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ORIGINAL PAPER

A systematic characterization of soil/dust ingestion for typical subpopulations in China

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Abstract An accurate assessment of human exposure to pollutants through the ingestion of dust and/or soil particles depends on a thorough understanding their rate of human ingestion. To this end, we investigated the load and size distribution patterns of dust/soil particles on the hands of three typical subpopulations, including preschoolers, college students, and security guards (outdoor workers). The geometric mean diameter of dust/soil particles on hands was observed to be 38.7 ± 11.2, 40.0 ± 12.1, and 36.8 ± 10.4 μm for preschoolers, college students, and security guards, respectively. The particle size distribution differed between subpopulations: Preschoolers were more exposed to fine particles, whereas security guards were exposed to more coarse particles. The geometric means of dust/soil particle loading on the hands were 0.126, 0.0163, and 0.0377 mg/cm^2 for preschoolers, college students, and security guards, respectively. Males had statistically higher dust/soil particle loadings on hands than females, notably for preschoolers and college students; preschoolers with frequent hand contact with the bare ground had higher dust/soil particle loadings compared to those of peers in contact with commercial and residential grounds. The mean total dust/soil particle ingestion rate was estimated to be 245, 19.7, and 33.1 mg/day for preschoolers, college students, and security guards, respectively. Our estimates for college students and security guards are close to the consensus central-tendency values recommended by the U.S. EPA's Exposure Factor Handbook for American adults, whereas the estimates for children are much higher than the upper percentile values recommended for American children.

Keywords Particle size distribution · Dust · Soil · Loading · Ingestion · Subpopulations

Introduction

As a reservoir and repository of numerous environmental contaminants, dust and soil particles are a mixture of particulate matter originating from various natural and anthropogenic sources (Wang et al., 2015; Yu et al., 2020b). Currently, human exposure to toxic chemicals in dust/soil particles is of great concern given that dust/soil particle ingestion by humans

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is often inadvertent and ubiquitous (Bu et al., 2019; He et al., 2018a; Jin et al., 2019; Sun et al., 2018; Van den Eede et al., 2012). Dust/soil particle ingestion is considered a critical pathway for human exposure to various indoor contaminants, such as flame retardants, tobacco chemicals, and recreational substances (Chen et al., 2019; Huang et al., 2022; Shin et al., 2013; Stuart et al., 2008; Vykoukalova et al., 2017; Yeh et al., 2022; Zhao et al., 2019). Earlier human exposure assessors often collected dust/soil particle samples from residential environments or workplaces (Cao et al., 2012, 2017; Liu et al., 2018) and quantified the levels of contaminants therein, whereby they estimated the human intake dose of contaminants in combination with a surveyed or documented total dust/soil ingestion rate (IR_{total}) (Ma et al., 2016; Oezkaynak et al., 2011; Wilson et al., 2013).

However, most existing human exposure assessments treat dust/soil particles of various sizes as a "bulk" phase without considering the variability in the ingestion rate between particle sizes. As a key property of dust/soil particles, particle size determines the transport, fate, and exposure potential of pollutants bound to particles (Sun et al., 2017; Zhang et al., 2020). Recent studies have shown that dust/soil particle ingestion occurs predominantly via hand-to-mouth contact (Li et al., 2021; Oezkaynak et al., 2011; Wang et al., 2021). Whether dust/soil particles can adhere to and be retained on the hand surface and ingested by humans depends on the particle size (Mercier et al., 2011). Recent studies have shown that the size distribution of dust and soil particles on hand surfaces is highly diverse (Cao et al., 2012, 2013, 2014; Cohen Hubal et al., 2000) because the characteristics of dust and soil particles (such as moisture content (Hsi et al., 2018a), organic carbon content, mineral content, and aggregation (Choate et al., 2006)) may vary greatly among countries or areas (Lioy Paul et al., 2002; Wensing et al., 2005). Previous laboratory tests have demonstrated that when the moisture content of these dust/soil particles increases, so does the adhesion of larger particles (Choate et al., 2006; Kissel et al., 1996b). Additionally, particle size can have a significant impact on the presence of contaminants in dust/soil particles and the rate of their transfer to human hands (Choate et al., 2006; Liu et al., 2015; Meng et al., 2015). Extensive studies have demonstrated that contaminants tend to accumulate on finer particles because of their higher absorption capacity resulting from their larger specific surface areas (Bergstrom et al., 2011; Cao et al., 2012; He et al., 2018b; Ikegami et al., 2014; Luo et al., 2011). Furthermore, the previous studies have deduced that the analytical results of the concentrations of toxic chemicals can vary up to tenfold with different size fractions of dust/soil particles (Cao et al., 2012, 2015; Lewis et al., 1999). In addition, the particle size also impacts the bioavailability of contaminants on the skin (for dermal exposure) and in the gut (for ingestion exposure) (Ferguson et al., 2021). Therefore, it is essential to comprehend the distribution of particle sizes and chemical distribution thereon to assess exposure and health risk resulting from contaminated indoor and outdoor dust/soil (Hsi et al., 2018b). Data on the size distribution of dust/soil particles in different populations in natural settings are currently lacking, particularly in densely populated developing countries, such as China.

Few studies have analyzed the size distribution of dust/soil particles, with inconsistent conclusions. An earlier hand-pressing trial by Que Hee et al. (1985) using size-segregated house dust samples indicated that dust/soil particles less than 246 μm adhered readily to children's hands. Similarly, Choate et al. observed that completely or moderately dry dust/soil particles smaller than 63 μm in diameter were efficiently transferred to the hands of healthy adults (Choate et al., 2006). Four adult volunteers were used as surrogates for children, and Hsi et al. found that most dust/soil particles on hands from their hand-washing samples were less than 150 μm in diameter (Hsi et al., 2018c). Because these studies were conducted under controlled conditions in the laboratory, they may not entirely represent realistic natural conditions where humans ingest dust from the environment, particularly those resulting from unintended hand-to-mouth transfers. In contrast, fieldwork by Duggan et al. revealed that about 90−98% of particles on children's hands were less than 10 μm in diameter (Duggan et al., 1985). The authors used a microscope interfaced with a Magiscan II automatic image analyzer, which may not be suitable for large-scale studies. To address this limitation, Yamamoto et al. (2006) used a laser particle size analyzer to determine the size distribution of dust/soil particles in hand-washing samples and reported an average size of 39 ± 26 μm. The above literature review indicates that available research on the size distribution of dust/soil particles in hands is largely limited to children, and the data are inadequate for application to individuals in other age groups such as teenagers and adults.

The IR_{total} resulting from hand-to-mouth contact depends closely on dust/soil loading on the hands, which varies among populations as a result of their different activity patterns, exposure scenarios, and distinct properties of the human skin. For example, Yamamoto et al. reported that 4-year-old children attending nursery school had an average dust/soil loading of 0.125 mg/cm^2 on their hands after a day of activity (Yamamoto et al., 2006). Ikegami et al. (2014) used wet cotton pads to wipe the hands of children aged 1–6 years in a nursery school and found that the average dust/soil loading ranged from 0.054 to 0.127 mg/cm^2. Wang et al. (2015) gathered hand wipe samples from children and teenagers in kindergartens, primary schools, and middle schools and determined the median dust/soil loading to be 0.230 mg/cm^2. Again, these existing relevant studies were limited to children (Jin et al., 2018), and there are currently insufficient data for adults (Melanie et al., 2014).

It has been demonstrated that dust/soil adherence, particle size, and dust/soil ingestion behavior via hand-to-mouth contact are important considerations when determining human exposure to contaminated dust/soil particles (Bergstrom et al., 2011; Li et al., 2021). However, to the best of our knowledge, available IR_{total} data are limited, with investigations in children mostly drawn from developed countries such as Canada (Doyle et al., 2012; Irvine et al., 2014) and the United States (Binder et al., 1986; Davis et al., 1990; Von Lindern et al., 2016). The IR_{total} of children from Canada or the United States is unlikely to be representative of the situation in developing countries because of the discrepancies in the residential environment, lifestyle, and behavioral habits between countries and populations (Lin et al., 2017). In recent years, haze pollution, one of the most important long-standing environmental problems, especially in northern China (Cao et al., 2018b, 2022; Yu et al., 2020a), has increased the risk of human exposure to settled dust and dust-bound chemicals (Cao et al., 2019). However, research in China is only available in Hubei (Central China) and Gansu (West China) (Lin et al., 2017; Ma et al., 2016; Wang et al., 2018a). A reliable IR_{total} for typical Chinese populations in other regions, especially northern China, has not yet been determined (Jin et al., 2018).

To address all these knowledge gaps, the specific objectives of this study were: (1) to explore the size distribution and loading of dust/soil particles on the hands of representative Chinese subpopulations exemplified by preschoolers, college students, and security guards (representative of outdoor workers); (2) to investigate potential influencing factors for human exposure to dust/soil particles; and (3) to estimate the dust/soil ingestion rate via hand-to-mouth contact ($IR_{dust/soil\text{-}hand}$) and IR_{total} and to provide more rigorous and reliable assessments of human exposure to chemical contaminants in dust/soil particles. Here, we do not differentiate between dust/soil particles sourced from indoor and outdoor environments since (1) they are commonly found together on hands and contribute together to human's overall chemical exposure, and (2) they often coexist within the same microenvironment due to the exchange of indoor and outdoor dust/soil particles.

Materials and methods

Sampling area and description of dust/soil particle samples

This study was conducted in Xinxiang, a medium-sized city in northern China. Hand-washing samples were collected from three typical subpopulations, namely, preschoolers (55 females and 52 males), college students (47 females and 48 males), and security guards working outdoors (35 middle-aged men) between May and July 2017. Furthermore, to explore the influence of area of activities on the characteristics of human exposure to dust/soil particles, we collected hand-washing samples from children after playing on bare ground (BG) ($n = 35$), residential ground (RG) ($n = 34$), and commercial ground (CG) ($n = 38$).

All participants were engaged in normal activities and did not wash their hands for at least 2 h before sampling. During sampling, they were asked to rinse their hands with 100 mL of deionized water, and the dust/soil particles adhered to their hands were completely removed from both hands by rubbing both hands (Yamamoto et al., 2006). Hand-washing samples were collected in individual polyethylene terephthalate jars; after sample collection, 0.2% (w/w) sodium hexametaphosphate (a dispersant) was immediately added to the samples to prevent particle coagulation (Hsi et al., 2018c). Participants were also asked to complete a simple questionnaire regarding their age, gender, and sampling location.

Particle size distribution of dust/soil particles on hands

The samples were analyzed using a laser particle size analyzer (Microtrac-S3500, Beckman Coulter, Brea, USA; measurable particle diameter range from 0.02 to 2000 μm) within 3 days after sampling. Accordingly, the size distributions were characterized by the volume fractions of particles in individual diameter ranges (Cao et al., 2022; Ferguson et al., 2020, 2021; Hsi et al., 2018a; Yamamoto et al., 2006).

The dust/soil loadings on hands

We used a calibration curve method to quantify the dust/soil loadings on the hands. Specifically, surface soil samples from the Henan Normal University campus were collected, dried, and sieved through a 250-μm stainless steel mesh and used as a reference, similar to the practice reported by Hsi et al. (2018b), Yamamoto et al. (2006), Hsi et al. (2018c), and Yamamoto et al. (2006). Here, 250-μm soil particles were used because earlier studies have consistently shown that soil particles larger than this size are not adherent and, therefore, less relevant to the subsequent analysis (Duggan et al., 1985). Using the readings of laser transmittance, a calibration curve was generated with different amounts of reference soil, that is, 6.00, 10.00, 15.00, 20.00, 30.00, and 100.00 mg, in 50-mL deionized water (Yamamoto et al., 2006). Figure S1 illustrates the calibration curve used to quantify dust/soil loading based on the measured laser intensities corresponding to various concentrations of the reference soil. The laser intensity traversing the particle suspension is governed by the Lambert–Beer law, which expresses the relationship between particle concentration and laser transmittance. Before the soil concentration reached 100.00 mg in 50-ml water, the linearity of the calibration line was guaranteed, with a coefficient of determination (R^2) of 0.9999. The dust/soil loading on the hand-washing samples was quantified using this calibration line according to the laser transmittance value read by the laser particle size analyzer.

Estimation of $\mathrm{IR}_{\mathrm{total}}$

Based on the methodology recommended by earlier studies (Cohen Hubal et al., 2000; Oezkaynak et al., 2011; Stapleton et al., 2008), the $\mathrm{IR}_{\text{dust/soil-hand}}$ and $\mathrm{IR}_{\mathrm{total}}$ in this study were estimated using the following equations:

$$\mathrm{IR}_{\text{dust/soil - hand}} = M_{\mathrm{surf}} \times \mathrm{TE} \times \mathrm{SAC} \times \mathrm{EF} \tag{1}$$

where $\mathrm{IR}_{\text{dust/soil-hand}}$ represents the daily rate of dust/soil ingestion from mouthing hands (mg/d), M_{surf} is the mass of dust/soil particles on the hands (mg), TE is the transfer efficiency of dust/soil particles, SAC is the proportion of the hand area in contact with the mouth via hand-to-mouth contact activities (%), and EF is the frequency of hand-to-mouth contact during a day (d^{-1}). In this study, we assumed that three types of subpopulations were exposed to dust/soil particles for 12 h per day (Wang et al., 2015). For the rest of the parameters, we used the literature-reported critically evaluated consensus values: a TE value of 0.5 (Li et al., 2021), an EF value of 7 for preschoolers and 2 for college students and security guards (Wang et al., 2015), and an SAC value of 10% (Stapleton et al., 2008).

$$\mathrm{IR}_{\mathrm{total}} = \mathrm{IR}_{\text{dust/soil - hand}} / \mathrm{R}_{\mathrm{htm}} \tag{2}$$

$\mathrm{IR}_{\mathrm{total}}$ represents the total daily dust/soil ingestion rate (mg/d), and R_{htm} is the ratio of dust/soil ingestion via hand-to-mouth contact to total dust/soil ingestion. Representative R_{htm} values of preschoolers, college students, and security guards were set as 0.58, 0.48, and 0.41, respectively, based on the most recent age-dependent estimates generated by the mouthing-mediated ingestion module of the PROTEX model (Li et al., 2021). Actually, these recommended values above, we used to calculate dust/soil ingestion of the general population, reFpresent the central tendency of dust/soil ingestion by "average" individuals in a population, but not "high-end" exposure level (i.e., soil pica).

Statistical analysis

Statistical analysis was conducted using SPSS statistical software package, version 26.0 (SPSS Inc., USA). The particle size of the dust/soil samples is represented by the geometric mean, geometric standard deviation, maximum value, and minimum value. The loading of dust/soil particles on the hands of preschoolers, college students, and security guards is summarized in a box diagram, with medians, means, 5th quantiles, 95th quantiles, maximums, and minimums. The particle size distribution and loadings of dust/soil particles on the hands were compared among subpopulations, genders, and sampling sites using an unpaired (i.e., independent sample) t-test at a significance level of 0.05.

Results

Particle size distribution of dust/soil particles on hands

Variation among subpopulations

Generally, the particle size distribution of dust/soil particles on the hands among the three subpopulations was found to be similar in the size range of 1.3−704 μm (Fig. 1a). Dust/soil particles on the hands of preschoolers, college students, and security guards had peak sizes of 28.5, 26.2, and 28.5 μm, respectively, and geometric means of 38.7 ± 11.2, 40.0 ± 12.1, and 36.8 ± 10.4 μm, respectively. In addition, we found that particles smaller than 100 μm accounted for approximately 91–95% of the total dust/soil particles adhered to the hands in all samples. This result is consistent with the previous findings from the U.K. and Japan (Table 1), which indicated that dust/soil particles less than 100 μm were more likely to be adhered to and retained by the human hands. Comparatively, the particle size distribution of dust/soil particles on the hands of the U.S. population was very different from that observed among Asians (Table 1). Figure 1b also indicates that finer particles are more abundant on preschoolers' hands than on the hands of college students and security guards. This is notable for the finest particles with diameters < 4.7 μm (25.1%). This implies that preschoolers are more susceptible to finer particles than are other subpopulations.

Gender differences

To investigate the disparity in dust/soil particle size distribution between genders, we compared handwashing samples from college students and preschoolers (Fig. S2). For college students, the gender difference is clear: The fine (< 20.2 μm) and coarse (> 37.0 μm) particles on average accounted for 11.9% and 44.4%, respectively, of the total dust/soil particles on male hands but 33.4% and 22.7%, respectively, of those on female hands. In contrast, for preschoolers, the size distribution of dust/soil particles was similar between sexes. While the exact mechanism responsible for this difference between preschoolers and college students is unknown, a possible reason is the difference in skin biophysical properties. For example, the previous studies have demonstrated that males tend to have higher sebum content than females of comparable age for college students, while no differences were found between male and female preschoolers (Man et al., 2009; Shetage et al., 2014).

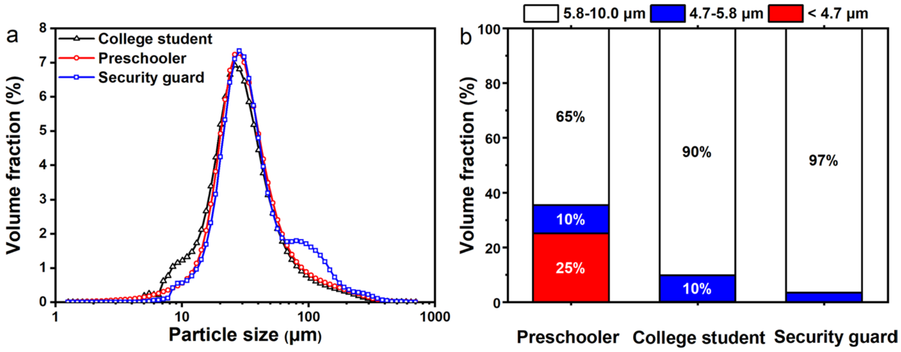

Fig. 1 Particle size distributions of dust/soil particles among the three subpopulations. **a** For all size fractions and **b** for fractions with particle size less than 10 μm

Table 1 Summary of results of particle size distribution of dust/soil particles on hands from prior studies

Particle size distribution (μm)	Location	Population	Method	References
$<246^a$	United States	6 children (3−10 years) and 10 adults	Sieve analysis	Que Hee et al. (1985)
<150 and $<250^b$	United States	Adults	Sieve analysis	Driver et al. (1989)
$<150^a$	United States	1 adult	Sieve analysis	Kissel et al. (1996b)
$<63.0^a$	United States	108 adults	Sieve analysis	Choate et al. (2006)
$250-2000^b$	United States	6 adults	Sieve analysis	Bergstrom et al. (2011)
$<63.0^a$	United States	10 households	Sieve analysis	Beamer et al. (2012)
$147-1166^c$	United States	103 children	Laser particle size analysis	Ferguson et al. (2020)
$<1020^c$	United States	98 children	Laser particle size analysis	Ferguson et al. (2021)
$<10.0^a$	United Kingdom	368 children	Sieve analysis	Duggan et al. (1985)
$<300^a$	Japan	10 children (4 years old)	Laser particle size analysis	Yamamoto et al. (2006)
$<150^a$	Taiwan, China	4 adults	Laser particle size analysis	Hsi et al. (2018c)
$1.3-704^a$	Xinxiang, China	107 preschoolers, 95 college students, and 35 security guards	Laser particle size analysis	Our study

[a] Particle size distribution of the dust/soil adhered to the hands, [b] particle size distribution of the dust/soil that was dry-sieved, and [c] particle size distribution of the sand adhered to the hands

Spatial variation and influence of exposure source

Because of preschoolers' frequent touch behavior, one may wonder whether the size distribution of dust/soil particles on preschoolers' hands mimics that on the ground. To explore this issue, we compared the size distribution of dust/soil particles in hand-washing samples collected from preschoolers playing on three different types of ground (bare, commercial, and residential) (Fig. S3). The results showed that, in general, dust/soil particles on the hands of preschoolers playing on different types of ground possess quite consistent size distributions, indicating that the type of ground, or the composition and size of dust/soil particles on the ground, plays a limited role in determining the size distribution of dust/soil particles on the hands. Therefore, we infer that the size distribution of dust/soil particles on preschoolers' hands depends largely on their skin properties. This inference is consistent with an earlier finding that there was no significant difference in sebum content and skin moisture content in children (Man et al., 2009; Xin et al., 2007).

Dust/soil loadings on hands

Variation among subpopulations

Figure 2a depicts dust/soil loadings on the hands of preschoolers, college students, and security guards in China, ranging from 0.007 to 0.996 mg/cm^2, which is similar to some earlier measurements from other Asian regions, but generally lower than those from the United States (Table 2). Specifically, the geometric mean of the dust/soil loadings increased in the following order: college students (0.016 mg/cm^2), security guards (0.038 mg/cm^2), and preschoolers (0.119 mg/cm^2). A statistically significant difference in dust/soil loadings for hands was found between preschoolers and college students ($p<0.05$), which is probably due to the distinct behavioral patterns and physiological properties of these two subpopulations (Belluck et al., 2003; Mukerjee, 1998). Preschoolers spend much time playing on the ground and touching various surfaces rich in dust/soil particles; on the other hand, preschoolers also possess a higher level of moisture on their hands compared to other age groups (Yamamoto et al., 2006). The lowest dust/soil loadings of college students among the three populations might be correlated to their non-occupational characteristics, tendency to stay in relatively clean living environments, and rare direct contact with dust/soil particles (Cao et al., 2018a).

Gender differences

Figure 2b shows the dust/soil loadings for different genders of college students and preschoolers. For college students, the geometric mean value of

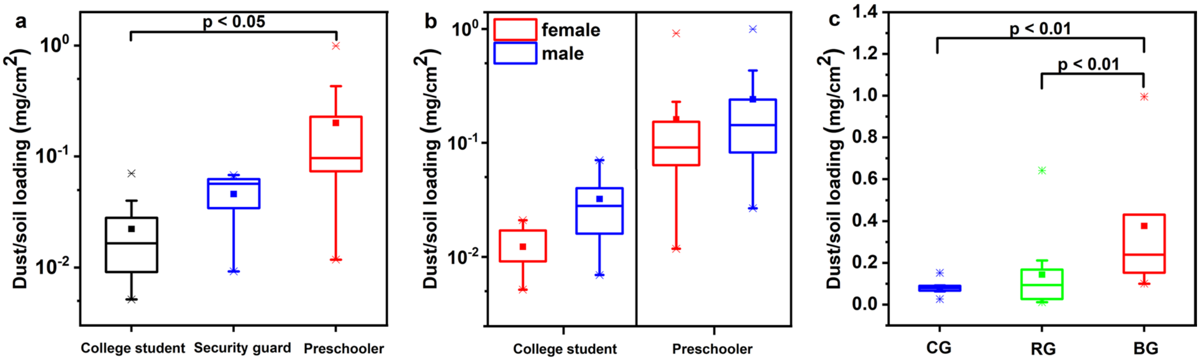

Fig. 2 **a** Dust/soil loadings on the hands of the three subpopulations, **b** dust/soil loadings on hands of different genders, and **c** dust/soil loadings on preschoolers' hands from three types of sampling sites

Table 2 Summary of results of dust/soil particles loading on hands from prior studies

Dust/soil particles loading (mg/cm^2)	Location	Population	Method	References
0.479−0.883	United States	Adults	Gravimetric	Driver et al. (1989)
0.520 ± 0.900	United States	Adults and children	Review	Finley et al. (1994)
0.200−1.00	United States	6 children, 1 adult, and 2 adult greenhouse workers	Gravimetric	Kissel et al. (1996a)
0.220−14.8	United States	1 adult	Hand-pressing trials method	Kissel et al. (1996b)
0.0400−0.350	United States	4 adults	Gravimetric	Kissel et al. (1998a)
0.700−1.10	United States	55 children and adults	Fluorometric and gravimetric methods	Kissel et al. (1998b)
0.0230−0.0760	United States	99 children and adults	Hand wipes method	Holmes et al. (1999)
0.700	United States	108 adults	Tape-strip method	Choate et al. (2006)
0.0605−20.5	United States	6 adults	Hand-washing method	Bergstrom et al. (2011)
31.7−40.4	United States	98−119 children	Hand-pressing trials method	Ferguson et al. (2020)
0.200−234	United States	122 children	Hand-pressing trials method	Ferguson et al. (2021)
0.0730−0.774	Japan	10 children (4 years old)	Hand-washing method	Yamamoto et al. (2006)
0.0540−0.127	Japan	69 children from nursery school	Hand wipes method	Ikegami et al. (2014)
0.0700−0.790	Hubei, China	120 children (2−17 years old)	Hand wipes method	Wang et al. (2015)
0.00600−0.153	Taiwan, China	86 children (4−< 9)	Hand-washing method	Tsou et al. (2018)
0.330−0.570	Taiwan, China	4 adults	Hand-pressing trials method	Hsi et al. (2018c)
0.460−1.65	Gansu, China	60 children (3−12 years old)	Hand wipes method	Ma et al. (2018)
0.0377−0.126	Xinxiang, China	107 preschoolers, 95 college students, and 35 security guards	Hand-washing method	Our study

dust/soil loadings on the hands was 0.024 mg/cm^2 for males, which was two times higher than that for females ($p = 0.072$). For preschoolers, the geometric mean value of dust/soil loadings on the hands was 0.157 mg/cm^2 for males and 0.091 mg/cm^2 for females ($p = 0.31$).

Sebum excretion is an important skin biophysical parameter that affects the adherence of dust/soil particles to the hand skin (Kim et al., 2006; Xin et al., 2007). Xin et al. demonstrated that the forehead sebum content did not differ between males and females under 12 years old, while the forehead sebum content of males was higher than that of females over 13 years old (Xin et al., 2007). While the available gender-specific data are for the forehead, we believe that this can also be the case for hand sebum content, and the difference in sebum excretion can also be responsible for the discrepancy in dust/soil loadings between genders for college students. However, studies have also reported that dust/soil loadings on the hands are sensitive to human behavior (Holmes et al., 1999; Kissel et al., 1996b). Compared to females, who generally pay more attention to hand hygiene, males engage in more outdoor activities and are more exposed to dust/soil particles from the ground. For preschoolers, the results above may reflect differences in the activity patterns of gender (Ma et al., 2018), including the type and intensity of activity, time spent outdoors, and type of toys. For example, compared to female preschoolers, male preschoolers are more active in contacting hard surfaces (e.g., toy models, basketballs, and footballs) (Ma et al., 2016). Hard surfaces favor the object-to-hand transfer of dust/soil particles compared to soft surfaces (e.g., stuffed toys and dolls) (Wilson et al., 2013). Interestingly, Wang et al. hypothesized that the contact with dust/soil particles of the surveyed Chinese residents demonstrated significant differences in gender and age, which is closely related to their education level and occupation (Wang et al., 2018b). This study provides preliminary evidence to support this hypothesis.

Spatial variation and influence of exposure source

As shown in Fig. 2c, the geometric mean of dust/soil loadings of preschoolers from the three different microenvironments increased in the following order: commercial ground (0.075 mg/cm^2) < residential ground (0.080 mg/cm^2) < bare ground (0.286 mg/cm^2). As expected, the commercial microenvironment was less dusty among the three microenvironments because of strict environmental cleaning and disinfection measures. Meanwhile, more dust/soil particles were found on the bare ground where preschoolers preferred to play, which is the dominant reason why the dust/soil loadings on preschoolers' hands were the highest on bare ground. The above results reveal that the cleanliness of the environment plays an important role in dust/soil loading on the hands of children. Given the observations from this study, future studies should carefully investigate the populations' daily lives and activities before sampling to determine the actual time spent in different microenvironments as accurately as possible, and then, these results will further facilitate the assessment of ingestion exposure to dust/soil and our understanding of the potential health effects.

Estimation of IR$_{total}$

As shown in Fig. 3, according to the dust/soil loading-activity pattern-based parametric formula method, the IR$_{\text{total}}$ for preschoolers, college students, and security guards was estimated to be 245, 19.7, and 33.1 mg/d, respectively. Preschoolers' higher IR$_{\text{total}}$ values are caused by not only the higher dust/soil loading on their hands but also their more frequent hand-to-mouth activities (Hsi et al., 2018a; Li et al., 2021). Table 3 summarizes the results of IR$_{\text{total}}$ from earlier studies, which were mostly drawn from western Europe and the United States. Our estimated IR$_{\text{total}}$ for preschoolers was higher than the "upper percentile" values for children (200 mg/d), and the estimates for college students and security guards were close to the consensus central-tendency values for adults (30 mg/d) reported in the U.S. EPA Exposure Factor Handbook (2011 edition, 2017 updated) (U.S. EPA, 2011). For preschoolers, our estimate was also higher than the estimates of 68.0 mg/d (Oezkaynak et al., 2011) and 61.0 mg/d (Wilson et al., 2013) for a similar age population (3−6 years) resulting

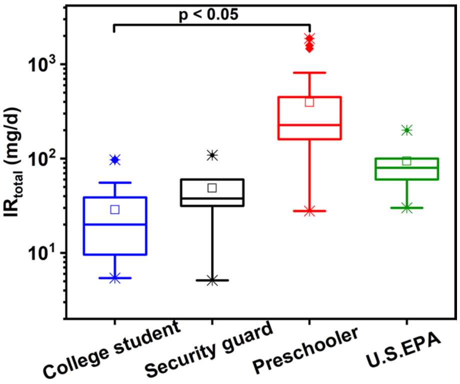

Fig. 3 Estimated IR$_{\text{total}}$ among the three populations and comparison with the U.S. EPA reference data [including central-tendency values and upper percentile values from children and adults (U.S. EPA, 2011)]

Table 3 Summary of results of IR_{total} from prior studies

IR_{total} (mg/d)	Location	Population	Method	References
181–184^{a}	United States	59 children (1–3 years old)	Tracer-based mass balance method (Al and Si)	Binder et al. (1986)
9.00–40.0^{b}	United States	64 children (1–4 years old)	Tracer-based mass balance method (Al, Si, and Y)	Calabrese et al. (1989)
45.0^{a}	United States	64 children (1–4 years old)	Tracer-based mass balance method (Al, Ba, Mn, Si, Ti, V, Y, and Zr)	Stanek and Calabrese (1995)
110^{c}	United States	478 children (1–6 years old)	Biokinetic model comparison method	Hogan et al. (1998)
68.0^{a}	United States	Children (3–6 years old)	Mechanistic time-activity pattern-based model	Oezkaynak et al. (2011)
51.0–67.0^{c}	United States	Several hundred children (2–9 years old)	Biokinetic model comparison method	Von Lindern et al. (2016)
90.0^{c}	Netherlands	18 children (2–4 years old)	Tracer-based mass balance method (Ti and Al)	Clausing et al. (1987)
0–90.0^{c}	Netherlands	Children (1–5 years old)	Tracer-based mass balance method (Ti and Al)	Van Wijnen et al. (1990)
75.0^{a}	Canada	7 adults (> 20 years old)	Tracer-based mass balance method (Al, Ce, La, and Si)	Doyle et al. (2012)
61.0 and 3.80^{a}	Canada	Toddlers (7 months–4 years old) and seniors (> 60 years old)	Mechanistic time-activity pattern-based model	Wilson et al. (2013)
32.0^{a}	Canada	10 adults (> 18 years old)	Tracer-based mass balance method (Al, Ce, La, and Si)	Irvine et al. (2014)
9.60^{a}	Taiwan, China	66 children (< 3 years old)	Tracer-based mass balance method (Si)	Chien et al. (2015)
27.5^{b}	China	120 children (2–17 years old)	Dust/soil loading-activity pattern-based parametric formula method	Wang et al. (2015)
6.60–7.70^{a}	China	60 children (3–12 years old)	Tracer-based mass balance method (Ce, Y, and V)	Ma et al. (2016)
52.0^{b}	China	177 children (2.5–11.9 years old)	Tracer-based mass balance method (Al, Ba, Ce, Mn, Sc, Ti, V, and Y)	Lin et al. (2017)
45.2^{a}	China	33 teenagers (12.0–16.5 years old)	Tracer-based mass balance method (Al, Ce, Sc, V, and Y)	Wang et al. (2018b)
19.7–245^{c}	China	107 preschoolers (1–12 years old), 95 college students (18–22 years old), and 35 security guards (> 45 years old)	Dust/soil loading-activity pattern-based parametric formula method	Our study

a, b, and c are the arithmetic, median, and geometric means, respectively

from the mechanistic time-activity pattern-based model method. Furthermore, based on the tracer-based mass balance method, Lin et al. estimated that the median IR_{total} for children (2.5–12 years) and teenagers (12–16.5 years) is 52.0 mg/d and 44.8 mg/d, respectively (Lin et al., 2017; Wang et al., 2018a). On the other hand, an earlier application of the biokinetic model gave an estimate of 51.0–67.0 mg/d (Von Lindern et al., 2016) for children aged 2–9. Obviously, the IR_{total} values from earlier studies are generally lower than ours, both for preschoolers. Similarly, our estimated IR_{total} for college students was higher than the estimate of 3.80 mg/d for a similar age population (12–19 years) by Wilson et al. (2013). However, as outdoor workers, the security guards in this study had a much lower IR_{total} than American construction workers (330 mg/d) (U.S. EPA, 2002).

Discussion

In this study, we used a hand-washing method for sample collection. Earlier studies have developed several methods to collect dust/soil particles adhered to the hand skin; however, they are associated with different levels of uncertainty in estimating IR_{total}. The hand-pressing method in less realistic laboratory settings (Tsou et al., 2018) may overestimate the rate of dust/soil ingestion compared to that in real conditions (Hsi et al., 2018c), because hand-pressing trials essentially gauge the maximum dust/soil loading that can adhere to the hand skin (Ferguson et al., 2021). In addition, this method does not account for the influence of hand-washing. With the tape-strip method, adhesive tape was used to collect adhered dust/soil particles on the hands (Wang et al., 2015); however, this method may underestimate adhered dust/soil loading, given that blank tape strips may remove sebum from the skin, which aids in the adherence of dust/soil particles before sampling (Choate et al., 2006). Furthermore, the hand-wiping method has been used to collect dust/soil particles on the hands (Wang et al., 2015). However, it is difficult to remove finer dust/soil particles within skinfolds, which may underestimate the actual dust/soil loadings on the hands. Overall, the hand-washing method adequately addresses the above limitations and can be used to almost entirely collect the dust/soil particles adhered to the hands; the estimated IR_{total} is expected to be more accurate and biologically relevant (Yamamoto et al., 2006).

In addition to calculating IR_{total} directly from the dust/soil loading on the hand skin in this study (dust/soil loading-activity pattern-based parametric formula method), other estimation approaches can also be used, such as the mechanistic time-activity pattern-based, biokinetic modeling, and tracer-based mass balance methods. These estimation approaches often yield varying IR_{total} values. The literature-reported IR_{total} estimated using the mechanistic time-activity pattern-based method is lower than our obtained result (Oezkaynak et al., 2011; Wilson et al., 2013). This method correlates data on hand-to-mouth and object-to-mouth activities, as well as time spent at different locations, with assumptions about the transport of dust/soil particles to and from hands to mouth and other exposure factors to generate estimates of IR_{total}, which provides the best information currently available on dust/soil ingestion estimates. The availability and caliber of the underlying data used to estimate IR_{total} are related to the restrictions and uncertainties associated with the time-activity pattern-based approach (Moya & Phillips, 2014). Direct measurements of biomarkers are typically compared with forecasts from a biokinetic model using the biokinetic modeling method (U.S. EPA, 2011). Under the condition that IR_{total} does not change significantly over time, this method can be used to back-calculate IR_{total}, which is indicative of prolonged exposures over several months. Sources of both positive and negative biases could be present in this approach. For instance, failing to account for all pertinent sources of a chemical tracer to which children are exposed could lead to an overestimation of IR_{total} by underestimating biomarker concentrations (Moya & Phillips, 2014). The tracer-based mass balance approach may suffer considerable uncertainty in IR_{total} estimation because of the deviation of a series of simplifying assumptions from ideal situations (Doyle et al., 2010; U.S. EPA, 2011; Wilson et al., 2013). For example, ingested tracers may not be absorbed entirely in the gastrointestinal tract, and a tracer can be taken in by humans through pathways other than dust/soil ingestion, such as food ingestion, inhalation, and dermal absorption (Wang et al., 2018b). In addition, the concentration of a tracer in dust/soil particles often varies greatly between locations and size fractions of dust and soil particles (Doyle et al., 2010; Moya & Phillips, 2014). In addition, the use of tracer levels in background dust/soil is likely to greatly overestimate or underestimate IR_{total} because the concentration of tracer elements in actual dust/soil particles (from indoors and outdoors) is source-dependent, and a large majority of non-occupational populations spend their activity time indoors (Diamond et al., 2021; Lin et al., 2017; Shin et al., 2020).

In this study, we estimated IR_{total} based on an extrapolation from $IR_{dust/soil\text{-}hand}$, which describes hand-to-mouth ingestion alone. Such an extrapolation may suffer uncertainties because an individual can ingest dust/soil particles through both hand-to-mouth and object-to-mouth transfers. In the object-to-mouth transfer calculation, the extrapolation ratio R_{htm} can also vary greatly between populations in different regions (Li et al., 2021). More specifically, estimates of IR_{total} could be based on the premise that hand-to-mouth transfer is a major determinant in defining IR_{total} apart from a lesser contribution from object-to-mouth transfer (Wilson et al., 2013). Humans' ingestion of chemicals apart from dietary origins comes from two parts, namely, the dust-/soil-bound fraction (settled on the floor or other indoor surfaces) and the surface residual fraction (including both the part forming layers of molecules adsorbed on indoor surfaces and the part dissolving in the organic film covering indoor hard surfaces), which can both be exposed through hand-to-mouth transfer and object-to-mouth transfer, contributing to mouth-mediated ingestion. Based on a specific estimation of IR_{total}, a direct method for determining IR_{total} and chemical concentrations in dust/soil is preferred to assess human exposure to dust-/soil-bound chemicals. Furthermore, to estimate the total mouth-mediated ingestion of chemicals, the fraction exposed from non-dietary ingestion of surface residues apart from dust/soil ingestion should be calculated separately (Li et al., 2021). In addition, our results suggest that for future assessment of human exposure to contaminants in dust/soil particles in China, dust/soil particles should be used from indoor or outdoor grounds with particle sizes ranging from 5 to 60 μm because they are the most relevant. For parameter optimization, one needs to use population- and even site-specific IR_{total} values.

To date, few field studies have characterized the particle size distributions and hand loadings of dust and soil particles simultaneously. Our study estimated IR_{total} simultaneously, taking both particle size analysis and mass determination into consideration. Overall, we observed a similar size distribution of dust/soil particles on the hands of the three subpopulations. In addition, the particle size distribution of dust/soil particles on the hands did not vary with the area of activities and showed no gender difference. Nevertheless, dust/soil loadings for the three populations were found to be strongly population- and microenvironment-dependent, and to a lesser extent, gender-dependent. Thus, the values of IR_{total} for the three populations were significantly different. Therefore, when studying dust/soil ingestion exposure, we should consider the differences between different subpopulations and living environments by applying specific and realistic parameters to achieve more accurate IR_{total} estimates.

Conclusions

This study investigated the size distribution of dust/soil particles and dust/soil loadings on the hands of three subpopulations (preschoolers, college students, and security guards) in China, and the total dust ingestion rate (IR_{total}) was estimated for these individual subpopulations. Our results indicate that the estimated IR_{total} values for Chinese college students and security guards were close to the consensus central-tendency values for American adults recommended by the U.S. EPA's Exposure Factor Handbook, but those for preschoolers were slightly higher than the recommended "upper percentile" values for American children. In addition, clear variation among subpopulations was observed due to the influence of occupation, living environment, and behavior pattern, indicating the significance of population- and even site-specific IR_{total} values in human exposure assessment. More studies should be conducted to systematically investigate the spatial, temporal, and population-dependent variation characteristics of the exposure of Chinese populations to dust/soil particles and contaminants through hand-to-mouth contact.

Authors' contributions NL helped in methodology, writing—original draft, writing—review and editing, data curation, and visualization. JZ helped in data curation. HY helped in writing—review and editing. MX helped in data curation. QF helped in data curation. JZ helped in data curation. XW helped in data curation. PW helped in writing—review and editing. YF helped in writing—review and editing. GY helped in visualization. WZ helped in visualization. ZC worked in conceptualization, supervision, funding acquisition, writing—original draft, and writing—review and editing. LL helped in methodology and writing—review and editing.

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Data availability All the data used for the present study appear in the article. The raw data may be provided upon reasonable requests.

Declarations

Conflict of 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.

Ethics approval Ethical approval for this investigation was obtained from the Research Ethics Committee of Henan Normal University.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication We give our consent for the publication of identifiable details, which can include figures, tables, and details within the text (all authors declare that they have no objection) to be published in this Journal.

Appendix A

The Supplementary material contains additional detailed information of materials and methods, some additional tables and figures, as noted in this study.

References

Beamer, P. I., Elish, C. A., Roe, D. J., Loh, M. M., & Layton, D. W. (2012). Differences in metal concentration by particle size in house dust and soil. *Journal of Hazardous Materials, 14*(3), 839–844. https://doi.org/10.1039/c2em10740f

Belluck, D. A., Benjamin, S. L., Baveye, P., Sampson, J., & Johnson, B. (2003). Widespread arsenic contamination of soils in residential areas and public spaces: An emerging regulatory or medical crisis? *International Journal of Toxicology, 22*(2), 109–128. https://doi.org/10.1080/10915810305087

Bergstrom, C., Shirai, J., & Kissel, J. (2011). Particle size distributions, size concentration relationships, and adherence to hands of selected geologic media derived from mining, smelting, and quarrying activities. *Science of the Total Environment, 409*(20), 4247–4256. https://doi.org/10.1016/j.scitotenv.2011.06.005

Binder, S., Sokal, D., & Maughan, D. (1986). Estimating soil ingestion: The use of tracer elements in estimating the amount of soil ingested by young children. *Archives of Environmental Health, 41*(6), 341–345. https://doi.org/10.1080/00039896.1986.9935776

Bu, Q., Wu, D., Xia, J., Wu, M., Liu, X., Cao, Z., et al. (2019). Polybrominated diphenyl ethers and novel brominated flame retardants in indoor dust of different microenvironments in Beijing, China. *Environment International, 122*, 159–167. https://doi.org/10.1016/j.envint.2018.11.005

Calabrese, E. J., Barnes, R., Stanek, E. J., III., Pastides, H., Gilbert, C. E., Veneman, P., et al. (1989). How much soil do young children ingest: An epidemiologic study. *Regulatory Toxicology and Pharmacology, 10*(2), 123–137. https://doi.org/10.1016/0273-2300(89)90019-6

Cao, Z., Wang, M., Chen, Q., Zhang, Y., Dong, W., Yang, T., et al. (2018a). Preliminary assessment on exposure of four typical populations to potentially toxic metals by means of skin wipes under the influence of haze pollution. *Science of the Total Environment, 613–614*, 886–893. https://doi.org/10.1016/j.scitotenv.2017.09.181

Cao, Z., Wu, X., Wang, T., Zhao, Y., Zhao, Y., Wang, D., et al. (2022). Characteristics of airborne particles retained on conifer needles across. *Science of the Total Environment, 806*(1), 154–210.

Cao, Z., Xu, F., Covaci, A., Wu, M., Wang, H., Yu, G., et al. (2014). Distribution patterns of brominated, chlorinated, and phosphorus flame retardants with particle size in indoor and outdoor dust and implications for human exposure. *Environmental Science and Technology, 48*(15), 8839–8846. https://doi.org/10.1021/es501224b

Cao, Z., Xu, F., Li, W., Sun, J., Shen, M., Su, X., et al. (2015). Seasonal and particle size-dependent variations of hexabromocyclododecanes in settled dust: Implications for sampling. *Environmental Science and Technology, 49*(18), 11151–11157. https://doi.org/10.1021/acs.est.5b01717

Cao, Z.-G., Yu, G., Chen, Y.-S., Cao, Q.-M., Fiedler, H., Deng, S.-B., et al. (2012). Particle size: A missing factor in risk assessment of human exposure to toxic chemicals in settled indoor dust. *Environment International, 49*, 24–30. https://doi.org/10.1016/j.envint.2012.08.010

Cao, Z., Yu, G., Chen, Y., Liu, C., Liu, K., Zhang, T., et al. (2013). Mechanisms influencing the BFR distribution patterns in office dust and implications for estimating human exposure. *Journal of Hazardous Materials, 252*, 11–18. https://doi.org/10.1016/j.jhazmat.2013.02.043

Cao, Z., Zhao, L., Kuang, J., Chen, Q., Zhu, G., Zhang, K., et al. (2017). Vehicles as outdoor BFR sources: Evidence from an investigation of BFR occurrence in road dust. *Chemosphere, 179*, 29–36. https://doi.org/10.1016/j.chemosphere.2017.03.095

Cao, Z., Zhao, L., Meng, X., Liu, X., Wu, P., Fan, X., et al. (2018b). Amplification effect of haze on human exposure to halogenated flame retardants in atmospheric particulate matter and the corresponding mechanism. *Journal of Hazardous Materials, 359*, 491–499. https://doi.org/10.1016/j.jhazmat.2018.07.109

Cao, Z., Zhao, L., Zhang, Y., Ren, M., Zhang, Y., Liu, X., et al. (2019). Influence of air pollution on inhalation and dermal exposure of human to organophosphate flame retardants: A case study during a prolonged haze episode. *Environmental Science and Technology, 53*(7), 3880–3887. https://doi.org/10.1021/acs.est.8b07053

Chen, Y., Cao, Z., Covaci, A., Li, C., & Cui, X. (2019). Novel and legacy flame retardants in paired human fingernails and indoor dust samples. *Environment International, 133*(Pt B), 105227. https://doi.org/10.1016/j.envint.2019.105227

Chien, L. C., Tsou, M. C., Hsi, H. C., Beamer, P., Bradham, K., Hseu, Z. Y., et al. (2015). Soil ingestion rates for children under 3 years old in Taiwan. *Journal of Exposure Science and Environmental Epidemiology, 27*(1), 33–40. https://doi.org/10.1038/jes.2015.61

Choate, L. M., Ranville, J. F., Bunge, A. L., & Macalady, D. L. (2006). Dermally adhered soil: 1. Amount and particle-size distribution. *Integrated Environmental Assessment and Management, 2*(4), 375–384. https://doi.org/10.1002/ieam.5630020409

Clausing, P., Brunekreef, B., & van Wijnen, J. H. (1987). A method for estimating soil ingestion by children.

International Archives of Occupational and Environmental Health, 59(1), 73–82. https://doi.org/10.1007/BF00377681

Cohen Hubal, E. A., Sheldon, L. S., Burke, J. M., McCurdy, T. R., Berry, M. R., Rigas, M. L., et al. (2000). Children's exposure assessment: A review of factors influencing Children's exposure, and the data available to characterize and assess that exposure. *Environmental Health Perspectives, 108*(6), 475–486. https://doi.org/10.2307/3454607

Davis, S., Waller, P., Buschbom, R., Ballou, J., & White, P. (1990). Quantitative estimates of soil ingestion in normal children between the ages of 2 and 7 years: Population-based estimates using aluminum, silicon, and titanium as soil tracer elements. *Archives of Environmental Health, 45*(2), 112–122. https://doi.org/10.1080/00039896.1990.9935935

Diamond, M. L., Okeme, J. O., & Melymuk, L. (2021). Hands as agents of chemical transport in the indoor environment. *Environmental Science & Technology Letters, 8*(4), 326–332. https://doi.org/10.1021/acs.estlett.0c01006

Doyle, J. R., Blais, J. M., Holmes, R. D., & White, P. A. (2012). A soil ingestion pilot study of a population following a traditional lifestyle typical of rural or wilderness areas. *Science of the Total Environment, 424*, 110–120. https://doi.org/10.1016/j.scitotenv.2012.02.043

Doyle, J. R., Blais, J. M., & White, P. A. (2010). Mass balance soil ingestion estimating methods and their application to inhabitants of rural and wilderness areas: A critical review. *Science of the Total Environment, 408*(10), 2181–2188. https://doi.org/10.1016/j.scitotenv.2010.02.007

Driver, J. H., Konz, J. J., & Whitmyre, G. K. (1989). Soil adherence to human skin. *Bulletin of Environment Contamination and Toxicology, 43*(6), 814–820. https://doi.org/10.1007/bf01702049

Duggan, M. J., Inskip, M. J., Rundle, S. A., & Moorcroft, J. S. (1985). Lead in playground dust and on the hands of schoolchildren. *Science of the Total Environment, 44*(1), 65–79. https://doi.org/10.1016/0048-9697(85)90051-8

Ferguson, A., Kumar Dwivedi, A., Ehindero, E., Adelabu, F., Rattler, K., Perone, H. R., et al. (2020). Soil, hand, and body adherence measures across four beach areas: Potential influence on exposure to oil spill chemicals. *International Journal of Environmental Research and Public Health, 17*(12), 4196. https://doi.org/10.3390/ijerph17124196

Ferguson, A., Rattler, K., Perone, H., Dwivedi, A. K., Obeng-Gyasi, E., Mena, K. D., et al. (2021). Soil-skin adherence measures from hand press trials in a Gulf study of exposures. *Journal of Exposure Science & Environmental Epidemiology, 31*(1), 158–169. https://doi.org/10.1038/s41370-020-00269-2

Finley, B. L., Scott, P. K., & Mayhall, D. A. (1994). Development of a standard soil-to-skin adherence probability density function for use in monte Carlo analyses of dermal exposure. *Risk Analysis, 14*(4), 555–569. https://doi.org/10.1111/j.1539-6924.1994.tb00270.x

He, R.-W., Li, Y.-Z., & Xiang, P. (2018a). Impact of particle size on distribution and human exposure of flame retardants in indoor dust. *Environmental Resources*. https://doi.org/10.1016/j.envres.2017.12.014

He, R. W., Li, Y. Z., Xiang, P., Li, C., Cui, X. Y., & Ma, L. Q. (2018b). Impact of particle size on distribution and human exposure of flame retardants in indoor dust. *Environmental Research, 162*, 166–172. https://doi.org/10.1016/j.envres.2017.12.014

Hogan, K., Marcus, A., Smith, R., & White, P. (1998). Integrated exposure uptake biokinetic model for lead in children: Empirical comparisons with epidemiologic data. *Environmental Health Perspectives, 106*(Suppl 6), 1557–1567. https://doi.org/10.1289/ehp.98106s61557

Holmes, K. K., Shirai, J. H., Richter, K. Y., & Kissel, J. C. (1999). Field measurement of dermal soil loadings in occupational and recreational activities. *Environmental Research, 80*(2), 148–157. https://doi.org/10.1006/enrs.1998.3891

Hsi, H.-C., Hu, C.-Y., & Tsou, M.-C. (2018a). Determination of hand soil loading, soil transfer, and particle size variations after hand-pressing and hand-mouthing activities. *Science of the Total Environment, 627*, 844–851. https://doi.org/10.1016/j.scitotenv.2018.01.308

Hsi, H.-C., Hu, C.-Y., Tsou, M.-C., Hu, H.-J., Ozkaynak, H., Bradham, K., et al. (2018b). Determination of hand soil loading, soil transfer, and particle size variations after hand-pressing and hand-mouthing activities. *Science of the Total Environment, 627*, 844–851. https://doi.org/10.1016/j.scitotenv.2018.01.308

Hsi, H.-C., Hu, C.-Y., Tsou, M.-C., Hu, H.-J., Özkaynak, H., Bradham, K., et al. (2018c). Determination of hand soil loading, soil transfer, and particle size variations after hand-pressing and hand-mouthing activities. *Science of the Total Environment, 627*, 844–851. https://doi.org/10.1016/j.scitotenv.2018.01.308

Huang, S., Li, Q., Liu, H., Ma, S., Long, C., Li, G., et al. (2022). Urinary monohydroxylated polycyclic aromatic hydrocarbons in the general population from 26 provincial capital cities in China: Levels, influencing factors, and health risks. *Environment International, 160*, 107074. https://doi.org/10.1016/j.envint.2021.107074

Ikegami, M., Yoneda, M., Tsuji, T., Bannai, O., & Morisawa, S. (2014). Effect of particle size on risk assessment of direct soil ingestion and metals adhered to children's hands at playgrounds. *Risk Analysis, 34*(9), 1677–1687. https://doi.org/10.1111/risa.12215

Irvine, G., Doyle, J. R., White, P. A., & Blais, J. M. (2014). Soil ingestion rate determination in a rural population of Alberta, Canada practicing a wilderness lifestyle. *Science of the Total Environment, 470–471*, 138–146. https://doi.org/10.1016/j.scitotenv.2013.09.037

Jin, M. T., Li, L. J., Zheng, Y. X., Shen, X. Y., & Wang, D. R. (2019). Polybrominated diphenyl ethers (PBDEs) in dust in typical indoor public places in Hangzhou: Levels and an assessment of human exposure. *Ecotoxicology and Environmental Safety, 169*, 325–334. https://doi.org/10.1016/j.ecoenv.2018.10.043

Jin, M., Li-Bo, P., Qin, W., Chun-Ye, L., Xiao-Li, D., & Hong, H. (2018). Estimation of the daily soil/dust (SD) ingestion rate of children from Gansu Province, China via hand-to-mouth contact using tracer elements. *Environmental Geochemistry and Health, 40*(1), 295–301. https://doi.org/10.1007/s10653-016-9906-1

Kim, M.-K., Choi, S.-Y., Byun, H.-J., Huh, C.-H., Park, K.-C., Patel, R. A., et al. (2006). Evaluation of gender difference in skin type and pH. *Journal of Dermatological Science, 41*(2), 153–156. https://doi.org/10.1016/j.jdermsci.2005.12.001

Kissel, J. C., Richter, K. Y., & Febske, R. A. (1996a). Field measurement of dermal soil loading attributable to various activities: Implications for exposure assessment. *Risk Analysis, 16*(1), 115–125. https://doi.org/10.1111/j.1539-6924.1996.tb01441.x

Kissel, J. C., Richter, K. Y., & Fenske, R. A. (1996b). Factors affecting soil adherence to skin in hand-press trials. *Bulletin of Environment Contamination and Toxicology, 56*(5), 722–728. https://doi.org/10.1007/s001289900106

Kissel, J. C., Shirai, J. H., Richter, K. Y., & Fenske, R. A. (1998a). Empirical investigation of hand-to-month transfer of soil. *Bulletin of Environment Contamination and Toxicology, 60*, 379–386. https://doi.org/10.1007/s001289900637

Kissel, J. C., Shirai, J. H., Richter, K. Y., & Fenske, R. A. (1998b). Investigation of dermal contact with soil in controlled trials. *Journal of Soil Contamination, 7*(6), 737–752. https://doi.org/10.1080/10588339891334573

Lewis, R. G., Fortune, C. R., Willis, R. D., Camann, D. E., & Antley, J. T. (1999). Distribution of pesticides and polycyclic aromatic hydrocarbons in house dust as a function of particle size. *Environmental Health Perspectives, 107*(9), 721–726. https://doi.org/10.2307/3434657

Li, L., Hughes, L., & Arnot, J. A. (2021). Addressing uncertainty in mouthing-mediated ingestion of chemicals on indoor surfaces, objects, and dust. *Environment International, 146*, 106266. https://doi.org/10.1016/j.envint.2020.106266

Lin, C., Wang, B., Cui, X., Xu, D., Cheng, H., Wang, Q., et al. (2017). Estimates of soil ingestion in a population of chinese children. *Environmental Health Perspectives, 125*(7), 077002. https://doi.org/10.1289/EHP930

Lioy Paul, J., Freeman Natalie, C. G., & Millette James, R. (2002). Dust: A metric for use in residential and building exposure assessment and source characterization. *Environmental Health Perspectives, 110*(10), 969–983. https://doi.org/10.1289/ehp.02110969

Liu, X., Cao, Z., & Yu, G. (2018). Estimation of exposure to organic flame retardants via hand wipe, surface wipe, and dust: Comparability of different assessment Strategies. *Environmental Science & Technology, 52*(17), 9946–9953. https://doi.org/10.1021/acs.est.8b02723

Liu, X., Zhai, Y., Zhu, Y., Liu, Y., Chen, H., Li, P., et al. (2015). Mass concentration and health risk assessment of heavy metals in size-segregated airborne particulate matter in Changsha. *Science of the Total Environment, 517*, 215–221. https://doi.org/10.1016/j.scitotenv.2015.02.066

Luo, X. S., Yu, S., & Li, X. D. (2011). Distribution, availability, and sources of trace metals in different particle size fractions of urban soils in Hong Kong: Implications for assessing the risk to human health. *Environmental Pollution, 159*(5), 1317–1326. https://doi.org/10.1016/j.envpol.2011.01.013

Ma, J., Pan, L.-B., Wang, Q., Lin, C.-Y., Duan, X.-L., & Hou, H. (2016). Estimation of the daily soil/dust (SD) ingestion rate of children from Gansu Province, China via hand-to-mouth contact using tracer elements. *Environmental Geochemistry and Health, 40*(1), 295–301. https://doi.org/10.1007/s10653-016-9906-1

Ma, J., Pan, L. B., Wang, Q., Lin, C. Y., Duan, X. L., & Hou, H. (2018). Estimation of the daily soil/dust (SD) ingestion rate of children from Gansu Province, China via hand-to-mouth contact using tracer elements. *Environmental Geochemistry and Health, 40*(1), 295–301. https://doi.org/10.1007/s10653-016-9906-1

Man, M. Q., Xin, S. J., Song, S. P., Cho, S. Y., Zhang, X. J., Tu, C. X., et al. (2009). Variation of skin surface pH, sebum content and stratum Corneum hydration with age and gender in a large Chinese population. *Skin Pharmacology and Physiology, 22*(4), 190–199. https://doi.org/10.1159/000231524

Melanie, G. N., Alice, D., Martie, V. T., Hilary, C., & Sean, S. (2014). Inadvertent ingestion exposure: Hand- and object-to-mouth behavior among workers. *Journal of Exposure Science and Environmental Epidemiology, 26*(1), 9–16. https://doi.org/10.1038/jes.2014.71

Meng, Q., Fan, S., He, J., Zhang, J., Sun, Y., Zhang, Y., et al. (2015). Particle size distribution and characteristics of polycyclic aromatic hydrocarbons during a heavy haze episode in Nanjing, China. *Particuology, 18*, 127–134. https://doi.org/10.1016/j.partic.2014.03.010

Mercier, F., Glorennec, P., Thomas, O., & Le Bot, B. (2011). Organic contamination of settled house dust, a review for exposure assessment purposes. *Environmental Science and Technology, 45*(16), 6716–6727. https://doi.org/10.1021/es200925h

Moya, J., & Phillips, L. (2014). A review of soil and dust ingestion studies for children. *Journal of Exposure Science & Environmental Epidemiology, 24*(6), 545–554. https://doi.org/10.1038/jes.2014.17

Mukerjee, D. (1998). Assessment of risk from multimedia exposures of children to environmental chemicals. *Journal of the Air and Waste Management Association, 48*(6), 483–501. https://doi.org/10.1080/10473289.1998.10463703

Oezkaynak, H., Xue, J., Zartarian, V. G., Glen, G., & Smith, L. (2011). Modeled estimates of soil and dust ingestion rates for children. *Risk Analysis, 31*(4), 592–608. https://doi.org/10.1111/j.1539-6924.2010.01524.x

Que Hee, S. S., Peace, B., Clark, C. S., Boyle, J. R., Bornschein, R. L., & Hammond, P. B. (1985). Evolution of efficient methods to sample lead sources, such as house dust and hand dust, in the homes of children. *Environmental Research, 38*(1), 77–95. https://doi.org/10.1016/0013-9351(85)90074-x

Shetage, S. S., Traynor, M. J., Brown, M. B., Raji, M., Graham-Kalio, D., & Chilcott, R. P. (2014). Effect of ethnicity, gender and age on the amount and composition of residual skin surface components derived from sebum, sweat and epidermal lipids. *Skin Research and Technology, 20*(1), 97–107. https://doi.org/10.1111/srt.12091

Shin, H. M., McKone, T. E., Tulve, N. S., Clifton, M. S., & Bennett, D. H. (2013). Indoor residence times of semivolatile organic compounds: Model estimation and field evaluation. *Environmental Science and Technology, 47*(2), 859–867. https://doi.org/10.1021/es303316d

Shin, H. M., Moschet, C., Young, T. M., & Bennett, D. H. (2020). Measured concentrations of consumer product chemicals in California house dust: Implications for sources, exposure, and toxicity potential. *Indoor Air, 30*(1), 60–75. https://doi.org/10.1111/ina.12607

Stanek, E. J., 3rd., & Calabrese, E. J. (1995). Daily estimates of soil ingestion in children. *Environmental Health Perspectives, 103*(3), 276–285. https://doi.org/10.2307/3432549

Stapleton, H. M., Kelly, S. M., Allen, J. G., McClean, M. D., & Webster, T. F. (2008). Measurement of polyhrominated diphenyl ethers on hand wipes: Estimating exposure from hand-to-mouth contact. *Environmental Science and Technology, 42*(9), 3329–3334. https://doi.org/10.1021/es7029625

Stuart, H., Ibarra, C., Abdallah, M. A., Boon, R., Neels, H., & Covaci, A. (2008). Concentrations of brominated flame retardants in dust from United Kingdom cars, homes, and offices: Causes of variability and implications for human exposure. *Environment International, 34*(8), 1170–1175. https://doi.org/10.1016/j.envint.2008.05.001

Sun, J., Xu, Y., Zhou, H., Zhang, A., & Qi, H. (2018). Levels, occurrence and human exposure to novel brominated flame retardants (NBFRs) and Dechlorane Plus (DP) in dust from different indoor environments in Hangzhou, China. *Science of the Total Environment, 631–632*, 1212–1220. https://doi.org/10.1016/j.scitoteov.2018.03.135

Sun, Z., Zhu, Y., Zhuo, S., Liu, W., Zeng, E. Y., Wang, X., et al. (2017). Occurrence of nitro- and oxy-PAHs in agricultural soils in eastern China and excess lifetime cancer risks from human exposure through soil ingestion. *Environment International, 108*, 261–270. https://doi.org/10.1016/j.envint.2017.09.001

Tsou, M. C., Hu, C. Y., Hsi, H. C., Hu, H. J., Ozkaynak, H., Hseu, Z. Y., et al. (2018). Soil-to-skin adherence during different activities for children in Taiwan. *Environmental Research, 167*, 240–247. https://doi.org/10.1016/j.envres.2018.07.028

U.S. EPA (2011). Exposure Factors Handbook 2011 edition (Final Report). Washington, DC, U.S. Environmental Protection Agency. https://cfpub.epa.gov/ncea/efp/recordisplay.cfm?deid=236252

U.S. EPA (2002). Supplemental guidance for developing soil screening levels for superfund sites. Washington, DC, U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=91003IJK.txt

Van den Eede, N., Dirtu, A. C., Ali, N., Neels, H., & Covaci, A. (2012). Multi-residue method for the determination of brominated and organophosphate flame retardants in indoor dust. *Talanta, 89*, 292–300. https://doi.org/10.1016/j.talanta.2011.12.031

Van Wijnen, J. H., Clausing, P., & Brunekreef, B. (1990). Estimated soil ingestion by children. *Environmental Research, 51*(2), 147–162. https://doi.org/10.1016/S0013-9351(05)80085-4

Von Lindern, I., Spalinger, S., Stifelman, M. L., Stanek, L. W., & Bartrem, C. (2016). Estimating children's soil/dust ingestion rates through retrospective analyses of blood lead biomonitoring from the Bunker Hill Superfund Site in Idaho. *Environmental Health Perspectives, 124*(9), 1462–1470. https://doi.org/10.1289/ehp.1510144

Vykoukalova, M., Venier, M., Vojta, S., Melymuk, L., Becanova, J., Romanak, K., et al. (2017). Organophosphate esters flame retardants in the indoor environment. *Environment International, 106*, 97–104. https://doi.org/10.1016/j.envint.2017.05.020

Wang, B., Lin, C., & Zhang, X. (2018a). A soil ingestion pilot study for teenage children in China. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2018.03.067

Wang, B., Lin, C., Zhang, X., Duan, X., Xu, D., Cheng, H., et al. (2018b). A soil ingestion pilot study for teenage children in China. *Chemosphere, 202*, 40–47. https://doi.org/10.1016/j.chemosphere.2018.03.067

Wang, S., Ma, L., Pan, L., Lin, C., Wang, B., & Duan, X. (2015). Quantification of soil/dust (SD) on the hands of children from Hubei Province, China using hand wipes. *Ecotoxicology and Environmental Safety, 120*, 193–197. https://doi.org/10.1016/j.ecoenv.2015.06.006

Wang, Y. L., Tsou, M. M., Pan, K. H., Ozkaynak, H., Dang, W., Hsi, H. C., et al. (2021). Estimation of soil and dust ingestion rates from the stochastic human exposure and dose simulation soil and dust model for children in Taiwan. *Environmental Science and Technology, 55*(17), 11805–11813. https://doi.org/10.1021/acs.est.1c00706

Wensing, M., Uhde, E., & Salthammer, T. (2005). Plastics additives in the indoor environment—Flame retardants and plasticizers. *Science of the Total Environment, 339*(1–3), 19–40. https://doi.org/10.1016/j.scitotenv.2004.10.028

Wilson, R., Jones-Otazo, H., Petrovic, S., Mitchell, I., Bonvalot, Y., Williams, D., et al. (2013). Revisiting dust and soil ingestion rates based on hand-to-mouth transfer. *Human and Ecological Risk Assessment, 19*(1), 158–188. https://doi.org/10.1080/10807039.2012.685807

Xin, S., Liu, Z., Shi, Y., Feingold, K. R., Elias, P. M., & Maoqiang, M. (2007). Study on the sebum content and stratum corneum hydration in the normal Chinese population. *Journal of Clinical Dermatology (china), 36*(3), 131–133.

Yamamoto, N., Takahashi, Y., Yoshinaga, J., Tanaka, A., & Shibata, Y. (2006). Size distributions of soil particles adhered to children's hands. *Archives of Environmental Contamination and Toxicology, 51*(2), 157–163. https://doi.org/10.1007/s00244-005-7012-y

Yeh, K., Li, L., Wania, F., & Abbatt, J. P. D. (2022). Thirdhand smoke from tobacco, e-cigarettes, cannabis, methamphetamine and cocaine: Partitioning, reactive fate, and human exposure in indoor environments. *Environment International, 160*, 107063. https://doi.org/10.1016/j.envint.2021.107063

Yu, H., Feng, J., Su, X., Li, Y., & Sun, J. (2020a). A seriously air pollution area affected by anthropogenic in the central China: Temporal–spatial distribution and potential sources. *Environmental Geochemistry and Health, 42*(10), 3199–3211. https://doi.org/10.1007/s10653-020-00558-7

Yu, H., Zhao, X., Wang, J., Yin, B., Geng, C., Wang, X., et al. (2020b). Chemical characteristics of road dust PM2.5 fraction in oasis cities at the margin of Tarim Basin. *Journal of Environmental Sciences, 95*, 217–224.

Zhang, W., Wang, P., Zhu, Y., Wang, D., Yang, R., Li, Y., et al. (2020). Occurrence and human exposure assessment of organophosphate esters in atmospheric PM2.5 in the Beijing–Tianjin–Hebei region, China. *Ecotoxicology and*

Environmental Safety, 206, 111399. https://doi.org/10.1016/j.ecoenv.2020.111399

Zhao, L., Jian, K., Su, H., Zhang, Y., Li, J., Letcher, R. J., et al. (2019). Organophosphate esters (OPEs) in Chinese foodstuffs: Dietary intake estimation via a market basket method, and suspect screening using high-resolution mass spectrometry. *Environment International, 128*, 343–352. https://doi.org/10.1016/j.envint.2019.04.055