



Exposure and Health Risk Assessment of Phthalates in House Dust among Schoolchildren in Phatthalung, Thailand

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Abstract

Phthalates are widely used chemicals that are not chemically bonded to materials. Therefore, they can be readily released into house dust. Children are at high risk of phthalate exposure through dust ingestion due to inadequate hygiene practices, which may adversely affect their health. Settled house dust samples were collected from 310 households of elementary school children in Phatthalung, Thailand, using a vacuum cleaner. Ten phthalates were then analyzed by gas chromatography-mass spectrometry. A quantitative health risk assessment for children via ingestion was conducted using the United States Environmental Protection Agency (US EPA) methodology. Di-2-ethylhexyl phthalate (DEHP) was the most abundantly detected compound, followed by di-n-octyl phthalate (DnOP) and dibutyl phthalate (DBP) (detection rates > 60%), with median concentrations ranging from 6.90 to 150.91 $\mu\text{g/g}$. The median concentration of total phthalates ($\Sigma 10\text{PAEs}$) was 190.71 $\mu\text{g/g}$. The median estimated daily intakes (EDIs) of DEHP, DnOP, DBP, and $\Sigma 10\text{PAEs}$ ranged from 3.95 to 112.56 ng/kg bw/day and 13.18 to 375.22 ng/kg bw/day under central-tendency and upper-percentile scenarios, respectively. The EDIs of DEHP, DnOP, and $\Sigma 10\text{PAEs}$ in children aged ≥ 9 years were significantly higher than those in younger children. The hazard quotient (HQ) and hazard index (HI) values for the three phthalates were less than 1. The CR for DEHP was below 1×10^{-4} ; however, one child exceeded this threshold under the upper-percentile scenario (1.001×10^{-4}). These findings suggest that DEHP exposure warrants attention given its potential carcinogenic risk, highlighting the need for appropriate risk management strategies to reduce phthalate exposure in indoor environments.

Keywords: Phthalates, Settled house dust, Health risk assessment, Children, Rural environment

What was Known

- DEHP, DnOP, and DBP were predominantly detected in settled house dust
- The EDIs of DEHP, DnOP, and $\Sigma 10\text{PAEs}$ in children aged ≥ 9 years were significantly higher than those in younger children.
- HQ and HI values for the three phthalates were <1 , indicating low non-carcinogenic risk
- The CR for DEHP was below 1×10^{-4} , with one exceedance under the upper percentile scenario.

What's New and Next

- Controlling and limiting the use of phthalates in consumer products is recommended to reduce exposure to house dust and protect children's health.

Introduction

Phthalates, also known as phthalate esters (PAEs), are semi-volatile organic compounds widely used as plasticizers in polyvinyl chloride (PVC) to enhance flexibility and durability⁽¹⁾. These compounds are typically colorless and odorless and are classified into two subgroups based on molecular weight. Low-molecular-weight phthalates (containing 3–6 carbon atoms), such as DBP, diethyl phthalate (DEP), dimethyl phthalate (DMP), and di-iso-butyl phthalate (DiBP), are commonly used in fragrances and are prevalent in personal care products, household products, cosmetics, insecticides, solvents, adhesives, waxes, inks, and paints. In contrast, high-molecular-weight phthalates (containing more than 6 carbon atoms), including DEHP, DnOP, and di-isononyl phthalate (DiNP), are primarily used in construction materials, consumer products, and as plasticizers in PVC^(2,3). Many of these products are present in residential environments, where individuals, particularly young children, spend considerable time⁽⁴⁾.

Phthalates are widespread indoor contaminants because they are not chemically bound to products and can be easily released, particularly into house dust, which is pervasive and can adsorb various household chemicals^(6,13). Elevated temperatures and humidity levels further facilitate the release of phthalates, which then tend to adhere to fine dust particles^(4,7,8). Since phthalates are also widely used as additives in numerous consumer products, avoidance and reduction of exposure are challenging. These compounds typically accumulate on floors, furniture, and other household surfaces⁽⁹⁾. Given that individuals spend over 90% of their time indoors,

indoor environments constitute a major source of phthalate exposure⁽¹²⁾. Ingestion of soil and house dust represents a significant exposure pathway, especially for children, who are more likely to encounter phthalates in domestic environments⁽¹⁰⁾. Children's hand-to-mouth behavior, inadequate hygiene, and frequent floor activities further increase their exposure to phthalates through dust, thereby increasing the likelihood of oral contact⁽¹¹⁾. As a result of this elevated exposure, potential health effects have become an increasing concern. Phthalates are recognized as endocrine-disrupting substances, and their effects, particularly in children, have been associated with adverse health outcomes such as asthma, allergies, reproductive system abnormalities, developmental delays, obesity, cancer, and precocious puberty^(14,15,16). While previous research has primarily focused on preschool-aged children, multiple studies indicate that elementary school-aged children are also at risk of phthalate exposure from house dust. For example, research conducted in Southern Taiwan demonstrated that children aged 6 to 11 years faced a risk of exposure to high levels of total phthalate dust comparable to that of preschoolers⁽¹⁶⁾. Additionally, studies from other countries, such as Japan, have shown that exposure to DEHP in floor dust among children aged 6 to 12 years is associated with parental reports of rhino conjunctivitis⁽¹⁷⁾. In China, findings suggest that schoolchildren aged 6 to 9 years are particularly susceptible to DEHP exposure, with a 30% likelihood of exceeding established safety limits⁽¹⁸⁾. A gap analysis in Thailand indicates that: (1) phthalates continue to be imported, with DEHP being the most frequently imported. In 2022, DEHP imports totaled 8,117 tons. DBP and DEP were imported in smaller quantities, with 635 tons and 317 tons, respectively, recorded in 2011⁽⁵⁾. (2) There is a lack of studies assessing the risk of phthalate exposure in children aged 5 to 12 years, although evidence from other countries indicates that this age group is also at high risk of such exposure. There is only one study that explicitly examined phthalate exposure in preschool children in Bangkok⁽³⁾. Furthermore, other reports indicated that a survey measured phthalate levels in dust from communities engaged in manual electronic waste (e-waste) sorting in southern Thailand⁽¹⁷⁾. However, phthalate exposure has not been evaluated in these contexts. In contrast, other countries, such as Japan and Korea, have conducted extensive research on this topic^(18,19). (3) To date, phthalate exposure via dust ingestion in rural areas has not been investigated. The differences in residential characteristics and lifestyles of the sample population are essential factors that contribute to variations in phthalate concentration levels and the risk of exposure to phthalates in household dust⁽²⁰⁾.

Therefore, the objective of this study was to assess the concentration of phthalates in settled house dust and evaluate the health risks associated with unintentional dust ingestion among elementary school children in Phatthalung Province, Thailand. This is important because children are a vulnerable population requiring protection and support to ensure a good quality of life and to minimize their risk of exposure to harmful chemicals or pollution in indoor environments. The findings provide baseline information that may help government agencies formulate risk-control and prevention guidelines and provide the public with evidence-based information to safeguard children from phthalate exposure in house dust.

Materials and Methods

1. Study design and data collection

This study was conducted in Pak Phayun and Ko Mak sub-districts in Phatthalung Province, Thailand, between February and April 2023 (Fig. 1). A cross-sectional descriptive design was used to assess the presence of ten phthalates (DMP, DEP, Dipropyl Phthalate (DPP), DiBP, DBP, Di-n-pentyl phthalate (DnPP), Diheptyl phthalate (DHP), Benzyl butyl phthalate (BBP), DEHP, and DnOP) in settled house dust. Settled dust samples were collected from 310 households with children. Eligibility criteria included families with at least one child aged 5 to 12 years. General demographic and household information, such as age, gender, body weight, underlying diseases, residential location (urban or rural), housing type (townhome or single-family home), and floor material, was collected using a questionnaire.

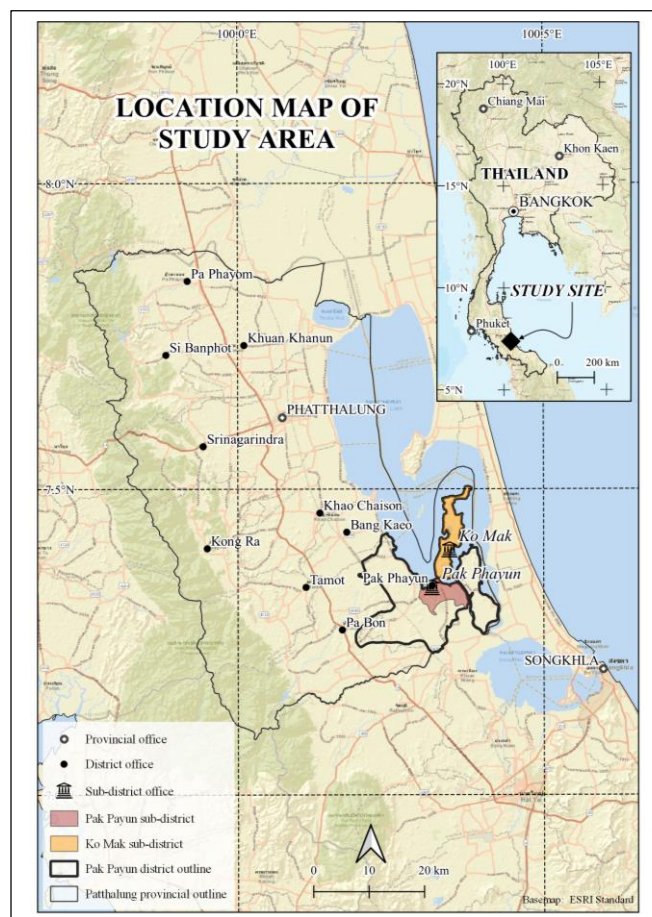


Figure 1 Study locations in Ko Mak and Pak Payun subdistricts

2. Settled house dust collection method

The settled dust collection method for phthalates followed a previously established vacuum-based sampling protocol⁽²⁰⁾. Settled dust samples were obtained from the living room, defined as a primary microenvironment for children's daily activities, using a portable vacuum with a two-layer nylon filter bag. Sampling was conducted separately from floor surfaces and accessible objects while keeping furniture positions undisturbed to maintain consistency across households. To minimize contamination, settled dust was not collected from background surfaces such as carpets or fabric- or plastic-based materials, which are known to contain phthalates. Each sample was collected until the mass-based endpoint of 20–150 mg of dust was reached. The measured concentrations were subsequently combined to represent overall indoor dust exposure. Collected dust samples were then sieved through a 100 μ m mesh. After sieving, samples were wrapped in aluminum foil and stored in conditions protected from light, elevated temperatures, heat, and humidity until analysis.

3. Sample extraction and analysis

Large particles and unwanted substances were filtered out using a filter bag and removed before extraction. Settled dust samples were weighed and stored in brown glass tubes, with each sample containing approximately 30 to 50 mg. The tubes were wrapped in aluminum foil and stored at -20 °C before extraction and analysis. Two milliliters of an internal standard solution prepared in acetone were used to extract each dust sample. Four deuterated phthalate analogs, D4-DEP, D4-DBP, D4-BBP, and D4-DEHP, each synthesized at a concentration of 2.5 mg/L, comprised the internal standard solution.

An ultrasonic water bath was used for 30 minutes to sonicate the samples after they had been vortexed. After overnight incubation at room temperature, the samples were centrifuged for 10 minutes at 3,000 rpm and 10 °C. The supernatant was collected, and 1 mL was transferred into a sample vial for gas chromatography-mass spectrometry (GC-MS) analysis (Agilent Technologies Inc., CA, USA). A DB-5MS capillary column (30 m, 0.25 mm, and 0.25 µm) was used. A flow rate of 1.2 mL/min was established for the carrier gas, which was helium (99.9995%). The injector port temperature was set at 290 °C. The GC temperature program was configured as follows: 50 °C for 1 minute as the initial oven temperature, then increased to 280 °C at a rate of 10 °C/min and maintained for 11.5 minutes. The instrument was configured for both scan and single ion monitoring (SIM) modes during the MS study. The temperature of the ion source was set at 230 °C. The quadrupole temperature was 150 °C, and 280 °C was the transfer line temperature. The split mode (split ratio of 1:1) was used to inject 1 µL of sample onto the GC. DMP, DEP, DPP, DiBP, DBP, DNPP, DHP, BBP, DEHP, and DnOP were the target analytes.

4. Quality Assurance and Quality Control

All glassware was thoroughly washed with purified water and then heated at 150 °C for two hours. To minimize environmental contamination with phthalates, glassware was rinsed with acetone, dried, covered with aluminum foil, and stored in a clean environment prior to use to control background phthalate levels. Acetone-based procedural blanks were included to assess instrumental efficiency and systemic contamination. The ten target phthalates have the following limits of quantification (LOQ): 0.01 mg/L for DnPP; 0.02 mg/L for DBP, DEP, and DPP; 0.05 mg/L for BBP, DMP, DnOP, and DEHP; and 0.10 mg/L for DHP and DiBP. Accuracy and precision of the analytical method were also evaluated. Each dust sample (50 mg) was divided into three sets of 15 samples each, and each set was placed in a glass tube. The first set served as a reference, while 20 mg and 40 mg of target phthalates were added to the second and third sets, respectively.

Duplicate samples from each batch were analyzed over five days. To calculate the % recovery, the samples were examined in duplicate using the NIST Standard Reference Material for Phthalates (SRM 2585). The % recovery of target phthalates ranged from 93.5% to 119%, while relative standard deviations (RSD) ranged from 1.41% to 9.27%, falling within the acceptable range of 80% to 120%.

5. Statistical analysis

The data analysis was performed using SPSS Statistics 18.0. For phthalate concentrations that were below LOQ, a value was assigned equal to the LOQ divided by the square root of 2. The $\Sigma 10\text{PAEs}$ was calculated by averaging the concentrations of each phthalate and summing the averages. Phthalate concentrations were evaluated for normality using the Kolmogorov-Smirnov test; a non-normal distribution was revealed by a p -value < 0.05 . Descriptive statistics were employed to characterize the sample and its various factors, including the GM, median, maximum, minimum, and percentiles. To analyze significant differences between groups, the non-parametric Mann-Whitney U test was utilized. A p -value of less than 0.05 was considered statistically significant.

6. Estimated phthalates in dust exposure and health risk

Exposure assessment focuses on the ingestion pathway, as settled dust collected from indoor surfaces is more relevant to children's hand-to-mouth behavior²². Three phthalates exceeded the LOQ in at least 60% of samples, including DEHP and DnOP (high-molecular-weight) and DBP (low-molecular-weight), were selected for individual risk assessment. In addition, the sum of all 10 phthalates ($\Sigma 10\text{PAEs}$) was used to evaluate total exposure. The estimated daily intake (EDI) of phthalates via dust ingestion was estimated using the following equation^{21,22}:

$$\text{EDI} = \frac{C_{\text{dust}} \times \text{IR} \times \text{FT} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (\text{Eq. 1})$$

where EDI is the daily intake of phthalates via dust ingestion (ng/kg bw/day), C_{dust} is phthalate concentration in dust sample (ng/g), IR is the dust ingestion rate (mg/day), FT is the time fraction for indoor exposure, estimated based on children's weekly activity patterns, assuming 8 hours at school on weekdays and full-time at home on weekends, resulting in an average indoor exposure time of 18.3 hours per day, which was converted into a unitless fraction ($\text{FT} = 0.76$) by dividing by 24 hours, EF is the frequency of exposure (days/year), ED is the duration of exposure (years), BW is body weight (kg), and AT is the averaging time (days). In this study, IR for elementary

school children was assumed to be 30 mg/day for the central tendency scenario and 100 mg/day for the upper percentile scenario, based on indoor settled dust ingestion rates reported in the U.S. EPA Exposure Factors Handbook (2017)⁽²²⁾. In addition, duration of exposure (ED) and body weight (BW) data were obtained from individual questionnaire data.

Following the EDI estimation, non-carcinogenic health risks were evaluated by calculating the hazard quotient (HQ) and hazard index (HI) using the following equation 2 and 3, respectively.

$$HQ = EDI / RfD \quad (\text{Eq. 2})$$

$$HI = \sum HQ_i \quad (\text{Eq. 3})$$

where HQ represents the risk ratio of exposure to non-carcinogenic phthalates, HI represents the hazard index, calculated as the sum of HQs, and Reference Dose (RfD) refers to the reference value for chemicals ingested (ng/kg bw/day). An HQ value greater than 1 suggests that the exposure dose exceeds the acceptable limit and may pose a risk to human health.

For carcinogenic health risks, DEHP has been classified as a Group 2B carcinogen (possible carcinogenicity to humans) by the International Agency for Research on Cancer (IARC). Therefore, this compound was assessed using Equation 4.

$$CR = EDI \times CSF \quad (\text{Eq. 4})$$

where CR is the cancer risk and CSF is the cancer slope factor ((ng/kg bw/day)⁻¹). Carcinogenic risk is typically categorized into three levels: A cancer risk (CR) less than 10⁻⁶ represents negligible risk; a CR between 10⁻⁶ and 10⁻⁴ represents acceptable risk; and a CR greater than 10⁻⁴ represents unacceptable risk or a high probability of cancer. All specific values used are summarized in Table 1.

Table 1 Exposure parameters used for EDI and risk assessment

Parameter (abbr.)	Value	Unit	Reference
IR	30 (central tendency) 100 (upper percentile)	mg/day	24
FT	0.76	-	-
EF	365	days/year	26
ED*	Individual data	years	-
BW*	Individual data	kg	-
AT	ED × 365 (non-cancer effects) 70 × 365 (carcinogenic effects)	days days	26
RfD	DBP = 1×10^5 DEHP = 2×10^4 DnOP = 1.2×10^4	ng/kg/day ng/kg/day ng/kg/day	27,28,29
CSF	DEHP = 1.4×10^{-8}	(ng/kg bw/day) ⁻¹	27

Remark; *= Based on individual questionnaire data

Result

1. Demographic characteristics

Table 2 presents the demographic characteristics of the participants. A total of 310 children were included in the study. Overall, the distribution of boys and girls was relatively balanced, with 51.0% of boys and 49.0% of girls. Regarding age, 40.3% of the children were younger than 9 years old, and 59.7% of the children were 9 years or older. The mean age was 9.0 ± 2.1 years.

Table 2 Demographic characteristics of study participants by group

Characteristics	n (%)
Total participants	310 (100.00)
Age group	
- ≥ 9 years	185 (59.7)
- <9 years	125 (40.3)
Age (mean =9.0 years, S.D. = 2.1)	
Sex group	
- Girl	152 (49.00)
- Boy	158 (51.00)

2. Concentration of phthalates in household dust

A total of 310 settled house dust samples collected from children's homes were analyzed, revealing the presence of ten distinct phthalates. Five of these were classified as low-molecular-weight phthalates: DBP, DEP, DiBP, DMP, and DPP. The remaining five were identified as high-molecular-weight phthalates: DEHP, DNPP, BBP, and DHP. Using the LOQ to determine the lowest detectable concentration, DEHP, DnOP, and DBP were detected in 100%, 96.5%, and 88.7% of samples, respectively. Other phthalates were present in less than 60% of the samples. Therefore, further analyses focused on DEHP, DnOP, and DBP, along with $\Sigma 10$ PAEs to represent overall exposure.

Among the detected compounds, DEHP exhibited the highest concentration, with a median of 150.91 $\mu\text{g/g}$ in dust, followed by DnOP and DBP, with median values of 8.98 $\mu\text{g/g}$ and 6.90 $\mu\text{g/g}$, respectively. The median value for $\Sigma 10$ PAEs was 190.71 $\mu\text{g/g}$ of dust, as presented in Table 3.

3. Health risk assessment of phthalate exposure

In this study, the EDI was calculated using two dust ingestion scenarios for elementary school children aged 5–12 years: a central tendency ingestion rate of 30 mg/day (typical exposure) and an upper percentile ingestion rate of 100 mg/day (high exposure) (Table 4; Figure 2). The results showed that median EDI values for DBP, DEHP, DnOP, and $\Sigma 10$ PAEs were 3.95, 88.91,

5.52, 112.56 ng/kg bw/day, respectively, under the central tendency exposure scenario. Under the upper percentile scenario, the median EDI values for DBP, DEHP, DnOP, and $\Sigma 10$ PAEs increased to 13.18, 296.38, 18.39, and 375.22 ng/kg bw/day, respectively.

Table 3. Concentration of phthalates in household dust in children's home

Type of Phthalate (n = 310)	Concentration ($\mu\text{g/g}$ of dust)					% detection	LOQ (mg/L)
	GM	Median	Max	Min	95 th		
DBP	6.44	6.90	248.95	0.51	71.10	88.70	0.02
DMP	0.60	0.57	1.35	0.57	0.85	8.40	0.05
DEP	0.51	0.45	27.64	0.45	0.99	13.90	0.02
DiBP	3.30	2.83	33.55	2.83	10.29	13.20	0.01
DHP	2.90	2.83	94.55	2.83	2.83	1.30	0.01
BBP	1.21	1.13	157.86	1.13	1.13	3.20	0.05
DPP	0.61	0.57	1.43	0.57	1.189	4.50	0.02
DnPP	0.61	0.28	4.13	0.28	3.77	33.60	0.01
DEHP	158.84	150.91	3,386.75	20.69	597.70	100.00	0.05
DnOP	9.50	8.98	123.66	1.41	35.71	96.50	0.05
$\Sigma 10$ PAEs	201.30	190.71	3441.88	37.35	636.82	-	-

Comparisons of EDI between two age groups and between genders are shown in Table 5. The results showed significant differences in EDI for DEHP, DnOP, and $\Sigma 10$ PAEs between the two age groups, with higher levels observed in children aged 9 years and older compared to those younger than 9 years under both exposure scenarios ($p < 0.001$, Mann-Whitney U test). In contrast, no significant age-related differences were observed for DBP. Regarding gender, no significant differences in EDI were observed for DBP, DEHP, DnOP, or $\Sigma 10$ PAEs between boys and girls.

Table 4. Summary statistics of EDI for individual and total phthalate using two dust ingestion scenarios (ng/kg bw/day)

Type of Phthalate	Central tendency				Upper percentile			
	GM	Median	Min - max	95 th	GM	Median	Min - max	95 th
DBP	3.84	3.95	0.15 - 171.04	38.13	12.81	13.18	0.50 - 570.14	127.11
DEHP			11.66 -					
	94.73	88.91	2144.94	418.14	315.75	296.38	38.87 - 7149.81	1393.81
DnOP	5.66	5.52	0.78 - 59.40	22.54	18.88	18.39	2.60 - 198.00	75.15
Σ10 PAEs			17.23 -					
	120.04	112.56	2179.86	452.85	400.13	375.22	57.44 - 7266.19	1509.51

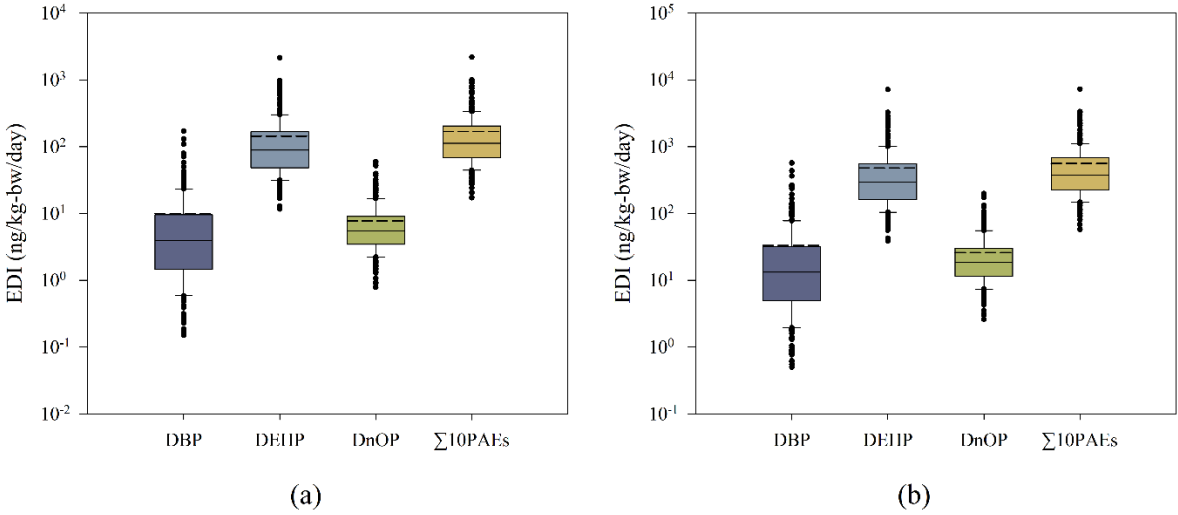


Figure 2 Distribution of EDI of DBP, DEHP, DnOP, and Σ10 PAEs via dust ingestion under (a) central tendency and (b) upper percentile exposure scenarios.

Table 5. Comparison of EDI of phthalates by demographic characteristics using the Mann–Whitney U test under two exposure scenarios (ng/kg bw/day)

Demographic determinants	DBP				DEHP				DnOP				$\Sigma 10$ PAEs			
	GM	Media n	95 th	p-value	GM	Media n	95 th	p-value	GM	Media n	95 th	p-value	GM	Media n	95 th	p-value
Age groups (n)																
<i>Central tendency</i>																
- ≥ 9 years (185)	4.69	5.20	42.40	0.64	135.1 2	136.84	638.84	<0.001 *	6.45	6.05	27.4 8	<0.001 *	164.6 4	179.24	671.66	<0.001 *
- <9 years (125)	3.71	3.67	30.66		75.60	72.71	270.69		4.78	4.42	21.5 9		96.87	93.89	299.20	
<i>Upper percentile</i>																
- ≥ 9 years (185)	15.6 3	17.32	141.3 3	0.64	450.4 0	456.12	2129.4 8	<0.001 *	21.4 9	20.16	91.6 1	<0.001 *	548.8 0	597.47	2238.8 6	<0.001 *
- <9 years (125)	12.3 5	12.25	102.2 1		252.0 1	242.38	902.31		15.9 3	14.73	71.9 6		322.9 0	312.96	997.32	
Gender (n)																
<i>Central tendency</i>																
- Girl (152)	4.30	4.34	38.08	0.13	96.85	87.47	476.02	0.57	5.91	6.10	21.2 4	0.17	122.5 7	112.56	494.00	0.54
- Boy (158)	3.45	3.20	39.02		92.72	90.40	366.41		5.44	5.13	25.8 2		117.6 6	112.27	396.83	
<i>Upper percentile</i>																
- Girl (152)	14.3 2	14.45	126.9 5	0.13	322.8 4	291.55	1586.7 4	0.57	19.7 0	20.32	70.7 8	0.17	408.5 6	375.22	1646.6 6	0.54
- Boy (158)	11.5 0	10.68	130.0 5		309.0 8	301.32	1221.3 6		18.1 2	17.09	86.0 6		392.1 9	374.23	1322.7 6	

Remark: *= significant difference between age groups ($p < 0.05$)

Table 6 presents the mean HQ for phthalate exposure via dust ingestion under two dust ingestion scenarios. Under the central tendency exposure scenario, the mean HQ values for DBP, DEHP, and DnOP were 9.95×10^{-5} , 7.19×10^{-3} , and 6.47×10^{-4} , respectively. The overall hazard index (HI) was 7.94×10^{-3} . In the upper percentile exposure scenario, the mean HQ values for DBP, DEHP, and DnOP increased to 3.32×10^{-4} , 2.40×10^{-2} , and 2.16×10^{-3} , respectively, resulting in an HI of 2.65×10^{-2} . All HQ and HI values remained below 1 under both exposure scenarios. Meanwhile, the mean CR of DEHP was estimated to be 2.01×10^{-6} under the central tendency exposure scenario and 6.71×10^{-6} under the upper percentile exposure scenario, with one individual sample exhibiting a CR exceeding the acceptable risk level (1×10^{-4}) under the upper percentile scenario, while all other participants remained within acceptable limits.

Table 6. Mean HQ and CR of phthalates via dust ingestion under two exposure scenarios

Parameter	Central tendency		Upper percentile	
	HQ	CR	HQ	CR
DBP	9.95×10^{-5}	-	3.32×10^{-4}	-
DEHP	7.19×10^{-3}	2.01×10^{-6}	2.40×10^{-2}	6.71×10^{-6} *
DnOP	6.47×10^{-4}	-	2.16×10^{-3}	-
HI	7.94×10^{-3}	-	2.65×10^{-2}	-

Remark: * = One individual sample exhibited CR for DEHP above the acceptable threshold (1×10^{-4}) under the upper percentile exposure scenario, with a value of 1.001×10^{-4}

Discussion

1. Occurrence of phthalates in house dust

The most common compounds found in settled house dust in this study were DEHP, DnOP, and DBP. The detection rate indicated that DEHP was the predominant phthalate, consistent with previous findings in China and Canada^(24,25,26,27), with a detection rate exceeding 90%. Additionally, DEHP was detected at levels comparable to those reported in earlier studies in China²⁴. DnOP was the second most frequently detected phthalate, accounting for 96.5% of detections, with concentrations ranging from 1.41 to 123.66 $\mu\text{g/g}$ of dust. This result aligns with findings from studies conducted in Nigeria and Qatar^(34,26). To date, no studies in Thailand have reported DnOP concentrations in house dust^(3,17). DBP was also detected in house dust, with concentrations ranging from 0.51 to 248.95 $\mu\text{g/g}$ and a detection rate of 88.70%, similar to a study

from Beijing, China⁽²⁷⁾. In contrast, the detection rates for DEP, DMP, DiBP, and DPP in house dust were detected at rates below 60%, consistent with previous studies in Beijing, China⁽²⁷⁾. The low levels of these phthalates may be attributed to their low molecular weight and high vapor pressure, which increase their volatility. The predominance of DEHP, DnOP, and DBP in house dust indicates that consumer products and household materials may contribute to their presence in house dust. PVC-containing products such as flooring, wall coverings, carpet tiles, and furniture are frequently linked to DEHP, DnOP, and DBP. DBP is also used in personal care and consumer products such as medical coatings and perfumes^(36,37).

When compared with concentrations reported in house dust from Bangkok, Thailand, in 2018, the levels of DEHP and DBP observed in the present study were lower⁽³⁾. This reduction may be associated with legal enforcement and regulatory controls on phthalate use in various products in recent years. Four out of more than thirty phthalates, including those currently in use, are listed under the Thailand Hazardous Substance Act as Type III Hazardous Substances, requiring specific registration and permission from the Department of Industrial Works for production, import, export, and possession. In Thailand, phthalate use is regulated only in three product categories: food wrapping films, cosmetics, and children's toys⁽⁵⁾. In 2023, the Ministry of Public Health issued a notice listing substances prohibited for use as ingredients in cosmetics production, including DBP, DEHP, Di(2-methoxyethyl) phthalate (DMEP), BBP, and phthalates with the main structure of n-pentyl-isopentyl phthalate, such as DnPP and Diisononylphthalate (DiPP)⁽⁵⁾. For $\Sigma 10$ PAEs, the median level in house dust was 190.71 $\mu\text{g/g}$, which is comparable to findings from a study conducted in Beijing, China⁽²⁷⁾. These results indicate that children may be simultaneously exposed to multiple types of phthalates in house dust, and that exposure to phthalate mixtures may have implications distinct from those of exposure to a single phthalate.

2. Phthalate exposure levels and associated health risks in children

The median EDI of DEHP was 88.91 ng/kg bw/day (central tendency) and 296.38 ng/kg bw/day (upper percentile), which were higher than those reported in children from northern Chinese cities^(28,29). However, the EDI of DEHP was also lower than values reported in Bangkok, Thailand, and Harbin, China^(3,29). The median EDI of DnOP (5.52 and 18.39 ng/kg bw/day for central tendency and upper percentile, respectively) exceeded those found in previous studies of New Zealand children⁽³¹⁾. In addition, the median EDI of DBP (3.95 ng/kg bw/day for central tendency and 13.18 ng/kg bw/day for upper percentile) was lower than values reported in studies of children from New Zealand and Bangkok, Thailand^(3,30). For the mixture of phthalates, the median EDI of $\Sigma 10$ PAEs was 112.56 ng/kg bw/day (central tendency) and 375.22 ng/kg bw/day (upper

percentile), both of which were higher than those reported in previous studies of Chinese children⁽³²⁾. In support, variability in phthalate exposure may be linked to variations in materials and usage patterns between rural and urban households, which affect the sources and concentrations of indoor phthalate contamination⁽³⁷⁾. The phthalate levels detected in dust samples from homes in Phatthalung Province appeared lower, potentially due to less frequent use of modern household products. Furthermore, this study primarily sampled single-family houses, whereas most studies in Bangkok have focused on high-rise buildings⁽³⁾. High-rise buildings often experience limited natural ventilation and are typically located in areas with heavy traffic and closer proximity to external phthalate sources. Previous research has shown that proximity to external phthalate sources correlates with elevated phthalate levels in indoor environments⁽³⁷⁾.

In comparison with demographic characteristics, the median EDIs of DEHP and DnOP for children aged 9 years and older were significantly higher than those younger than 9 years under both central tendency and upper percentile scenarios (see Table 5), indicating a potential age-related difference in exposure. Also, the median EDI of Σ 10PAEs for children aged 9 years and older also exhibited significantly higher levels than those younger than 9 years under both scenarios. In contrast, a pilot study conducted in Germany reported that daily DEHP intake measured in urine generally decreased with increasing age in children, likely due to higher food intake relative to body weight in younger children⁴². However, a previous report from China showed that the relative contribution of dust to total DEHP exposure increased with age (25.85% to 30.11%), while dietary contribution decreased. This difference may reflect the dominant role of dietary intake in total exposure, whereas dust becomes relatively more important in older children. This pattern is consistent with this study⁽¹⁸⁾. Regarding the EDI of DnOP, households where residents frequently used skincare products, such as body creams and lotions, showed higher dust concentrations of DnOP⁽⁴³⁾. Survey results also indicated that younger children use fewer cosmetics than older children⁽³⁷⁾, which may contribute to the higher DnOP exposure observed in older children. Overall, children aged 9–12 years exhibited a higher EDI for Σ 10PAEs than younger children, possibly due to age-related differences in exposure patterns and product use, leading to increased exposure to individual phthalates.

Compared with the RfD values, the EDI values for DEHP, DnOP, and DBP among children in this study were all below the recommended thresholds, with the mean HQ and HI values of all below 1 under both central tendency and upper percentile scenarios, indicating that non-carcinogenic risk is unlikely, consistent with findings from studies conducted in China and Nigeria^(25,28,31). In contrast, previous reports indicated that the EDI of DEHP via dust ingestion

among preschool children in urban Bangkok exceeded the US EPA RfD³. Moreover, a study across 12 European countries reported that 17% of children and adolescents also reported HQ values for DEHP exceeding 1⁽³²⁾. For carcinogenic effects, the mean CR value of DEHP under both central tendency and upper percentile scenarios was less than 1×10^{-4} (2.01×10^{-6} and 6.71×10^{-6}), indicating negligible risk. These results suggest that elementary school children are not at significant risk of DEHP exposure, consistent with findings from a previous study in China⁽²⁸⁾. Notably, the CR of DEHP for one child exceeded the acceptable threshold under the upper percentile scenario (1.001×10^{-4}). Under these circumstances, children with high exposure to house dust may warrant attention due to the potential carcinogenic risk associated with DEHP exposure. Minimizing exposure among children remains the most effective strategy to reduce cancer risk. In addition, although the HI and HQ are currently within acceptable limits, several practical measures to reduce exposure are recommended for the public. These strategies may include the use of phthalate-free products, awareness of exposure sources, and good hygiene practices, particularly for children. Recommended government interventions may include restricting the use of phthalates in products intended for young children, limiting permissible levels in household products, and enhancing transparency through product labeling. Such measures could help reduce phthalate use and associated environmental contamination⁽³⁷⁾.

Conclusion

This study investigated the occurrence of phthalates in settled house dust and evaluated the associated risks of phthalate exposure among elementary school children in Phatthalung Province, Thailand. Overall, DEHP, DnOP, and DBP were the predominant compounds detected in settled house dust (detection rates ranged from 88.7 to 100%), with DEHP as the most prevalent, followed by DnOP and DBP (median concentrations ranged from 6.90 to 150.91 $\mu\text{g/g}$). Other phthalates were detected with less than 60% detection rates. Consumer products and household materials may contribute to the presence of DEHP, DnOP, and DBP in house dust. The median concentration of $\Sigma 10\text{PAEs}$ in dust was 190.71 $\mu\text{g/g}$, reflecting the phthalate mixture to which children can be exposed. For exposure assessment, the median EDIs of DEHP, DnOP, and $\Sigma 10\text{PAEs}$ for children aged 9 years and older were found to be significantly higher than those younger than 9 years, indicating a potential age-related difference in exposure patterns. The mean HQ and HI values of DEHP, DnOP, and DBP were all below 1 under both central tendency and upper percentile scenarios, indicating that non-carcinogenic risk is unlikely. Meanwhile, the mean

CR value of DEHP was also below the acceptable threshold; however, one child exceeded this threshold under the upper percentile scenario (1.001×10^{-4}), warranting attention due to the potential carcinogenic risk associated with DEHP exposure. Therefore, practical measures to reduce exposure are recommended for the public to minimize exposure and long-term health risks among children. The results provide baseline data to support risk assessment and inform strategies to reduce children's exposure to phthalates in indoor environments.

Ethical Approval Statement

The study received approval from the Ethics Committee of the Faculty of Tropical Medicine, Mahidol University (TMEC 23-001), in accordance with the Declaration of Helsinki, the International Council for Harmonization (ICH) Good Clinical Practice guidelines, and other international guidelines for the protection of human research participants.

Author Contributions

NL, KT, and OK designed the study and developed the conceptual framework, methodology, validation procedures, manuscript preparation, and supervision. NL and SI were responsible for statistical analysis. NL and OK prepared the original draft. OK and KT served as project administrators. NL, OK, KT, and SI contributed to writing, review, and editing. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors state that there are no known competing financial interests or personal relationships that could have influenced the work presented in this paper.

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