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Review article

Airborne particles in indoor environment of homes, schools, offices and aged care facilities: The main routes of exposure

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ABSTRACT

It has been shown that the exposure to airborne particulate matter is one of the most significant environmental risks people face. Since indoor environment is where people spend the majority of time, in order to protect against this risk, the origin of the particles needs to be understood: do they come from indoor, outdoor sources or both? Further, this question needs to be answered separately for each of the PM mass/number size fractions, as they originate from different sources. Numerous studies have been conducted for specific indoor environments or under specific setting. Here our aim was to go beyond the specifics of individual studies, and to explore, based on pooled data from the literature, whether there are generalizable trends in routes of exposure at homes, schools and day cares, offices and aged care facilities. To do this, we quantified the overall 24 h and occupancy weighted means of PM_{10}, $PM_{2.5}$ and PN - particle number concentration. Based on this, we developed a summary of the indoor versus outdoor origin of indoor particles and compared the means to the WHO guidelines (for PM_{10} and $PM_{2.5}$) and to the typical levels reported for urban environments (PN). We showed that the main origins of particle metrics differ from one type of indoor environment to another. For homes, outdoor air is the main origin of PM_{10} and $PM_{2.5}$ but PN originate from indoor sources; for schools and day cares, outdoor air is the source of PN while PM_{10} and $PM_{2.5}$ have indoor sources; and for offices, outdoor air is the source of all three particle size fractions. While each individual building is different, leading to differences in exposure and ideally necessitating its own assessment (which is very rarely done), our findings point to the existence of generalizable trends for the main types of indoor environments where people spend time, and therefore to the type of prevention measures which need to be considered in general for these environments.

1. Introduction

Exposure to airborne particulate matter (PM) is one of the most significant environmental risks people face. Recent 'Global Burden of Disease' (GBD) assessments placed exposure to $PM_{2.5}$ (mass concentration of particulate matter with aerodynamic diameter < 2.5 μm) among the top ten risks leading to worldwide lower life expectancy and/or lives with disease (Forouzanfar et al., 2015). Most of the PM exposure occurs indoors, because this is where people spend a large fraction of their lives.

Indoor particles are a mix of ambient particles that have infiltrated indoors, particles emitted indoors, and particles formed indoors through reactions of gas-phase precursors originating from both indoor and outdoor sources, as schematically presented in Fig. 1. Ambient

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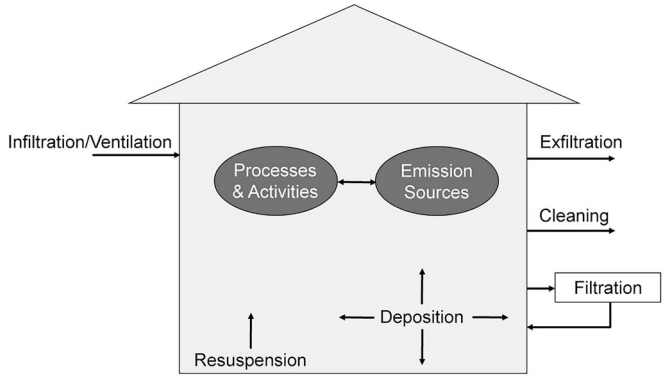

Fig. 1. Schematic diagram of the key factors influencing indoor air particle concentrations, adapted from Thatcher and Layton (1995).

(atmospheric) aerosols in urban environment originate predominantly from fossil fuel burning, automobile emissions, resuspension, or chemical and thermodynamic processes e.g. Belis et al. (2013), but also from long range transport. In an indoor environment, activities such as cooking or indoor combustion, e.g. Wallace (2006); smoking, e.g. Wallace (1996) and Waring and Siegel (2007); vaping, e.g. Schripp et al. (2013); secondary formation processes, e.g. Waring (2014); and dust resuspension, are the most significant sources of aerosols. Because of these different sources, airborne particles span a range of diameters from a few nanometers to tens of micrometers. Equivalent diameter d_p (e.g. μm, nm) is the classical descriptor of particle size in aerosol science, based on which particle transport, dynamics, and fate can be described (Nazaroff, 2004).

Exchange of air between indoors and outdoors plays a crucial role in indoor air pollution control. An air exchange rate (AER) [h^{-1}] is a measure of the volume added to or removed from a space divided by the volume of the space ASHRAE (2013). AERs parameterize air exchange mechanisms due to the individual or combined effects of infiltration through the building envelope and mechanical or natural ventilation (ASHRAE, 2013). Outdoor-air exchange introduce ambient aerosols indoors (El Orch et al., 2014; Johnson et al., 2016; Riley et al., 2002) and dilute any existing indoor aerosols, as well as any SVOCs that are precursors to aerosol formation indoors (Weschler and Shields, 2000; Weschler and Shields, 2003; Youssefi and Waring, 2014). Whichever of the three outdoor-air exchange mechanisms dominates, it strongly impacts the magnitude of the overall ambient aerosol source contribution. That is, the natural ventilation airflows move through large openings almost without aerosol loss, though infiltration and mechanical ventilation flows move through cracks in the building envelope or through filters, respectively, so the outdoor aerosol source contribution is lessened.

Many different facets of particulate matter are potentially of significance to health, including their physical properties such as size and its distribution, shape or surface area, as well as chemical composition and microbiology. Particle characteristics depend on the sources from which they originated and on the post emission processes involving the particles, and therefore the composition and toxicity of indoor particles is very complex, with similarities but also differences to outdoor aerosols.

The theory of basic processes driving aerosol dynamics is reasonably well established and has mathematical description. Numerous experimental studies quantified the relevant parameters of indoor environments and indoor air. Various types of modelling approaches exist, including those based on balance equations, physico-chemistry, computational fluid dynamics (CFD), Monte Carlo modelling, or combinations of these approaches, and they have been employed in many research projects to gain insight into the nature of indoor aerosol dynamics (Holmberg and Li, 1998; Hussein and Kulmala, 2008; Hussein et al., 2015; Loth, 2000; Nazaroff and Weschler, 2004; Rackes and Waring, 2013).

Despite this large body of knowledge, the complexity of the processes taking place in or affecting indoor environment makes drawing conclusions about general significance of various factors or processes, a very challenging task. In particular, *one of the key questions is the origin of the particles, whether they come from indoor or outdoor sources*, as very different prevention measures need to be put in place in each of these two cases. And finally, *are the concentrations encountered in various indoor environments, a health risk?* In the absence of answers to these questions, the effects of exposure to indoor air pollution cannot be quantified, nor can indoor air pollution be effectively managed, since no clear recommendations can be given to legislators or building owners, whether public or private.

The aim of this work was to provide a general overview, based on literature published, of: 1) the origin – indoor or outdoor – of different particle size fractions for selected key indoor environments; and (2) the significance of this knowledge for exposure control and management of indoor air quality. Particle size fractions considered were $PM_{2.5}$, PM_{10} (mass concentration of particulate matter with aerodynamic diameter < 2.5 μm and < 10 μm, respectively) and UFP (ultrafine particles, < 0.1 μm), measured typically as particle number concentration. The focus of this work was on homes, schools and day cares, offices and age care facilities, which are of significance as the most typical indoor environments where people spend the majority of their time. Following a comprehensive literature review, comparative analysis of the available data was conducted to elucidate the role of the key factors and processes affecting airborne particles in the above indoor microenvironments. Not included in the review were sources of and factors specific to: bioaerosols, cigarette smoke and e-cigarettes or indoor biomass burning, as these are very specific types of aerosols/sources, each a topic for a separate review.

2. Materials and methods

2.1. Literature search

Literature search was conducted to identify studies, which investigated both indoor and outdoor concentrations of various particle metrics in the indoor environments of interest. Many of such studies were identified by our earlier work Morawska et al. (2013), with several more published since then.

Studies were selected for inclusion based on whether they reported a mean and standard deviation in any of these environments. Another inclusion criterion was the presence of residents, studies conducted in empty test buildings were excluded, as well as studies where the participant were given restrictions in their daily habits (e g not allowed to cook).

2.2. Data analysis

Data from measurement periods of 24 h or a multiple thereof (e.g. 48 h, 168 h) were analysed in this section as “24 h” averages. For data which were recorded during the occupancy hours at schools, day care centres and in offices, these have been analysed as “Occupancy” averages. Due to very limited amount of reported data on occupancy time concentrations in homes (which from exposure assessment point of view seem to be the most relevant in any microenvironment) analysis of home environments was conducted for 24 h averages and their multiple thereof. For homes only data from publications reporting simultaneous and continuous measurements of both indoor and outdoor concentrations were included. Excluded were studies where smoking occurred, performed in unoccupied homes i.e. no residents and no indoor sources and studies assessing specific indoor sources in laboratory conditions. Due to lower amount publications on schools, day cares centres and offices as well as the fact that indoor/outdoor ratios were not calculated, the studies have not been restricted to those reporting both

indoor and outdoor concentrations.

To quantitatively summarize and compare the results of the studies, weighted means of the respective particle metrics (PM_{10}, $PM_{2.5}$ and PN – particle number concentration covering submicrometer size range) and pooled standard errors of estimates of these means were calculated from the results reported in the papers. Analysis was restricted to those studies with a reported mean, standard deviation and averaging period for the relevant parameters in each location. Studies were weighted by the number of individual locations within each study; when the number of locations was not reported, it was assumed to be 1, in order to maximise the standard error of the estimate of the mean from that study.

Some of the studies also reported median values of the concentrations, and for completeness these values are included in the tables listing all the studies identified. However, analysis of the medians was not conducted, as not all of the studies reported them, and also, including the median in the analysis would make it substantially more difficult to interpret. This is because weighting medians from other studies does not guarantee a meaningful result, as it is likely that the median will just be the median value from the largest study in the middle of the pack.

3. Results and discussion

The studies identified are listed in Tables S1 (homes), S2 (schools), S3 (day cares), and S4 (offices), together with particle concentrations reported, and are discussed in Sections 3.1 to 3.3 below. Overall, there have been 58 studies reported for homes, 50 for schools and 12 for day care centres, 12 for offices and only 3 studies for aged care facilities. The studies which were included in the analysis are noted in these tables by † (studies with a reported mean, standard deviation and averaging period for the relevant parameters in each location).

Table 1 presents the values of the calculated means and their standard errors for homes, schools/day care centres and offices, along with the number of sites and studies that were included in the calculations. As the number of studies identified on aged care facilities was too small for such analysis, they are discussed separately in Section 3.4.

Fig. 2 presents the results of the calculated 24 h and occupancy hours means of indoor and outdoor concentrations for each environment under investigation, and the individual studies that the mean is comprised of.

From inspection of Fig. 2, conclusions can be drawn regarding the concentration of the individual particle metrics in the environments investigated and based on this, regarding the factors and process driving them. These are discussed for each of the environments under consideration in the following sub-sections.

3.1. Homes

Approximately 65% of daily time spent by people in developed countries is at home (Brasche and Bischof, 2005; Leech et al., 2002), and by the very young and elderly, even more. Thus, air quality in homes is of significance to human health.

One of the critical aspects affecting indoor air quality is the exchange between indoor and outdoor air. In the U.S air exchange of residences is mostly from the combined effects of infiltration and natural ventilation only, since mechanical ventilation is typically non-existent except in some new constructions. In some European countries, however, up to ~1/2 to 3/4 of certain types of homes use mechanical ventilation to provide the desired AER (Litiu, 2012). In a recent review (Hodas et al., 2015), noted these facts and summarized residential AERs from 22 studies throughout the world, reporting a median value of 0.5 h^{-1} (with 95% confidence interval of 0.08 to 8.2 h^{-1}). Within this world distribution, some broad trends exist. For example, infiltration only AERs in residences have smaller magnitudes—e.g. GM = 0.5 h^{-1} and GSD = 2.1 for 2844 U.S. homes (Murray and Burmaster, 1995)—than actual in-use measured AERs due to combined infiltration and natural ventilation owing to doors and windows—e.g. median of 0.71 h^{-1} (Yamamoto et al., 2010) and GM = 0.75, GSD = 2.1 (Waring, 2014). Another trend identified is that newer homes tend toward lower AERs to conserve energy (Offermann, 2009; Persily et al., 2010). While outside the scope of this analysis, of importance is to keep in mind that there are many factors affecting the infiltration of particles from outdoors to indoors. They include construction materials (mainly wood in North America, bricks in central Europe, concrete in Southern and Eastern Europe etc.), quality of windows and doors and their sealing, respectively (better insulation and consequently likely a lower infiltration in colder regions than in warmer regions) as well as differences in ventilation habits based on the climatic conditions (more open windows and doors in warmer than in colder regions and during summer than during winter).

Particle mass and number concentrations encountered in homes are listed in Table S1. Homes with smoking and studies assessing specific indoor sources in laboratory conditions have not been included in this summary.

3.1.1. Overall variation in PM concentrations

It can be seen from Table S1 that the indoor particle concentrations vary to a great degree, with the minimum and maximum PM_{10} and $PM_{2.5}$ concentrations ranging from 15 to 259 μg/m^3 and from 3 to 202 μg/m^3, respectively. It is important to note that the presented ranges comprise results of measurements with different instruments, for varying averaging times (hours, days, weeks, months or year), and in different geographical locations affected by varying outdoor concentrations. Regarding the reported number concentrations, they are even more difficult to compare due to varying lower size detection limits of the instruments that have a major influence on the total number concentrations measured. This applies, for example, to particles from combustion processes; i.e., the lower the measured size limit, the higher the total number concentrations measured. Studies that used the same instruments e.g. Bekö et al. (2013) and Isaxon et al. (2015), report indoor PN concentrations ranging from 1200 to 1.2×10^6 particles cm^{-3}.

3.1.2. Peak concentrations due to indoor sources

Typically, in indoor environments sudden increases in particle concentration are observed due to specific indoor activities such as cooking, candle or incense burning. The time between an indoor activity begins until peak concentration is reached, have been reported to range between 10 to over 200 min for different cooking activities and candles burning, respectively (Bekö et al., 2013; Buonanno et al., 2014; Wallace, 2006; Wierzbicka et al., 2015). This highlights that the observed changes occur on the scale of minutes, thus only time-resolved measurements can reflect the true range of concentrations encountered in homes. Peak concentrations for specific cooking activities and candle burning have been reported to range from 8×10^3 up to 1.2×10^6 particles cm^{-3} (Bekö et al., 2013; He et al., 2004; Isaxon et al., 2015; Wallace, 2006; Wan et al., 2011; Wierzbicka et al., 2015). Not only did PN concentrations increase dramatically during specific indoor activities, short term increases of $PM_{2.5}$ due to different type of cooking were reported to range between 2 and 100 times more than background (pre-activity level) or outdoor concentrations (Abt et al., 2000b; He et al., 2004; Morawska et al., 2003a; Wallace et al., 2004; Wierzbicka et al., 2015). The decrease in concentrations after the peak was reached has a slope depending on the air exchange and deposition rates with the latter dependent on the size of the particle and the available surfaces for the deposition. The time until the concentration returns to the pre-activity levels, has been reported to range from 20 min to 12.5 h (Bekö et al., 2013; Kearney et al., 2011; Wallace, 2006; Wierzbicka et al., 2015). The magnitude of the concentrations reached and the prevalence of high concentrations for prolonged periods of time (long decay time of the concentrations), are conditions

Table 1
Means and pooled standard errors (SE) of PM_{10}, $PM_{2.5}$ and PNC concentrations across multiple studies, where all values are given in units: cm^{-3} for PN, $\mu g\ m^{-3}$ for PM. The column Study size refers to the total number of monitoring sites across the number of studies (presented in brackets) used in the analysis (these data were used to generate Fig. 2).

Environment	Location	Weighted PM_{10} mean	Weighted SE	Study size	Averaging time
Day care	Indoors	75.91	3.16	30 (2)	24 h
Day care	Outdoors	81.40	1.83	10 (1)	24 h
Home	Indoors	63.29	14.44	87 (5)	24 h
Home	Outdoors	74.42	11.92	87 (5)	24 h
Office	Indoors	15.35	1.55	49 (4)	24 h
Office	Outdoors	22.70	1.68	47 (2)	24 h
School	Indoors	116.92	7.80	78 (2)	24 h
School	Outdoors	37.26	3.25	168 (3)	24 h
Office	Indoors	16.74	0.33	43 (2)	Occupancy
Office	Outdoors	31.22	0.88	41 (1)	Occupancy
School	Indoors	182.03	39.51	281 (5)	Occupancy
School	Outdoors	203.47	40.89	73 (4)	Occupancy

Environment	Location	Weighted $PM_{2.5}$ mean	Weighted SE	Study size	Averaging time
Day care	Indoors	44.27	0.53	304 (2)	24 h
Day care	Outdoors	42.37	0.42	300 (1)	24 h
Home	Indoors	28.09	8.89	201 (7)	24 h
Home	Outdoors	47.34	17.66	41 (7)	24 h
Office	Indoors	36.77	4.86	123 (5)	24 h
Office	Outdoors	64.38	8.61	123 (5)	24 h
School	Indoors	40.47	51.95	18 (5)	24 h
School	Outdoors	14.33	8.65	26 (3)	24 h
Day care	Indoors	52.31	2.82	63 (2)	Occupancy
Day care	Outdoors	7.60	1.18	18 (1)	Occupancy
Office	Indoors	8.07	0.55	33 (2)	Occupancy
Office	Outdoors	13.00	0.82	25 (1)	Occupancy
School	Indoors	50.14	17.86	159 (10)	Occupancy
School	Outdoors	33.92	21.36	97 (7)	Occupancy

Environment	Location	Weighted PN mean	Weighted SE	Study size	Averaging time
Home	Indoors	14,377	7723	109 (5)	24 h
Home	Outdoors	13,119	4388	75 (4)	24 h
Office	Indoors	344	39	13 (1)	24 h
Office	Outdoors	4360	286	13 (1)	24 h
School	Indoors	11,123	1037	103 (5)	24 h
School	Outdoors	18,162	2919	75 (3)	24 h
Office	Indoors	3685	223	42 (1)	Occupancy
Office	Outdoors	15,086	304	42 (1)	Occupancy
School	Indoors	14,024	1533	190 (9)	Occupancy
School	Outdoors	18,767	1688	183 (8)	Occupancy

under which coagulation can be a processes of significance.

3.1.3. Particle number size distribution

Detailed characterisation of the number size distribution of particles in indoor environments has been conducted by a handful of studies; however, the majority of the assessments comprise integrated mass concentration measurements, without time or size resolution. This is due to the fact that until recently instruments allowing time and size resolved measurements were bulky, noisy, and required regular attendance, which meant nuisance to the occupants and logistics difficulties. The number size distribution of the particles indoors resulting from operation of active combustion sources is dominated by particles smaller than 300 nm, with the majority of the particles being smaller than 100 nm, which is within the UFP range (Dennekamp et al., 2001; He et al., 2004; Hussein et al., 2006; Morawska et al., 2003a; Ogulei et al., 2006; Wallace, 2006; Wallace et al., 2004; Wierzbicka et al., 2015). Modes within the UFP fraction vary to a great degree and are source specific. Recently, small and portable instruments have opened up new possibilities for conducting measurements in larger numbers of indoor environments with estimation of the average particle diameters, but care should be taken to assure validation of their accuracy (Asbach et al., 2012; Buonanno et al., 2014; Wierzbicka et al., 2015).

3.1.4. Outdoor versus indoor source contributions

Based on the above insights and Fig. 2, the origin of the particles, whether from indoor or outdoor sources can be inferred as follows.

1. The home outdoor PM_{10} and $PM_{2.5}$ weighted mean concentrations are higher than home indoors, which in general implies that the outdoor air is the predominate source of indoor PM_{10} and $PM_{2.5}$ – thus infiltration/ventilation is an important process influencing home indoor PM_{10} concentrations. Of importance to note is that in general both indoor and outdoor 24 h mean concentrations for homes are high and above those reported by for example, Putaud et al. (2010) in urban areas in Europe. The study reported annual mean PM_{10} concentrations, where the lowest and highest annual outdoor means among the reported cities were in Zurich (19 $\mu g/m^3$) and Manchester (31 $\mu g/m^3$). The discrepancy may result from at least two factors. Firstly, the studies included in our comparison were conducted not only in developed countries, where in general outdoor PM_{10} and $PM_{2.5}$ concentrations are lower, but also in developing countries (such as India or Egypt) where they are higher, particularly in urban areas. However, since the concentrations reported presented a spectrum of values, and it was not always that the values were high in developing countries; there was no obvious

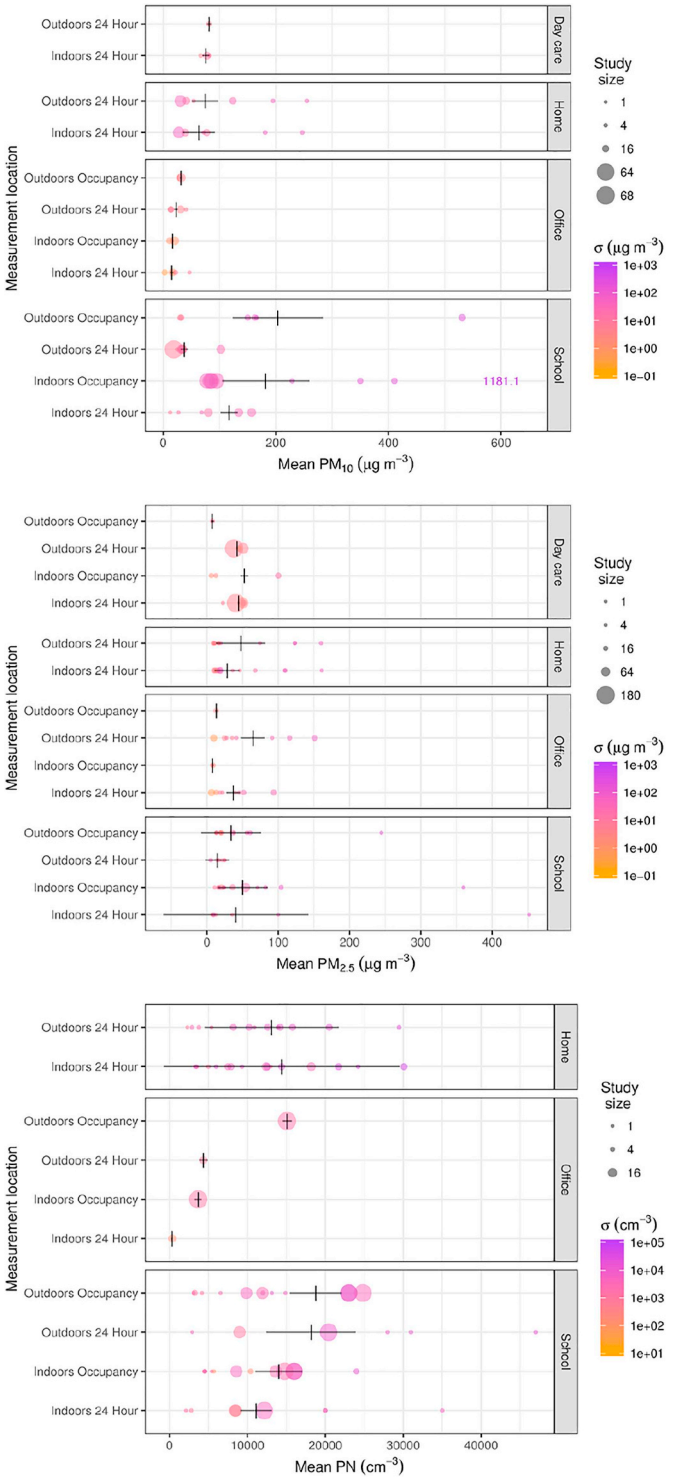

Fig. 2. The calculated 24 h and occupancy hours means of indoor and outdoor PM_{10}, $PM_{2.5}$ and PN concentrations for each measurement environment, and the individual studies that the mean is comprised of. The size of the point represents the number of measurement locations for that study and the points are coloured based on the study's respective standard deviation, with purple representing a large amount of variability in measurements and orange representing a small amount of variability. The weighted means for each location are shown as vertical strokes with their 95% confidence intervals represented as a horizontal line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concentration level beyond which exclusion of the studies would have been justified. Secondly, monitoring stations, from which data are typically used for comparisons between cities, are normally away from pollution sources to represent airshed concentrations, while residential environment may have elevated levels of dust, resulting from the local sources and activities of the occupants. This means that outdoor air quality around the house is worse that this in the airshed, which is of particular concern since concentration indoors in homes depend strongly on influence from local outdoor sources.

2. For PN concentrations, contrary to PM_{10} and $PM_{2.5}$, indoor sources overall contribute more than outdoor air. While there are no health guidelines regarding PN concentrations, the weighted 24 h mean for the homes of 1.31×10^4 particles cm^{-3} (outdoors) and 1.44×10^4 particles cm^{-3} (indoors) are above the mean PN concentrations of 2.61×10^3 particles cm^{-3} in clean background environments reported in a review by Morawska et al. (2008), and comparable to the concentrations in urban background locations of 7.29×10^3 particles cm^{-3} and urban locations of 1.04×10^4 particles cm^{-3}Morawska et al. (2008)

It is of importance to stress that the peak concentrations reported for indoor environment both for PN and PM, are not captured in Fig. 2, and that such instantaneous indoor concentrations during some indoor activities such as cooking or burning candles can be tenfold or more higher than the outdoor concentrations. When this elevation occurs, particle coagulation can occur, particularly in poorly ventilated environments.

3.2. Schools and day care centres

Schools and day care centres are complex indoor environments with very specific building designs, ventilation conditions, and types of activities conducted. For children, school is the second most important indoor environment, where they spent a significant fraction of the day, and children are a population subgroup susceptible to air pollution due to their receiving relatively higher than adult lung doses of airborne particles (Farhat et al., 2005). Moreover, the type of activities taking place at schools (dynamic movement), and the numbers of pupils in a confined space enhance the risk of exposure to air pollution (Mazaheri et al., 2014). Recent review of air quality at schools and its impact on children well-being has demonstrated that worldwide, conditions in many schools are in need of improvement (Salthammer et al., 2016).

For schools, which have high occupant densities, the ASHRAE standard dictates minimum ventilation rates of 8 L/s/person, which would yield AERs of $\sim 3\ h^{-1}$ in classrooms (Daisey et al., 2003). However, real school outdoor-AERs span a range from 1.8 to 31 L/s/person (Canha et al., 2013, Canha et al., 2016; Nielsen, 1984; Turk et al., 1989; Turk et al., 1987; WHO, 2015) implying that some schools are greatly under ventilated, while others, greatly over ventilated.

The results of our literature search on the studies reporting on air quality in and around schools and day care centres are summarized in Tables S2 and S3. The main conclusions and observations of this body of literature can be summarized as follows.

3.2.1. Outdoor versus indoor source contributions

It can be seen from Fig. 2 that:

1. School indoor weighted 24 h mean PM_{10} concentration is significantly higher than the outdoor concentration, while for the occupancy hours the indoor weighted mean is slightly lower than the outdoor mean, with several studies reporting extremely high values. As discussed by numerous studies, resuspension is a very significant source of indoor particles in schools and likely the main reason for the elevated PM_{10} concentrations. The particles are brought inside directly by the children on their shoes or clothing. Regarding $PM_{2.5}$, indoor 24 h weighted mean concentration is similar or slightly higher than the outdoor, with the difference larger for the school

hours (occupancy), implying the role of indoor source contribution, again most likely particle resuspension. Our previous review concluded that $PM_{2.5}$ concentrations were similar for both indoor and outdoor school environments, demonstrating also the impact of outdoor vehicle emissions (Morawska et al., 2013).

2. By contrast, weighted mean PN concentrations inside schools for both, 24 h and the occupancy period are significantly lower than the respective outdoor mean concentration, which points out to an overall small if any impact of indoor sources of PN within the schools, and to the outdoor air being the main source of these particles. Numerous studies reported the impact of traffic outside schools as a significant source of PN concentrations (and in some cases also mid-day outdoor SOA) (Buonanno et al., 2012; Laiman et al., 2014; Mazaheri et al., 2016).Indoors the particles are affected by indoor processes (as discussed in Section 2), with the most significant being deposition and removal by ventilation, since the reported concentrations are not sufficiently high for coagulation to compete with these two processes. Most of the investigated schools were naturally ventilated except in very cold or hot climates, thus pointing to role of the local climate in affecting indoor air quality through the ventilation practices. The weighted mean of the indoor PN concentrations during school hours (1.40×10^4 particles cm^{-3}) is comparable to the urban locations, based on Morawska et al. (2008).

It should, however, be pointed out that there are departures from this overall situation when there are school specific particle emission/formation sources in operation. For example, Morawska et al. (2009), reported significantly elevated classrooms particle PN in a primary school, on many occasions exceeding the outdoor levels by about one order of magnitude (Table S2). The study was conducted in classrooms that were used for art classes and high PN concentrations were attributed to formation of SOA due to the presence of precursors emitted from paints and glues used during the art classes, as well as from the cleaning detergents.

Separately than schools, we reviewed and analysed data from day care centres (also called child care centres, kindergartens, or preschools), attended by younger than school children, who are therefore potentially even more susceptible to air pollution than school aged children. Fonseca et al. (2014) found that the estimated exposure doses were higher in children attending urban preschools; 3 to 5-year-old children suffered an exposure in terms of UFPs from 4 to 6 times higher than adults with similar daily schedules. However, the airborne particle monitoring in day care centres are limited, with only 12 studies found (see Table S3). The studies reported that the majority of the day care centres were naturally ventilated, and the studies predominantly focused on PM_{10} and $PM_{2.5}$, with only 4 studies measuring particle number concentrations. There were more studies conducted for $PM_{2.5}$ than for PM_{10} concentrations in day care centres, and the relationship between mean $PM_{2.5}$ indoor and outdoor was found to be are very similar to this for schools, implying similar role of the respective sources in day care centres as in schools.

3.3. Offices

The office is an important indoor microenvironment where large fraction of the working adult population spends about 30% of their time on a workday. Over the past decades, the number of occupational health complaints from office workers has increased, with the symptoms often attributed to poor building ventilation and indoor air pollution (Horemans and Van Grieken, 2010). A recent study demonstrated that office indoor air pollution may present a serious health risk for workers (Zhu et al., 2015), though effective air quality management may be possible on a dynamic scale (Rackes and Waring, 2014). However, so far, limited number of studies has focused on office airborne particles.

Non-residential buildings, such as offices, have typically outdoor-air exchange provided by mechanical ventilation, with much smaller contribution from infiltration or natural ventilation. The predominance of mechanical ventilation has been demonstrated, for example, by a large study of 100 U.S. offices, showing the distribution of ventilation-AERs of GM = 1.13 h^{-1} and GSD = 2.59 (Rackes and Waring, 2015). These large rates are partially due to the fact that ~75% of systems employed economizer cycles, which increase the outdoor-AER by introducing cool air from outdoors when desirable in relation to thermal comfort.

3.3.1. Outdoor versus indoor source contributions

A summary of the available literature data on office indoor and outdoor particle concentrations is given in Table S4. Based on Fig. 2 it can be seen that all weighted mean particle metrics in office indoor air are lower than in outdoor, and for PN, significantly lower. Therefore it can be concluded that overall, it is the outdoor air which is the main source of office indoor particles, with office indoor sources playing a much smaller role.

Since, as discussed above, mechanical is the ventilation type mostly commonly used in office buildings, it can be further concluded that ingress of outdoor particles is limited, particularly when efficient filters are used, and therefore indoor concentrations are lower than the outdoor (but a contaminated or faulty installed filter or poorly maintained air duct can also be a major source of pollutants or spread of disease through the ventilation system).

Again, similar to the schools, it has been shown that there are situations when operation of office specific sources, such as laser printers, can lead to significantly elevated office particle concentrations, well above the outdoor levels He et al. (2007). It is therefore important to consider the potential impact of such sources on indoor airborne particles and prevent it by replacing or isolating the sources (e.g., locating the printers in an isolated room).

3.4. Aged care facilities

The three studies reported on aged care facilities did not constitute a sufficient number to include in the comparative 24-hour weighted mean analyses with other indoor environments, and therefore they discussed qualitatively below.

Although elderly are considered a group susceptible to air pollution and they spend the majority of their time indoors, we identified only three studies reporting particle concentrations in aged care facilities. Hopke et al. (2003) reported that in a retirement facility in the U.S. the average indoor $PM_{2.5}$ concentration (7.9 $\mu g\ m^{-3}$) was significantly lower than outdoors (21.7 $\mu g\ m^{-3}$). By contrast, Kim et al. (2014) reported that average indoor $PM_{2.5}$ concentration (23.3 $\mu g\ m^{-3}$) was slightly higher than outdoors (21.2 $\mu g\ m^{-3}$) in four aged care facilities in South Korea. Mixed results were reported by Almeida-Silva et al. (2015), who conducted measurements in four facilities in Portugal. The study found that the average living room PM_{10} concentration (18.5 $\mu g\ m^{-3}$) was slightly lower than outdoors (20.7 $\mu g\ m^{-3}$), but the average bedroom concentration (10.9 $\mu g\ m^{-3}$) was significantly lower than outdoors (23.5 $\mu g\ m^{-3}$). In two of the facilities, the average living room PM_{10} concentrations were clearly higher than outdoors. The higher concentrations found in the living rooms than the bedrooms were attributed to a larger number of the occupants of the former, as well as the higher ingress of the outdoor pollution through the doors and windows which were frequently opened when the living rooms were occupied.

4. Exposure control

One of the key questions which need to be addressed in order to control indoor particle concentrations and assess their impact on

human exposure is the origin of the pollutant: are the particles brought inside with outdoor air, or are they emitted by indoor sources or formed indoors from gaseous precursors? We attempted to answer this question based on the results of quantitative comparison of the studies presented in Fig. 2 and discussion in Section 3, above.

It should be stressed that in doing this we expected to uncover the existence of any generalizable trends for the main types of indoor environments where people spend significant fractions of their time. This does not change the fact that each individual building is different, a case study of its own, with its own specific sources of indoor and outdoor pollution, and characteristics, leading to differences in exposure and ideally necessitating its own assessment. With such individual assessments very rarely done, understudying of the overall most significant routes of exposure is a guide as to the type of prevention measures which need to be considered in general for these types of environments.

The effect of the different types of air exchange mechanisms on the indoor aerosol concentration depends on concentration gradients between outdoor and indoor environments, the strength of indoor sources, and the removal ability of the building envelope or filters in the supply or ventilation airflow. In spaces such as offices or classrooms or residences under certain conditions, when indoor sources are weak such that the aerosol burden is due to the ambient air, increasing outdoor-AERs increases the aerosol concentration indoors, as well as affects aerosol size distribution (El Orch et al., 2014; Rackes and Waring, 2013). Conversely, residences typically have stronger indoor sources, e.g. from cooking or candle burning (Wallace, 2006), so higher outdoor-AERs can have a mitigating effect on the indoor size distribution.

Fig. 3 is a schematic representation of the overall outcome of the analysis of the indoor versus outdoor origin of indoor particles.

4.1. Homes

Based on the studies included in the analysis it can be concluded that overall, the main origin of home PM_{10} and $PM_{2.5}$ is outdoor air. This means that indoor sources of these particle mass fractions are not as significant compared to the outside concentrations, and that increased ventilation (without filtration) can lead to increase in indoor concentrations and exposures. Control of exposure therefore requires that focus is placed on outdoor PM_{10} and $PM_{2.5}$ of the urban environment surrounding homes, and particularly on any local sources of the particles. However it should be noted that decreased ventilation may lead to accumulation of gas-phase pollutants of indoor origin which may initiate and enhance indoor chemistry, which should be avoided. By contrast, the main drivers of home PN are indoor sources, which mean various combustion processes and also secondary particle formation. While increased ventilation help in removing these particles outside, the primary focus should be in controlling emissions from the indoor PN sources. It should be noted that the number of studies reporting particle concentrations in offices and day care centres were very limited.

4.2. Schools and day care centres

Contrary to home environment, indoor sources are the main drivers of PM_{10} and $PM_{2.5}$ concentrations, while outdoor air, of PN concentrations. Studies pointed out to dust re-suspension in these facilities as the main reason for elevated particle mass concentrations, and outdoor traffic, often school related, of PN concentrations from vehicle emissions. The most obvious control measure to reduce particle mass is increase in overall cleanliness of the schools and prevention of dust ingress in the first place, by, for example, requirement of changing shoes when entering the classrooms. Locating school buildings away from busy arterial roads and anti-idling regulations in the proximity and within the school grounds are measures to reduce school PN exposures.

4.3. Offices

Outdoor air is the source of all three particle size fractions, and in general office air is cleaner than home or school indoor air.

4.4. Aged care facilities

With only three studies reporting on indoor air quality in these facilities, and each presenting different findings, it is not possible to draw general conclusions as to exposure routes of the residents. Considering that elderly are more susceptible to air pollution than younger adults, and that they spend more time indoors, there is a clear need to better understand the main routs of exposure in such facilities.

Of importance also is to note is that concentrations reported for the key indoor environments are often above the World Health Organization (WHO) guidelines. This is the case in general for indoor PM_{10} and $PM_{2.5}$ 24 h mean concentrations, which often exceed the 24 h WHO guideline value of 50 and 25 μg m^{-3}, respectively (WHO, 2005). School indoor $PM_{2.5}$ exceed the WHO 24 h guidelines (remembering of course, that children do not spend 24 h at school), and school PM_{10} exceeds the WHO annual guideline value. By contrast, PM values in offices are in general below the guideline values; however, since the outdoor particles are the main contributor to the office indoor particle concentrations, there may be situations when the impacts of the outdoor air are significant, especially during high pollution episodes, fires, or dust storms. For example, WHO $PM_{2.5}$ 24-hour guideline concentration value (25 μg m^{-3}) was exceeded for offices in China and Turkey (winter only) due to very high outdoor $PM_{2.5}$ concentrations (62 to 151 μg m^{-3}). Therefore, meteorological conditions and office

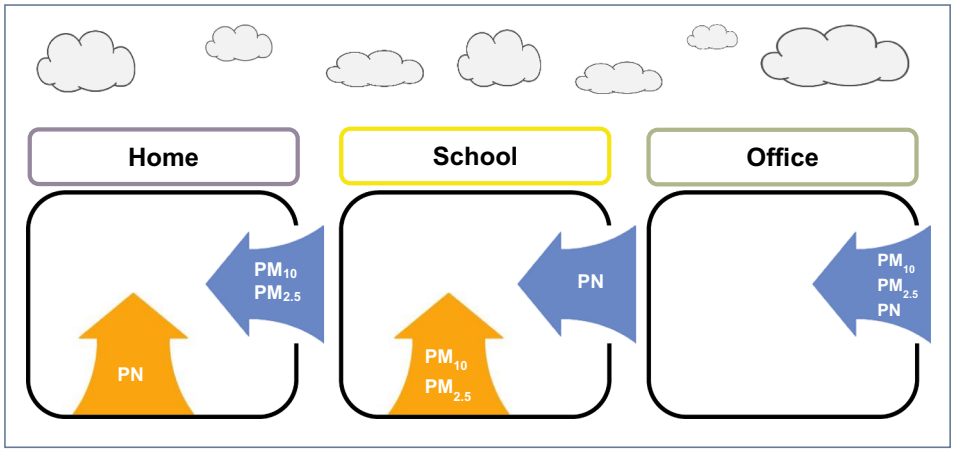

Fig. 3. Schematic representation of the overall outcome of the analysis regarding the indoor source versus outdoor origin of indoor particles. e.g. dominating processes influencing the concentrations in given environments. It should be kept in mind that the illustrated processes are not the only ones to be taken into account for efficient indoor particle concentration control strategy.

building location and orientation within the urban environment have an impact on office particle concentrations.

It should be stressed that the main limitation of the inter-comparison conducted, and the general conclusions derived, is that there are still relatively few studies reported for even the key indoor environments. Further, the studies were conducted using different instruments and/or designs making it difficult, or in fact impossible in many cases, to compare the results obtained or to conduct comparative exposure analyses. Thus it is of high importance that more studies on indoor particulate matter, and in general, on indoor air pollution are conducted in the future to close the existing knowledge gaps, and that the future studies are conducted according to standardized protocols, which would enable inter comparisons between the studies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2017.07.025.

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