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Questioning the appropriateness of sieving for processing indoor settled dust samples

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Abstract

Dust is a widely-used matrix for estimating human exposure to chemicals or as a screening tool for the identification of indoor chemicals of concern. As dust sampling became more common in exposure assessment, techniques used in processing soil have been adapted to dust samples, and separation of dust particles by sieving is common practice. However, there are no defined pore sizes, which results in inconsistent or difficult data interpretation and exposure estimates. Moreover, dust consists of more particle types than soil, particularly fibers, which behave differently during the sieving process. In this study, composite samples from seven microenvironments (homes, apartments, kindergartens, schools, public spaces, offices, and cars) were used to investigate the impact of the separation of dust by sieving on the observed chemical distributions. Dust was sieved to four particle size fractions (1-2 mm, 0.5-1 mm, 0.25-0.5 mm, and < 0.25 mm) and each fraction was analyzed for organic carbon content and polycyclic aromatic hydrocarbons (PAHs), and images of dust samples were taken by optical microscope. We identified irregular distributions across size fractions for carbon and PAHs as well as for fibrous particles. Based on the combination of chemical analyses and microscopy, we recommend careful consideration of pre-processing of dust samples to limit bias in dust exposure assessments, and sieving should be used only when necessary.

Keywords: Indoor dust, size fractions, dust exposure, polycyclic aromatic hydrocarbons, dust composition



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INTRODUCTION

Indoor dust has consistently been shown to be a crucial matrix in understanding human exposure to chemicals. It serves as both an important exposure pathway, particularly through dermal contact with dust and non-dietary ingestion, as well as a practical screening tool or early warning signal for chemicals present in indoor environments, given the high concentrations of many chemicals of concern in dust. However, our use of indoor dust as a consistent tool for these purposes is challenged by the lack of reproducibility in the techniques used to collect and quantify dust composition. Some attention has been given to this variability in chemical analysis^[1,2]; interlaboratory comparisons have highlighted that variations in techniques used for dust extraction, clean-up, and quantification can lead to inconsistencies in reported concentrations across laboratories applying different techniques and implementing different QA/QC practices.

Furthermore, sampling choices can also lead to significantly different outcomes in reported concentrations of chemicals in dust. Dust within individual rooms shows significant heterogeneity^[3-5], and the choice of sampling location can impact reported concentrations^[6], as can the technique used to collect the dust (e.g., collection from a vacuum bag, or use of a dedicated filter or sock)^[7].

One step of dust processing that has received limited attention is the “pre-processing” applied to dust after collection and before extraction. The most common pre-processing is sieving to remove large non-dust materials from the samples and retain the sample that reflects indoor settled dust under a certain particle size. This is widely applied using a single sieve size to retain only the smaller sizes of settled dust that are most relevant to human exposure.

Consensus exists that finer particle sizes are more likely to adhere to skin and objects and therefore be accidentally ingested^[8,9], and Cao *et al.* recommend that particle size of dust be considered in exposure and risk assessment^[9]. Yet consensus does not exist as to which cut-off should be selected as a threshold for adherence and relevance for ingestion exposure; soil and dust ingestion studies have identified that primarily finer particles are ingested (particles < 250 μm ^[10,11], < 150 μm ^[12,13] cited in Ref.^[9], or 10-50 μm ^[14]). Relatedly, there is no consensus on the sieve sizes that should be used to separate dust for chemical analysis and exposure estimates. In studies from the past 15 years on chemical compositions of indoor dust, sieves with pore sizes ranging from 20 μm to 2 mm have been used. There is a trend that studies quantifying metals in indoor dust generally used smaller sieve sizes (typically < 100 μm pore size)^[15-20], while studies focussing on organic compounds, particularly flame retardants, tend to use coarser sieves (typically 150 μm to 1 mm)^[21-26], or limit the pre-processing only to manual removal of larger materials^[27,28]. This may be due to the understanding that coarser particles can also be relevant for understanding sources and exposures to plastic additives due to the importance of abrasion and direct partitioning as emission pathways from synthetic products^[29-31], although this distinction is not clearly stated anywhere.

While no consensus exists on the best sieving choices for the chemical analysis of indoor dust, greater attention has been given to the issue of the particle sizes of indoor dust in recent years. An increasing number of studies used a series of multiple sieve sizes to characterize the distributions of chemicals on indoor dust more comprehensively. This is typically applied to better understand migration pathways to dust, and to better estimate human exposure by more accurately-determined concentrations on fine dust fractions.

Despite numerous such studies conducted over the past 10 years, the results are inconsistent. Many studies found no relationship between the size fractions of settled indoor dust and the sorbed chemicals, whether for flame retardants^[14,32-36], bisphenols^[37], PAHs^[38,39], or trace metals/elements^[40,41]. Others do report

consistent trends; in all cases, higher levels of the compounds in question are associated with finer particle fractions, for flame retardants^[42,43], phthalates^[44], pesticides^[45], PAHs^[45], and PCBs^[46]. There can be several factors contributing to this; one being, as with the sieving choices discussed above, there is a great deal of variability in the sieve sizes and cut-offs used for these comparisons, with some studies not even covering the same range of particle sizes, which does limit comparability. Second, many studies identify that the migration pathway from consumer products to dust influences the observed distribution. For example, Al-Omran and Harrad reported differences in the distribution patterns of FRs in settled dust according to the molecular weight of the FR, with lower molecular weight FRs showing a consistently increasing trend with decreasing particle size, attributed to volatilization and partitioning as a migration pathway, while heavier molecular weight FRs (e.g., BDE 209, DBDPE) showed no trend, because of the greater influence of physical migration pathways such as abrasion^[35].

Yet only recently has consideration been given to methodological influences that can create such variability, namely, how sieving and the physical composition of indoor dust lead to inconsistent profiling of chemical distributions according to size fraction. Sieve analysis is intended to separate generally spherical particles; it cannot give reliable results for elongated/non-spherical particles. Caban and Stepnowski highlighted how sieving is problematic in indoor dust samples with substantial fiber content because the shape of fibers prevents reasonable separation by the typical stainless steel sieves^[37]. As more attention is given to the composition of indoor dust, particularly the synthetic components such as microplastic fibers^[47], our techniques for characterizing the chemical content of dust must not introduce bias into the characterization.

In this study, we consider the implications of sieving for pre-processing dust samples and the impact of this technique on the measurements of chemicals in dust. Using composite dust samples from seven different microenvironments (pre-fab apartment blocks, new homes, kindergartens, schools, offices, public spaces, and cars), we investigated the effect of sieving on the observed chemical distributions by size fraction for dust of 1-2 mm, 0.5-1 mm, 0.25-0.5 mm, and < 0.25 mm. Analyses of polycyclic aromatic hydrocarbons (PAHs) in dust fractions were combined with carbon analysis and optical microscopy to address the impact of sieving on the composition of dust particle size fractions.

PAHs receive limited attention as pollutants of indoor concern; they are largely attributed to outdoor sources, and outdoor air/PM levels are typically in greater focus. PAHs are not quantified in indoor dust as often as chemicals originating from consumer products, e.g., flame retardants and plasticizers. However, PAH levels are typically higher indoors than outdoors^[48-50], and dust has the potential to be an important exposure source, particularly for the higher molecular weight particle-bound PAHs^[51,52]. Recent studies have emphasized the importance of PAHs indoors for both human exposure and health impacts such as carcinogenicity and mutagenicity, with particular hazards for children^[48,52].

Moreover, the typical pathway for PAHs entering indoor dust allows these compounds to be a useful tool in understanding the impact of dust pre-processing methods on observed distributions. PAHs are not contained in consumer products and building materials, meaning that emissions pathways such as abrasion of products that can lead to irregular distributions of chemicals across dust particles should be of limited importance for PAHs^[29]. The major pathway for PAHs to indoor settled dust is via air, from gaseous or particulate emission to air^[52], and subsequent partitioning, coalescence and/or deposition to settled dust. In this case, the physical-chemical factors, which govern these environmental processes, should control the distribution of dust^[53]. This suggests that, in the absence of a methodologically-introduced bias, we should see size fraction and/or organic carbon-driven distributions of PAHs in dust, as is typical for outdoor particles^[54-56].

METHODS

Sample collection

Indoor settled dust was collected from seven types of indoor microenvironments in 2019 in Brno, Czechia, a mid-sized central European city. Dust samples from residential locations (new homes built > 2005, and pre-fabricated concrete apartment blocks built between 1970 and 1990), kindergartens, schools, public spaces, and offices were taken from vacuum bags from household or professional vacuum cleaners supplied by the home residents and cleaning workers from facilities. Dust from cars was collected from seats, floors, and trunk by researchers using a household vacuum cleaner directly into one vacuum cleaner bag, to replicate similar conditions to the other microenvironment sampling. The collection locations are summarized in [Supplementary Table 1](#). After collection, all dust samples were transported to the RECETOX Laboratories, Brno, Czechia, and stored at -18 °C until processing.

Sieving and pre-processing

To reduce individual sample variability and emphasize differences according to microenvironment type, composite dust samples were created by pooling according to microenvironment type, leading to seven composite dust samples. First, the individual contents of each vacuum bag were sieved with a coarse (2 mm) sieve to remove large debris. Particles > 2 mm were discarded. Each remaining dust sample was individually weighed. Then, equal masses of individual dust samples to be combined into one composite sample were sequentially added to a sieve stack with sieves of 1 mm, 0.5 mm, and 0.25 mm pore sizes. Samples were manually dry sieved, and each fraction was then separately homogenized overnight on an inverting shaker. Masses of each fraction were recorded. Bulk homogenized composite dust was then reconstituted from the individual size fractions based on their relative masses. Car dust was all collected from vehicles into one single vacuum bag, so the same procedure was followed without the compositing step. Samples were aliquoted for separate analytical procedures and stored in a freezer until extraction. One aliquot (50 mg) of the dust was taken for carbon analysis, one for PAH analysis, and other aliquots were taken for analysis of pesticides, flame retardants and plasticizers (presented elsewhere; in preparation). The remaining dust was used for optical microscopy characterization of dust composition.

PAH analysis

Bulk dust and each size fraction from the different microenvironments were analyzed. 100 mg of each composite dust sample/size fraction was used for the determination of PAHs, as well as a range of other chemical compounds (results presented elsewhere).

First, a recovery internal standard was added to each sample, consisting of three deuterated PAHs [D_8 -naphthalene, D_{10} -phenanthrene, and D_{12} -perylene (Merck)]. The 100 mg of composite dust was then extracted by ultrasonic extraction with 5 ml of 1:1 acetone:n-hexane as a solvent. Extraction was conducted by 20 minutes of sonication, followed by 20 minutes of settling. After settling, the solvent from each sample was transferred into separate vials. This extraction step was repeated two more times, using 3 ml of 1:1 acetone:n-hexane in each step. All three portions of extract were combined into one extract for each sample.

The extracts were reduced in volume to approximately 5 ml by evaporation under nitrogen and split by mass into two fractions: 30% and 70%. The 30% fraction was cleaned with column chromatography (5 g of activated silica gel, 1 cm of sodium sulfate, eluted with 20 mL of DCM) and prepared for analysis of PAHs. p-Terphenyl (Absolute Standards, Inc.) was used as an instrumental internal standard. The remaining 70% aliquot was retained for the analysis of polychlorinated biphenyls, organochlorine pesticides, and flame retardants, results of which are presented elsewhere.

The samples were analyzed for 29 PAHs [Supplementary Table 2]. PAHs were analyzed on 8890A GC (Agilent, USA) equipped with a 60 m × 0.25 mm × 0.25 μm Rxi-5Sil-MS column (Restek, FR) coupled to a 7000D MS (Agilent, USA). The temperature program for GC started at 80 °C (2 min hold), then continued with 15 °C min⁻¹ to 180 °C (no hold) and lastly 5 °C min⁻¹ to 310 °C (20 min hold). The inlet temperature was 280 °C. The injection volume was 1 μl in pulsed-splitless mode. The carrier gas was helium with a flow rate of 1.5 mL min⁻¹. The temperature of the transfer line was 310 °C and of the ion source 320 °C. The mass spectrometer was operating in selected ion monitoring (SIM) mode.

Carbon analysis

Total carbon (TC) and total organic carbon (TOC) were analyzed by Vario TOC Cube (Elementar, Germany). For total carbon, 20-60 mg of dust was placed in tin foil and a capsule was formed from the foil. For total organic carbon, 20-60 mg of dust was placed in silver foil, wetted by water, and then three drops of concentrated hydrochloric acid were added to remove inorganic carbon. The sample was dried in the oven for 1 hour at 75 °C. In both cases, the foil capsule was added to the combustion tube, where carbon dioxide was released and then detected by an infrared detector.

Total inorganic carbon (TIC) was calculated based on the difference between the total carbon and TOC. In cases where TC values were lower than TOC values, TIC values were assumed to be below detection. This can occur due to heterogeneity in individual samples.

QA/QC

The homogeneity of the individual dust size fractions was evaluated by analysis of four subsamples taken from one of the indoor microenvironment dust pools. All size fractions demonstrated acceptable homogeneity according to TC and TOC. Relative standard deviations of the replicates ranged from 1%-10% [Supplementary Figure 1]. TIC, which is calculated from the difference between TOC and TC, had greater variability, but this is generally due to the very low TIC content [Supplementary Figure 1].

The PAH method was previously validated with the use of NIST SRM 2528, and all quantified PAH values were comparable to certified values [Supplementary Figure 2]. The instrumental method for PAH analysis is accredited according to ČSN EN ISO/IEC 17025:2018. The recoveries of measured analytes were quantified based on deuterated standards. Recoveries were on average 101% ± 13.8% for d8-naphthalene, 134% ± 11.4% for d10-phenanthrene, and 59.8% ± 26.9% for d12-perylene. PAH masses were adjusted based on the recovery of the nearest molar mass standard.

Certified reference material B2188 Soil Standard (Chalky) (Elemental Microanalysis Ltd, UK) was used for verification of the calibration range and proper analyzer operation of the carbon analyzer.

Five laboratory blanks were processed as per the dust samples. All vials were weighed, including those of blank samples, and blank sample vials were opened for roughly the same time as other samples. Extraction and chromatography were done in batches, with every batch containing at least one blank sample.

Method detection limits (MDLs) were established based on the levels detected in the blanks [Supplementary Table 3]. The method detection limit was calculated as MDL = [(average of the mass in the blanks) + (3 × standard deviation of the blanks)]. For compounds with a mass greater than the MDL, the average concentration of the blanks was subtracted from the sample mass. If an analyte was not detected in any blanks, the instrumental detection limit was used in place of the MDL. For data analysis, a value of MDL/2 was substituted for samples below MDL.

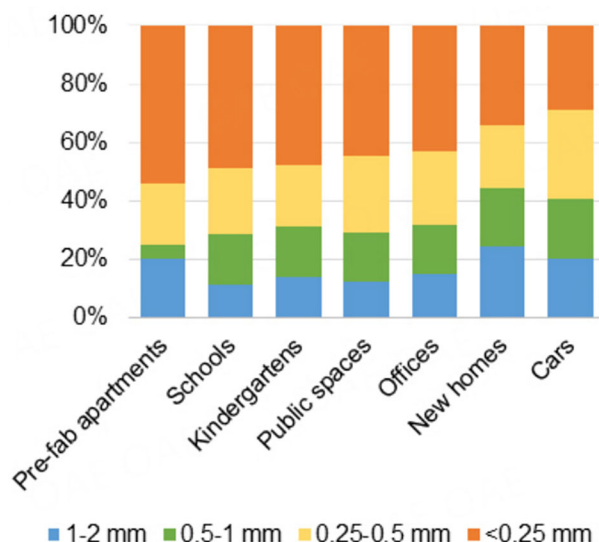


Figure 1. Distribution of dust by mass among particle size fractions.

Optical microscopy

Images of dust samples were taken by stereoscopic microscope Olympus SZ61 with attached camera model Artcam 300MI. The software used was QuickPHOTO MICRO 3.2 with a resolution of 2048 × 1536. For a better depiction of samples of variable thickness, the Deep focus 3.4 function was used, combining three images. Images were taken with automatic exposure mode and adjusted image settings.

RESULTS AND DISCUSSION

Mass distributions

The relative distributions of dust masses among each size fraction had some small variations by microenvironment, with pre-fab apartments dominated by the finest fraction, while cars had the lowest contribution of fine dust [Figure 1]. However, as will be discussed further below, these mass fraction distributions should not be assumed to reflect the true distribution of the dust, but rather are likely biased by the sieving technique used.

Carbon composition

The TC content of all dust samples was high, ranging from 11%-31% of the bulk dust, and in some individual fractions up to 41% [Figure 2]. TC content was highly variable among size fractions and microenvironments, with notably lower levels in cars, public spaces, and kindergartens. For cars and public spaces, this may correspond to a greater contribution of outdoor-origin particles, as these are the environments where people are almost exclusively wearing outdoor footwear, which has been associated with greater tracking of outdoor materials into indoor spaces^[57]. Shoes are not typically worn in kindergartens; however, it has been previously noted that kindergartens may be associated with higher levels of inorganic silica in indoor dust^[58], presumed to be due to the presence of sandboxes in the outdoor play space.

TOC was dominant in all cases, and in 31% of samples, all carbon was in the organic form. TIC content was very low, in many cases below the instrumental detection limit, and in all cases under 12% [Supplementary Table 4]. The highest contributions of TIC to bulk dust were seen in public spaces (4.5%) and cars (2.3%), which again may be due to the tracking of outdoor material.

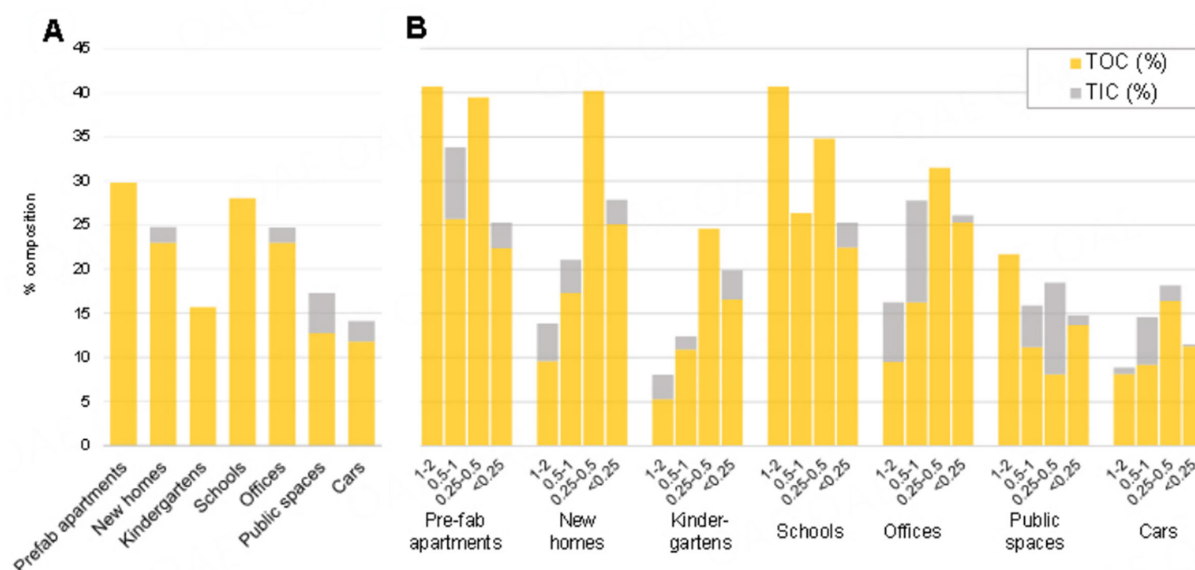


Figure 2. Organic and inorganic carbon composition (in %) of indoor dust in (A) bulk dust and (B) according to particle size fraction. TIC: Total inorganic carbon; TOC: total organic carbon.

We also note the inconsistent distributions among size fractions, although two patterns do seem apparent: in new homes, kindergartens, offices, and cars, the highest carbon content is found in the 0.25-0.5 mm fraction, while pre-fab apartments, schools, and public spaces have higher peaks in both the coarsest (1-2 mm) and 0.25-0.5 mm fractions. This cannot be generalized to types of environments with more/less tracking of outdoor material (e.g., based on locations where people typically do not wear shoes indoors), and rather suggests the significant variability in the carbon content of indoor dust.

The variability and frequently high levels of TOC in indoor dust are similar to what has been previously reported, e.g., 2%-34% TOC in homes in Germany^[32], 16%-40% in houses in the UK^[35], and 15%-37% in homes in Canada^[59]. The organic carbon content of indoor dust is generally much higher than topsoil, where the typical values fall in the range of 5%-10%^[59,60]. These high levels emphasize the significant capacity of settled dust to retain organic chemicals, with impacts on both chemical concentrations and bioaccessibility of contaminants^[41]. However, the quality of organic carbon in indoor settled dust may differ substantially from that in soil; soils contain amorphous organic carbon with adsorptive capacity and soot with strong adsorptive capacity. The composition of the organic carbon in modern indoor settled dust has not been well-studied, but likely consists of many plastic polymer particles and fibers with an unclear contribution to sorptive capacity.

PAH concentrations

Of the 29 targeted PAHs, all except cyclopenta[cd]pyrene were detected in at least one sample. In bulk dust, the highest concentrations of Σ_{28} PAHs were detected in kindergartens (6270 ng/g, Σ_{EPA-16} PAHs: 4980 ng/g) and offices (6260 ng/g, Σ_{EPA-16} PAHs: 4820 ng/g), while the lowest were in pre-fab apartments (1430 ng/g, Σ_{EPA-16} PAHs: 1100 ng/g) [Figure 3]. Profiles of PAH compounds were relatively consistent across the microenvironments, with dominant contributions to the dust from phenanthrene, fluoranthene, pyrene, benz[a]anthracene, and chrysene [Figure 3]. As these are composite samples, levels in the bulk dust cannot be directly attributed to location-specific sources; however, we do note that lower levels in pre-fab apartments may be due to the lack of large indoor combustion sources (no fireplaces or wood stoves), as well as being at higher building floor levels above road and traffic sources. In contrast, the new homes

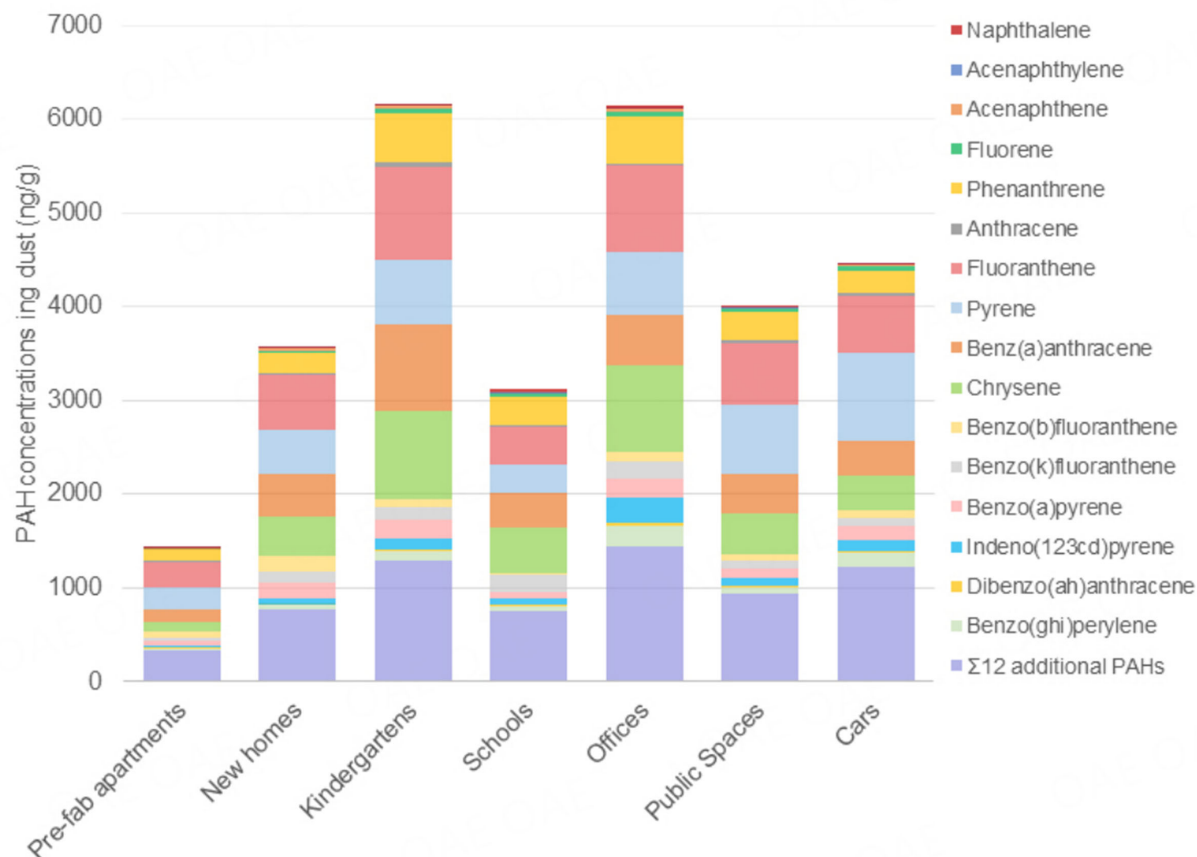


Figure 3. PAH concentrations in bulk dust. PAH: Polycyclic aromatic hydrocarbon.

sampled did have wood fireplaces, which are known to contribute to elevated levels of PAHs indoors^[61]. Kindergartens were expected to have low levels of PAHs; however, one of the kindergartens used to create the composite sample had unexpectedly high indoor PAH levels, which likely biased this composite dust^[62].

In general, the levels in the dust were comparable to those reported for other European locations. The $\Sigma_{\text{EPA-16}}$ PAH in our dust ranged from 1100 ng/g to 4980 ng/g in bulk dust, and 639-4850 ng/g in < 0.25 mm dust, which is generally within the range of what has been reported for indoor dust in North America, Europe and some regions of Asia^[39,61,63-67]. However, the detected levels were lower than in most samples from China, where the greater concentrations are attributed to higher use of coal and elevated outdoor PAH levels^[68-71]. This suggests that the general sources that have been highlighted as the major contributors to PAH levels in indoor and urban locations are also relevant for our samples: domestic heating, cooking, traffic and industry via outdoor-to-indoor transfer^[52].

PAH contamination according to size fraction

Investigating the distribution of the PAHs among individual dust size fractions provides some insight into the mechanisms driving PAH contamination. First, there is significant variability in the levels and patterns of contamination - finest dust fractions do not consistently have the highest levels of PAHs, and in selected samples (notably the 0.5-1 mm fraction of pre-fab apartments), extremely high levels of PAHs were detected [Figure 4A].

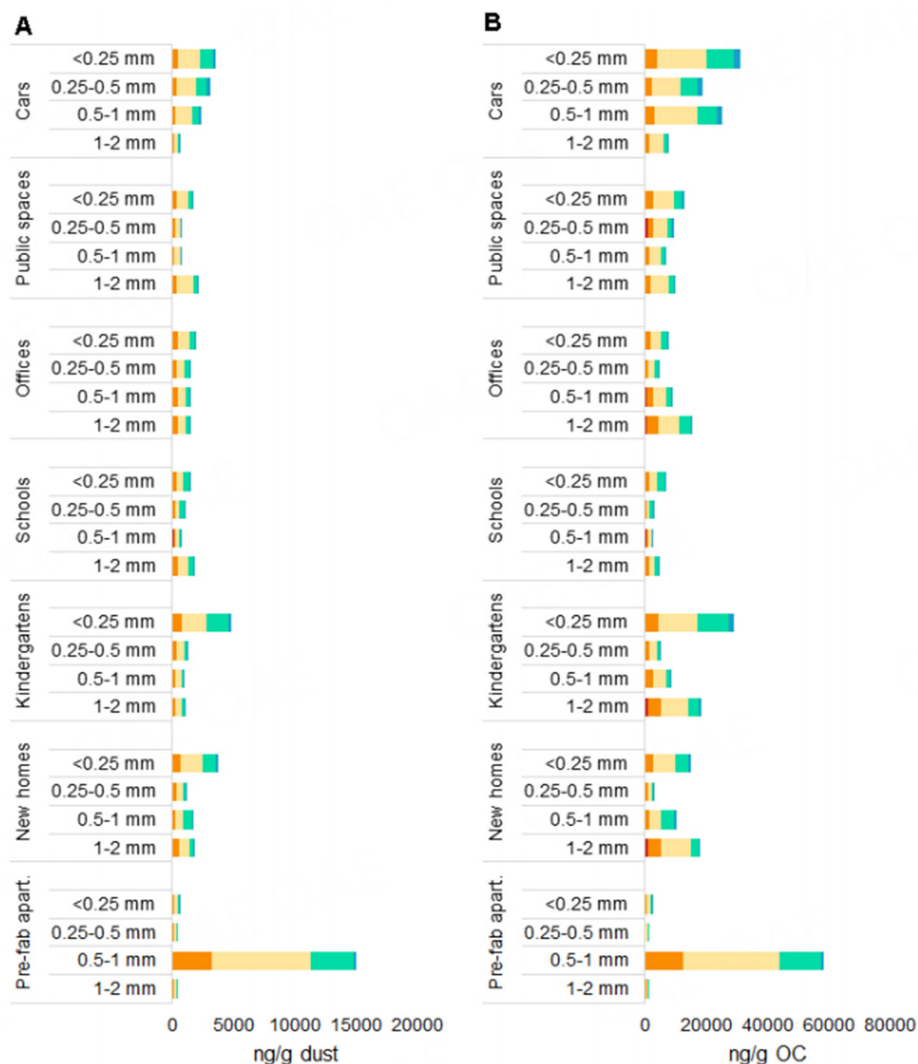


Figure 4. PAH concentrations in individual dust size fractions in (A) ng/g and (B) ng/g organic carbon. OC: Organic carbon; PAH: polycyclic aromatic hydrocarbon.

This irregular distribution across dust size fractions from different microenvironments is consistent with what has been reported in other studies of PAH distributions in dust indoors^[38,39], but differs from what is reported in other particle matrices: aerosols, outdoor dust, and soils. The reported distributions of PAHs in atmospheric particles according to size fraction are consistent: finer atmospheric aerosols are consistently associated with higher levels of PAHs, whether by mass or normalized to organic carbon content^[55,72-74]. Similarly, in the few studies considering outdoor dust (typically road dust), the same general pattern of higher concentrations on finer particles has been reported^[75,76], although this can vary among sites^[77]. Similar distributions of decreasing PAH content with increasing particle size have also been reported for soils, most frequently attributed to the variations in organic carbon content^[78,79].

In our dust samples, normalization by organic carbon alters some of the distributions among size fractions (e.g., higher OC-normalized concentrations of PAHs in 1-2 mm fractions); however, it does not “explain” much of the variability, e.g., the very high PAH levels in 0.5-1 mm dust from pre-fab apartments is not due to high organic carbon content [Figure 4B]. The OC-normalized distributions are in fact more irregular

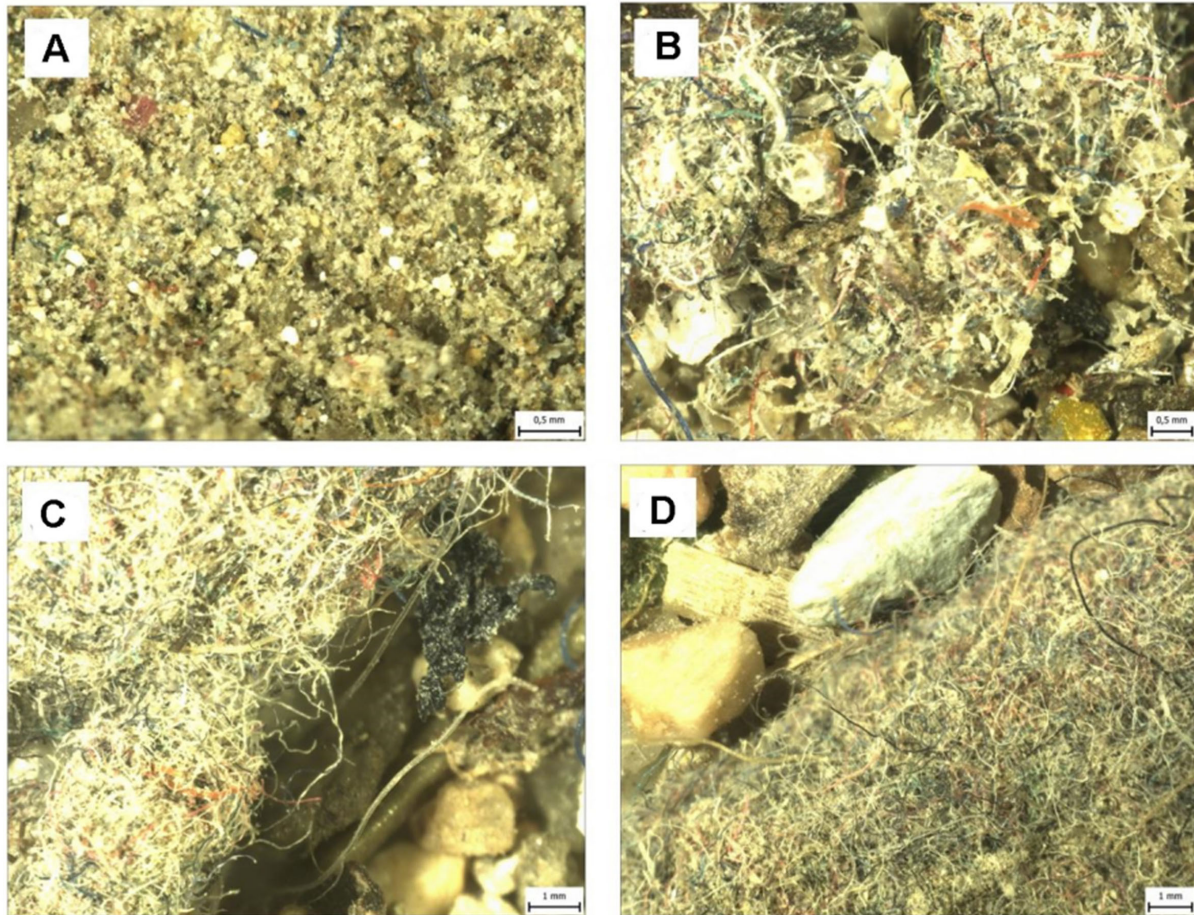


Figure 5. Optical microscopy images of kindergarten dust size fractions (A) <0.25 mm, (B) 0.25-0.5 mm, (C) 0.5-1 mm, and (D) 1-2 mm.

than those by dust mass, suggesting that the OC content is not the dominant factor driving the levels and distributions.

PAHs are not contained in consumer products and building materials, meaning that emissions to dust from physical abrasion of materials or by mass transfer from products to dust, which are important for polymer additives such as flame retardants^[29,30], should be of limited importance. The major pathway for PAHs to indoor settled dust should be via air, through partitioning or deposition to dust. In this case, the physical-chemical factors which govern these environmental processes should control distributions in dust^[53]. However, the lack of consistency in PAH concentrations or carbon content across size fractions in indoor dust suggests additional factors contributing to the observed distributions.

Microscopy

Visual examination of the indoor dust size fractions provides insight into the sources of variability. The coarsest fractions from all microenvironments do not contain only particles larger than 1 mm. Rather, they contain substantial agglomerations of fine fibers, and the agglomerations also contain fine particles with diameters < 1 mm [Supplementary Figure 3]. Moreover, the finest fractions have much lower fiber content than coarser fractions, suggesting that the distributions of chemical content according to size fraction are significantly biased by the impact of sieving on failing to separate, or even creating, the agglomerations of

fibers and fine particles. Some of these agglomerations may already be present in the settled dust in the microenvironment, but based on visual examination of the dust during sample collection, it is more likely they are created during the sample collection (vacuuming) or sieving process. In the example presented for the kindergarten dust [Figure 5], it is clear that fine fibers are present throughout all size fractions except the finest fraction. This agrees with estimates by Lanzerstorfer that 10% of fine dust in house samples can be discarded with 2 mm fractions alone, and much more in subsequent stages^[40]. This provides clear support for the hypothesis that indoor dust separation by sieving may not be achieving the intended goal of distinguishing between particles with more or less potential for human exposure via dermal adherence and/or unintentional ingestion, and provides a possible explanation for why many studies relying on sieving to determine differences in the chemical content for different size fractions find very irregular distributions.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of different dust size fractions for carbon and PAH content showed irregular distributions across size fractions and did not follow the theoretical understanding of partitioning to size fractions with greater surface area and/or carbon content. The combination of chemical data with microscopy imaging suggests that unclear separation of fibers and fine particles adhering to fibers may be contributing to this. Another important factor may be the composition of the organic matter in indoor dust, which is hypothesized to have substantial contributions from polymer particles and fibers, but this variable is not well-known, and is recommended for further study. This suggests caution should be used in interpreting chemical distributions among size fractions separated by sieving and limits the applicability of such size-segregated fractions for estimates of human exposure. Fine dust fractions determined by physical sieving may not accurately reflect the fine fractions to which people would be exposed in indoor spaces, as they will lack the fibrous content that is an important part of indoor dust. Sieving and discarding of coarser fractions may preferentially remove fibrous components of dust and therefore bias the chemical content of fine dust.

To avoid such bias, it is important to consider when such sieving is truly necessary, and when bulk dust could be appropriate (perhaps with only manual removal of large debris). This dust would retain the fiber content that may be important for exposure, and these fibers, due to their different origin, may have a very different chemical content than other dust particles.

However, in some studies, separation or sorting of particles can be necessary. Given the growing awareness and attention to the fibrous content of indoor dust, it is clear that caution is needed in adapting techniques from other fields (e.g., sieving, from soil science) to avoid introducing bias in the samples. Conventional sieving, relying on agitation/vibration of stainless steel woven wire mesh sieves, pore size typically between 0.63 μm and 2 mm, can alter the particle size distributions of indoor dust by creating dust agglomerates. Techniques such as wet sieving, which is recommended for very fine powders in industrial chemistry, are not appropriate when the objective is subsequent chemical characterization because of the potential that some chemicals can be “washed” from the dust. When separation is necessary, techniques using air, while infrequently used, may be appropriate for indoor dust. A few studies on the chemical characterization of indoor dust have demonstrated the applicability of such methods. Lewis *et al.* used an air classifier to separate respirable fractions of house dust^[45]; Lanzerstorfer and Logiewa combined sieving with the use of a laboratory-scale air classifier to improve the separation of road dust, while Lanzerstorfer *et al.* used rubber balls to separate agglomerations during sieving of house dust^[80]; however, this was not sufficient and was followed by air classification^[40]. Gustafsson *et al.* used manual brushing of dust on sieves to de-agglomerate the dust followed by an ash cyclone and filter to collect the finest dust^[81]. All these methods are likely to improve the separation of particles; however, they may introduce additional uncertainties into the dust pre-processing, and none is routinely applied.

Overall, a better understanding of the impact of the physical composition of dust on human exposure is needed. Typical size cut-offs to separate dust of relevance to human exposure, such as $< 63 \mu\text{m}$ or $< 150 \mu\text{m}$ may not apply to fibrous particles, but it is not clear what guidance should be used to select dust of greatest relevance to exposure. Given the importance of dust as an important human exposure route for many chemicals of concern, potential biases introduced by sample pre-processing are deserving of more careful attention.

DECLARATIONS

Author's contributions

Conceptualization, Methodology, Writing: Melymuk L

Methodology, validation, investigation, writing, review and editing: Jílková SR

Investigation: Kolář M

Investigation: Svobodová P

Conceptualization, writing, review and editing: Vrana B

Conceptualization, writing, review and editing: Hilscherová K

Availability of data and materials

All measured data (PAH and TOC/TIC) are given in the Supplementary Information, available online at doi.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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