecting this external contribution would result in an underestimation of indoor concentrations by at least 50 %. This impact is expected to be even more pronounced in indoor environments where indoor emission sources are weak or where ambient air pollution is elevated, such as during hazy or smog-prone

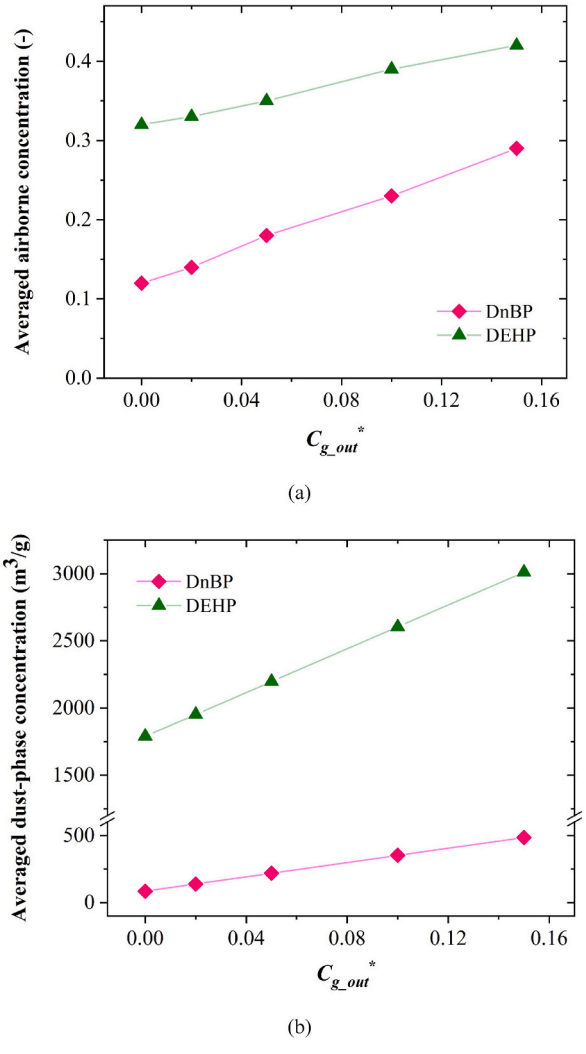

Fig. 4. Impact of outdoor phthalate concentrations on normalized indoor concentrations (average value over the 2500-h simulation). (a) Airborne phase; (b) Dust-phase.

periods. These findings provide convincing evidence that ambient phthalates, especially in densely populated or industrialized areas, may significantly contribute to indoor exposure levels in Chinese civil buildings. Therefore, accurate assessments of indoor phthalate exposure should incorporate ambient sources, particularly in urban regions where the disparity between indoor and outdoor concentrations is narrowing due to declining indoor emissions and persistent environmental contamination.

3.2. Exposure estimates

Fig. 5 illustrates the impact of outdoor phthalates on children's daily intakes via different exposure pathways: inhalation, dermal absorption, dust ingestion and the total intakes (the sum of the three pathways) indoors. Intake values were normalized against the baseline scenario (i.e., without inclusion of outdoor phthalates). The results clearly indicate that ambient air concentrations significantly influence total indoor exposure, particularly for more volatile compounds. For DnBP, increases in outdoor gas-phase concentrations (C_{g_out}*) from 0.02 to 0.15 resulted in an increase of total daily intake by approximately 40 %–300 %. These changes were observed across all exposure routes, with the most pronounced effect seen in dust ingestion, which was the most sensitive pathway to fluctuations in outdoor concentrations. This sensitivity is attributable to the substantial rise in dust-phase DnBP concentrations (ranging from 64 %–471 %) over the same C_{g_out}* range, compared to a 17 %–142 % increase in the airborne phase. For DEHP, although the overall response to outdoor concentrations was less dramatic due to its lower volatility, the influence remained notable. As C_{g_out}* increased from 0.02 to 0.15, the average total daily intake of DHEP rose by 9 %–65 %. Similar to DnBP, dust ingestion route was the most affected, though to a lesser extent. This reinforces the conclusion that even indoor exposure to lower-volatility phthalates can be affected meaningfully when outdoor concentrations are elevated. Collectively, these results emphasize the critical role of ambient air as a non-negligible source of indoor phthalate exposure, particularly among vulnerable populations such as children. According to the criteria established in Section 2.4 ($RD \geq 20$ %), outdoor phthalates must be incorporated into the indoor transfer model when assessing indoor children's exposure or health risks if C_{g_out}* exceeds 0.02 (DnBP) or 0.05 (DEHP). Failure to account for these outdoor sources would lead to significant underestimation in the computational results.

3.3. Sensitivity analysis

Among all the input parameters in our model, the total area of indoor emission sources (A_e) and the natural air exchange rate (α_n) emerged as critical factors influencing the origin and spatial transport of indoor phthalates. These parameters are closely linked to indoor furnishing style, occupants' living habits and/or outdoor climatic conditions, and are therefore subject to considerable variability and uncertainty. To evaluate the influence of these uncertainties on indoor phthalates exposure estimates, a sensitivity analysis

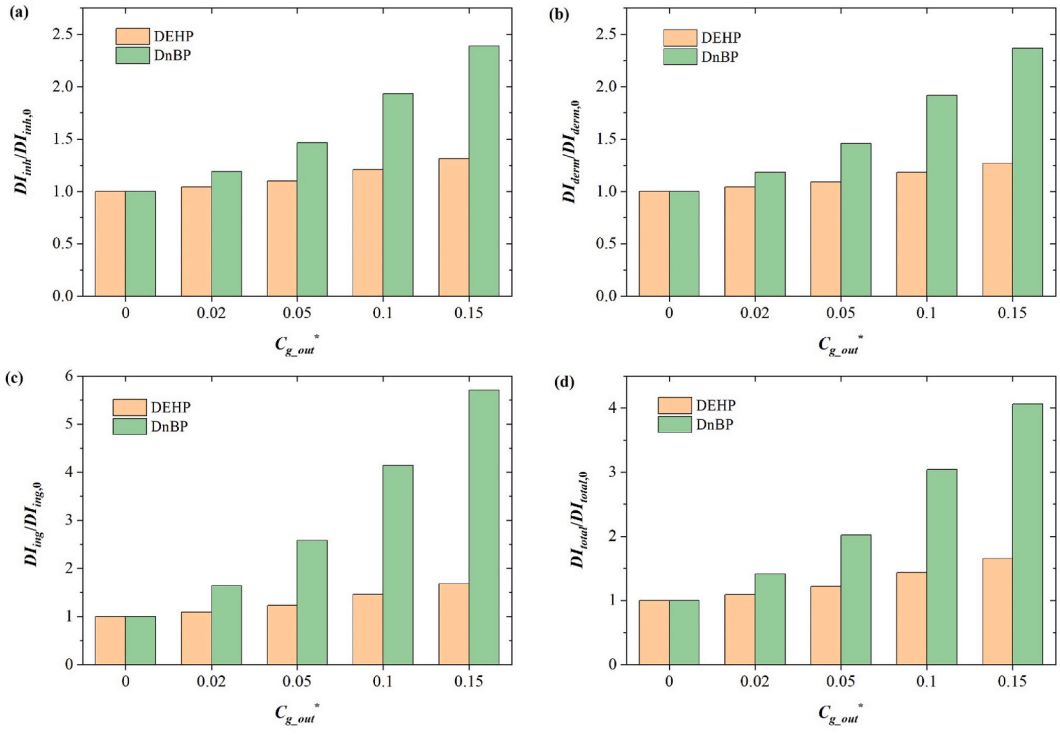

Fig. 5. Normalized children's daily intakes of targeted phthalates via different pathways. (a) Inhalation; (b) Dermal absorption; (c) Dust ingestion; (d) Total. The subscript "0" represents corresponding daily intakes when C_{g_out}* = 0.

was conducted by varying A_e and α_n within a plausible range-specifically, by halving or doubling their baseline values.

The results of sensitivity analysis are presented in Fig. S2. Variations of A_e and α_n were found to have a greater influence on indoor exposures to DnBP than to DEHP, consistent with DnBP's higher volatility and greater sensitivity to ventilation and emission dynamics. Moreover, the sensitivity to these parameters becomes more pronounced under conditions of elevated outdoor phthalate concentrations. For example, when $C_{g\,out}{}^* = 0.02$, variations in A_e resulted in normalized indoor DnBP exposures ranging from −14 %–26 %, whereas under higher ambient levels ($C_{g\,out}{}^* = 0.15$), the corresponding variation in normalized intakes widened to −35 %–70 %. In comparison, for DEHP, the sensitivity of A_e was much smaller: −4 %–7 % at $C_{g\,out}{}^* = 0.02$, and −18 %–36 % at $C_{g\,out}{}^* = 0.15$. These results indicate that ambient air contributions are relatively suppressed when total indoor emissions are elevated, as indoor sources dominate overall indoor phthalates. Conversely, the impact of ambient air is amplified under conditions of increased ventilation. For example, at $C_{g\,out}{}^* = 0.15$, increasing α_n from its baseline value to $2\alpha_n$ resulted in a 66 % increase in normalized daily DnBP intakes and a 29 % increase for DEHP. These findings underscore the complex interplay between indoor source strength, ventilation, and outdoor pollutant levels in shaping indoor exposure outcomes. In summary, this analysis highlights the sensitivity of indoor exposure estimates to key physical and behavioral parameters, and the importance of incorporating such variability in exposure modeling. It also reinforces the necessity of context-specific parameterization when assessing indoor exposure risks in diverse residential environments.

3.4. Illustrative examples for residences in Chinese cities

To illustrate the real-world impacts of outdoor phthalates on indoor exposure, we incorporated long-term monitoring data of outdoor phthalate concentrations from typical Chinese cities [28,30,38]. The extracted datasets used as inputs are summarized in Table 2, while additional details and time series visualizations are provided in SI Figs. S3-S5. The selected data indicate that outdoor phthalate concentrations during heavily-polluted days were approximately 2–5 times higher than those recorded during lightly-polluted days. The averaged values of $C_{g\,out}{}^*$ during heavily-polluted days exceed the benchmarks proposed in Section 3.2, i.e., 0.02 for DnBP, and 0.05 for DEHP. It is expected that the ambient phthalates can be a potential contributor of indoor contamination under this condition. The following results will provide evidence supporting our hypothesis.

We simulated indoor multi-phase DEHP concentrations in representative residential settings in Shanghai and Harbin over an extended period. As shown in Figs. 6–7, incorporating ambient DEHP concentrations into the model significantly increased indoor phthalate levels, with the magnitude of increase closely correlated to the degree of outdoor pollution. During lightly polluted days, the inclusion of ambient DEHP led to an approximate 20 % increase in indoor airborne DEHP concentrations and a 40 % increase in dust-phase concentrations. These impacts were even more pronounced during heavily polluted days, with airborne levels increasing by 60 % and dust-phase levels by 120 % when outdoor DEHP was included. Across all modeled conditions, indoor DEHP concentrations were 32 %–71 % higher when ambient concentrations were accounted for, compared to simulations that excluded them. As further illustrated in Table 3, using Hangzhou residences as a case study, modeled indoor phthalate concentrations increased by a factor of 1–3 when outdoor phthalates were incorporated into the exposure assessment. These findings demonstrate the substantial influence of outdoor air on indoor phthalate pollution, particularly during high-smog events, and highlight the importance of including ambient sources in indoor exposure and risk assessments, especially in urban areas with high background contamination levels.

To further evaluate the impact of outdoor phthalates on residential exposure, we estimated children's daily intake under two exposure scenarios: (1) excluding and (2) including ambient phthalate contributions. The average daily intake values under both conditions are presented in Table 4. The results clearly demonstrated that children's daily phthalate intake increases significantly when outdoor phthalates are included in the exposure assessment. This increase was particularly evident for the dust ingestion pathway, which remains the dominant route for phthalate exposure in indoor environments. For all selected Chinese urban settings, omitting outdoor phthalates led to an underestimation of total daily intake by no less than 40 %, with even greater discrepancies observed during high pollution periods. When evaluated against the threshold ($RD = 20$ %) defined in Eq. (15), the results exceed the proposed significance criterion. Based on this benchmark, we conclude that ambient phthalate contributions should be regarded in children's residential exposure estimates in urban environments-especially in urban regions such as Hangzhou, Shanghai, and Harbin, where outdoor phthalate levels are consistently elevated.

3.5. Implications for indoor phthalate removal by air cleaning interventions

We further extended our analysis to evaluate the effectiveness of indoor air cleaning interventions in reducing phthalate exposure,

Table 2
Summary of outdoor phthalate concentrations (μg/m^3) used for modelling.

		Gas-phase		Particle-phase	
		Lightly	Heavily	Lightly	Heavily
Shanghai[a]	DEHP	0.01 ± 0.01	0.05 ± 0.02	0.07 ± 0.06	0.21 ± 0.09
Harbin[a]	DEHP	0.02 ± 0.02	0.08 ± 0.01	0.04 ± 0.02	0.17 ± 0.13
Hangzhou[b]	DEHP	0.41	1.65	0.06	0.10
	DnBP	0.16	0.18	0.01	0.03

[a] Outdoor daily concentrations between two continuous sampling events were obtained using a linear interpolation method.
[b] Mean values were used for concentration modelling.

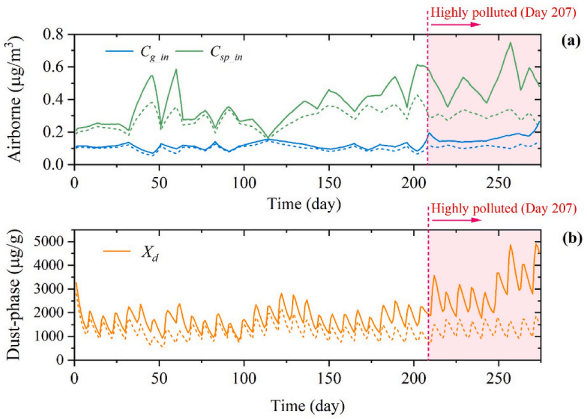

Fig. 6. Modeled residential DEHP concentrations in Shanghai. (a) Airborne phase; (b) Dust-phase. The solid and dashed lines represent modeled results with and without considering outdoor phthalate concentrations, respectively.

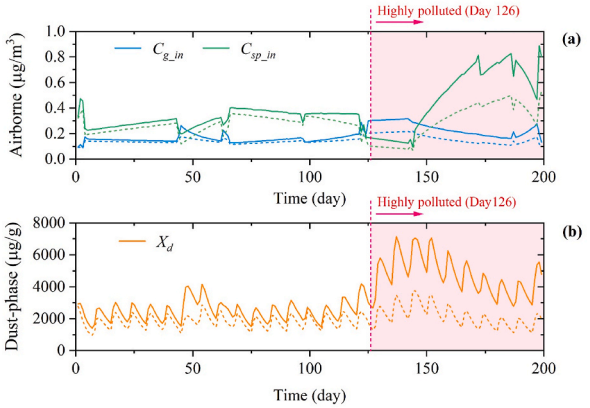

Fig. 7. Modeled residential DEHP concentrations in Harbin. (a) Airborne phase; (b) Dust-phase. The solid and dashed lines represent modeled results with and without considering outdoor phthalate concentrations, respectively.

Table 3
Modeled mean phthalate concentrations in Hangzhou residences with/without the inclusion of outdoor phthalates.

	DnBP		DEHP	
	without	with	without	with
Gas-phase (μg/m^3)	0.18	0.33	0.13	0.41
Particle-phase (μg/m^3)	0.03	0.06	0.25	0.80
Dust-phase (μg/g)	133	384	1550	5970

Table 4
Modeled children's indoor daily intakes (μg/kg/day) with/without the inclusion of outdoor phthalates.

	Hangzhou		Shanghai	Harbin
	DnBP	DEHP	DEHP	DEHP
Inhalation	0.19/0.10	0.58/0.18	0.25/0.19	0.35/0.21
Dermal absorption	0.40/0.22	0.50/0.16	0.16/0.12	0.21/0.18
Dust ingestion	0.77/0.27	12.0/3.1	4.0/2.5	6.7/3.9
Total	1.4/0.59	13.1/3.5	4.4/2.8	7.2/4.3

particularly in urban residences. When an air cleaning intervention (e.g., portable air cleaner) was introduced in the model, modifications were made to the mass balance equations governing indoor air dynamics. Specifically, Eqs. (1), (2) and (5) were adjusted to account for the additional removal term introduced by the air cleaner. The revised equations are given as follows:

$$\frac{dC_g}{dt}=\frac{A_e h_m}{V}\left(y_0-C_g\right)-\left(\alpha_n+\alpha_{inf}\right)\left(C_g-C_{g\_out}\right)-\frac{A_{surf}h_m}{V}\left(C_g-\frac{C_{surf}}{K_{surf}}\right)$$
$$-\sum_i\frac{A_{sp,i}C_{p,i}h_{mp,i}}{\rho_p}\left(C_g-\frac{C_{sp,i}}{C_{p,i}K_p}\right)-\sum_i\frac{A_f}{V}h_m A_{sp,i}\frac{M_i}{\rho_d}\left(C_g-\frac{X_{d,i}}{K_d}\right)-\eta_g\alpha_c C_g \tag{16}$$

$$\frac{dC_{sp,i}}{dt}=\alpha_n\left(C_{sp\_out,i}-C_{sp,i}\right)+\alpha_{inf}\left(P_i C_{sp\_out,i}-C_{sp,i}\right)+\frac{A_{sp,i}C_{p,i}h_{mp,i}}{\rho_p}\left(C_g-\frac{C_{sp,i}}{C_{p,i}K_p}\right)$$
$$-\nu_{d,i}C_{sp,i}+\frac{A_f}{V}R_i M_i X_{d,i}-\eta_{p,i}\alpha_c C_{sp,i} \tag{17}$$

$$\frac{dC_{p,i}}{dt}=\alpha_n\left(C_{p\_out,i}-C_{p,i}\right)+\alpha_{inf}\left(P_i C_{p\_out,i}-C_{p,i}\right)-\nu_{d,i}C_{p,i}+\frac{A_f}{V}R_i M_i-\eta_{p,i}\alpha_c C_{p,i} \tag{18}$$

where η_g (−) and η_p (−) are the removal efficiencies of gas- and particle-phase phthalates for air cleaners, respectively. The removal efficiency for indoor particles is assumed to be the same as that for particle-phase phthalates. α_c (s^{-1}) is the air exchange rate corresponding to a portable air cleaner (i.e., the ratio between the airflow rate produced by the air cleaner and the room volume).

To further evaluate the influence of outdoor atmospheric contributions under air cleaning scenarios, we selected Hangzhou and Shanghai as representative Chinese urban environments. Simulations were conducted over 365 and 274 days, respectively, to assess the effectiveness of air purifiers in reducing indoor phthalate concentrations under real-world conditions. As summarized in Table 5, the results show that neglecting outdoor phthalate contributions in the model significantly underestimates indoor concentrations, particularly for the dust-phase. This also led to an overestimation of the estimation of the effectiveness air cleaning interventions, especially at higher airflow rates (α_c). For instance, in the absence of outdoor phthalates, an air purifier operating at baseline airflow rate reduced total indoor concentrations by 70 % relative to a no-purifier scenario. These findings align with previous studies, such as Shi and Zhao [32], which reported reductions between 55 % and 86 % across different settings and pollutants under air cleaning interventions. Further increasing the purifier airflow rate to five times the baseline value achieved reductions of over >90 % in total airborne-phase phthalates. However, when ambient phthalate contributions, the reductions in dust-phase concentrations were considerably more limited. At baseline airflow, airborne-phase concentrations were still reduced by approximately by 70 %, but dust-phase of DnBP and DEHP were only reduced by 37 % and 50 %, respectively. Even with a fivefold increase in airflow (α_c), airborne-phase concentrations decreased by about 90 %, while dust-phase concentrations were only reduced by 43 % for DnBP and 67 % for DEHP. These results suggest that while portable air cleaners are effective in controlling vapor- and particle-bound phthalates in the air, their impact on dust-phase concentrations is constrained, particularly in the presence of continuous outdoor phthalate influx. The diminished marginal benefit of increasing α_c underlines the importance of integrating ambient source control alongside indoor interventions when designing comprehensive exposure mitigation strategies for semi-volatile organic compounds (SVOCs) such as phthalates.

For both target phthalates, dust ingestion contributes a significant portion of total indoor exposure, with this route being particularly dominant for DEHP, where oral intake via dust accounts for the majority of total exposure. Our analysis demonstrates that, under realistic conditions (especially in areas with severe outdoor pollution), conventional air purification technologies show limited effectiveness in reducing dust-phase concentrations of DnBP and DEHP. As a result, overall reductions in total human exposure remain modest, despite apparent improvements in airborne-phase removal. Importantly, even multi-fold increases in purifier airflow rates (which proportionally elevate pressure drop as well as energy consumption) do not achieve proportionate reduction in exposure. These findings underscore urgent need for the development of advanced air purification materials and technologies. Specifically, there is a growing necessity for high-efficiency filtration media that can effectively capture semi-volatile organic compounds (SVOCs) like phthalates across all phases, while maintaining low airflow resistance to ensure energy efficiency and user comfort. Such innovations will be crucial to enhancing indoor air quality and reducing human exposure to persistent chemical pollutants in both residential and urban environments. Given the limited reduction of dust-phase phthalates by air cleaners alone, residents are advised to combine portable air purification with regular surface cleaning or vacuuming to effectively lower overall exposure risks.

Table 5
Modeled mean indoor concentrations of airborne (μg/m^3) and dust-phase phthalates (μg/g) under different air cleaning scenarios.

		Without outdoor impacts			With outdoor impacts		
		$\alpha_c=0$	α_c	$5\times\alpha_c$	$\alpha_c=0$	α_c	$5\times\alpha_c$
Hangzhou (DnBP)	Airborne	0.21	0.07	0.02	0.39	0.13	0.04
	Dust-phase	133	35.7	6.7	384	243	217.4
Shanghai (DEHP)	Airborne	0.39	0.10	0.03	0.52	0.13	0.04
	Dust-phase	1243	361	42.4	2004	1000	662

3.6. Limitations and further study

Fewer existing studies have concurrently reported gas-phase and particle-phase phthalate concentrations in outdoor environments. To address this gap, we applied an equilibrium model to estimate missing phase-specific values based on available measurements. However, when estimating particle-phase concentrations from gas-phase measurements using this approach may lead to overestimation of indoor impacts (due to overestimated particle-phase levels), and vice versa (due to underestimated gas-phase concentrations). Furthermore, due to limited size-resolved measurement data, our model only considered two outdoor particle size fractions (i.e., $d_p \leq 2.5$ μm, and $d_p = 2.5$–10 μm). In many cases, empirical values from literature were used to estimate these fractions, which may compromise the accuracy of indoor exposure predictions. Future studies should prioritize field measurements of phase-resolved and size-resolved phthalates to refine indoor exposure models and reduce such uncertainties.

This study focused on two representative phthalates-DnBP and DHEP-commonly found in Chinese indoor environments, for two key reasons: First, these compounds exhibit relatively high indoor concentrations, which poses a greater health risks and disease burdens. Second, only these compounds have well-characterized emission parameter (y_0) for indoor source materials. While these compounds are among the most significant in terms of health risks and exposure burden, the model proposed in this study can be extended to other SVOCs with similar chemical properties or transport behaviors. However, it should be noted that the model assumes well-mixed indoor air. Therefore, it is not applicable to SVOC transport problems under non-uniform mixing conditions, such as exposure scenarios in personal microenvironments influenced by thermal plumes. Future work could focus on developing dual-zone or multi-zone models to address indoor SVOC transport under non-uniform conditions [39]. Furthermore, to improve model applicability and accuracy, it is essential to extensively measure source emission and adsorption parameters of various SVOCs to enrich the input data, as well as to investigate the influence of suspended particle size distribution indoors or outdoors on the SVOC partitioning coefficient.

Our model did not account for dynamic indoor physical parameters (e.g., temperature and ACH). Although indoor temperatures fluctuate in real environments would increase/reduce y_0, under the long-term exposure simulation conditions established in this study (e.g., 300 days or longer), the impact of temperature variations on average concentration or exposure is partially mitigated. However, for short-term simulations, the influence of temperature must be considered. For instance, when the room temperature exceeds 25 °C, the y_0 value of the emission source increases. If the outdoor phthalate concentration remains unchanged, the contribution of outdoor sources to indoor exposure decreases due to the reduction in the dimensionless parameter $C_{g\,out}$*. Conversely, at lower temperatures, the impact of outdoor pollution on indoor exposure increases, as the dimensionless parameter $C_{g\,out}$* rises, thereby reducing the relative contribution of indoor sources. Sensitivity analyses indicated variations in ACH only become significant under extreme outdoor pollution conditions (e.g., $C_{g\,out}$*>0.1), which are infrequent. Additionally, human activity patterns (e.g., floor cleaning frequency, dust removal efficiency) were not explicitly incorporated, potentially contributing to model uncertainty. Future work should aim to incorporate stochastic and behavioral variables, possibly through probabilistic modeling approaches, to enhance the robustness of exposure predictions.

Due to limited experimental data, the removal efficiencies of household air cleaners for gas-phthase phthalates were assumed to be constant. In reality, filter performance may degrade over time, particularly in the absence of routine maintenance. These assumptions could lead to an overestimation of air cleaner effectiveness and underestimation of long-term indoor concentrations. Furthermore, temperature and humidity effects, and SVOC re-emission from filter media are not considered. Such effects could significantly influence both the adsorption mechanisms and kinetic processes governing pollutant removal by the filter. Future research should investigate the dynamic removal efficiencies of phthalates by commercial filters.

4. Conclusions

This study employed a mechanistic model to evaluate the influence of outdoor phthalate concentrations on indoor pollutant dynamics and human exposure within typical residential environments. By taking two representative phthalates (DnBP and DEHP) as examples, their fate across airborne and dust-bound phases under varying outdoor pollution levels was examined. A new parameter, dimensionless outdoor gas-phase concentration ($C_{g\,out}$*), defined as the ratio of the outdoor gas-phase concentration to indoor emission parameter (y_0), was introduced as a criterion for determining whether outdoor contributions need to be considered. When $C_{g\,out}$* increased from 0 to 0.05, over a 2500-h simulation, airborne indoor concentrations increased by 50 % for DnBP and 10 % for DEHP, respectively. Dust-phase concentrations demonstrated even more pronounced changes, increasing by 160 % and 23 %, respectively. These consequently resulted in increases of children's total exposure: a doubling (100 %) for DnBP and a 22 % increase for DEHP. Outdoor phthalates must be incorporated into the indoor transfer model when assessing indoor children's exposure or health risks if $C_{g\,out}$* exceeds 0.02 (DnBP) or 0.05 (DEHP). Long-term simulations incorporating field-measured outdoor phthalates in Chinese cities demonstrated that neglecting outdoor contributions leads to underestimation of children's indoor exposure by ~40 %. Additionally, the model reveals that the penetration of outdoor phthalates may reduce the effectiveness of air purifiers, particularly in mitigating dust-phase concentrations, due to their limited removal efficiency for dust-borne compounds.

This study elucidates the transport mechanism of outdoor-origin phthalates into indoor environments and develops a conceptual framework for determining when this influence must be incorporated. Furthermore, it offers foundational mechanistic insights that challenge the status quo of modeling and pollution control of indoor SVOCs. These findings necessitate a paradigm shift in estimating exposure to SVOCs in built environment by explicitly accounting for outdoor sources, particularly in areas with significant outdoor pollution. The insights are critical for designing the next generation of air cleaning systems, guiding the development of advanced materials and operational strategies to effectively mitigate the combined impact of indoor and outdoor phthalates, thereby enabling

more accurate health risk assessments and targeted intervention strategies.

CRediT authorship contribution statement

Yiming Cui: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Zhu Cheng:** Writing – review & editing, Methodology, Funding acquisition, Data curation. **Daniel Mmereki:** Writing – review & editing, Validation. **Le Kang:** Software, Data curation. **Tao Yu:** Validation, Software. **Wenjun Leng:** Validation. **Songwei Wang:** Data curation. **Zonghui Lv:** Validation. **Zhongming Bu:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Data curation, 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.jobe.2025.114510.

Data availability

Data will be made available on request.

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