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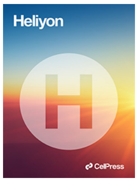

Review article

A systematic literature review on indoor $PM_{2.5}$ concentrations and personal exposure in urban residential buildings

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ABSTRACT

Particulate matter with an aerodynamic diameter less than 2.5μm ($PM_{2.5}$) is currently a major air pollutant that has been raising public attention. Studies have found that short/long-term exposure to $PM_{2.5}$ lead detrimental health effects. Since people in most region of the world spend a large proportion of time in dwellings, personal exposure to $PM_{2.5}$ in home microenvironment should be carefully investigated. The objective of this review is to investigate and summary studies in terms of personal exposure to indoor $PM_{2.5}$ pollutants from the literature between 2000 and 2021. Factors from both outdoor and indoor environment that have impact on indoor $PM_{2.5}$ levels were explicated. Exposure studies were verified relating to individual activity pattern and exposure models. It was found that abundant investigations in terms of personal exposure to indoor $PM_{2.5}$ is affected by factors including concentration level, exposure duration and personal diversity. Personal exposure models, including microenvironment model, mathematical model, stochastic model and other simulation models of particle deposition in different regions of human airway are reviewed. Further studies joining indoor measurement and simulation of $PM_{2.5}$ concentration and estimation of deposition in human respiratory tract are necessary for individual health protection.

1. Introduction

In past several decades, epidemiologic studies have found striking health threating incidents with short/long-term exposure to particulate matter (PM) (Abdullahi et al., 2013; Achilleos et al., 2017; Oh et al., 2019). Exposure to PM could cause occurrences of morbidity and substantial losses of life documented in numerous literatures. As such, inhalation of PM represents a significant exposure pathway for humans for its penetration deeply into the lungs, causing respiratory and circulatory system diseases (Monn, 2001; Hänninen et al., 2010; Anderson et al., 2012; Mölter et al., 2013; Steinle et al., 2013; Zaatari and Siegel, 2014; Mentese et al., 2015; Sánchez-Soberón et al., 2015; Wyzga and Rohr, 2015; Xu et al., 2016; Achilleos et al., 2017; Chen et al., 2017; Kastury et al., 2017; Li et al., 2017b). Aerosol particles with different sizes ranging from a few nm to 10μm deposit in respiratory system. As shown in Figure 1, invasion depth of particles is inversely proportional to the diameter of particles. Particles >11.0μm are mostly captured by the nasal mucosa, thus rarely access to human respiratory system. Particles entering into the respiratory system of body usually have a diameter of <7.0μm. Of them, particles ranging from 7.0μm to 3.3μm deposit in the upper and lower trachea airway. Particles <3.3μm are easy to penetrate into the bronchial airways. More seriously, particles at 1.1μm–0.65μm have the potential of approaching to the pulmonary alveoli, moving to each part of body through blood circulation, in that sense, causing serious health outcomes. Therefore, it is clear that $PM_{2.5}$ (particulate matter with an aerodynamic <2.5μm) suspended in air penetrate into human body through respiratory tract (Sánchez-Soberón et al., 2015; Achilleos et al., 2017; You et al., 2017; Zwozdziaka et al., 2017; Hwang and Lee, 2018).

$PM_{2.5}$ has been of great attention in public concerns, which derives from epidemiological studies for adverse effects to human beings as well as from toxicological and clinical studies (Logue et al., 2011; Li et al., 2016; Sundell, 2017). In past decades, abundant studies have been conducted on outdoor ambient $PM_{2.5}$ and its various adverse health outcomes (Li et al., 2017a,b). Outdoor $PM_{2.5}$ concentrations are widely studied for particle control and population health protection, especially in areas with heavy busy traffic and with significant sources in outdoor environment (Sánchez-Soberón et al., 2015). In last two decades, researchers in all over the world made investigations on chemical

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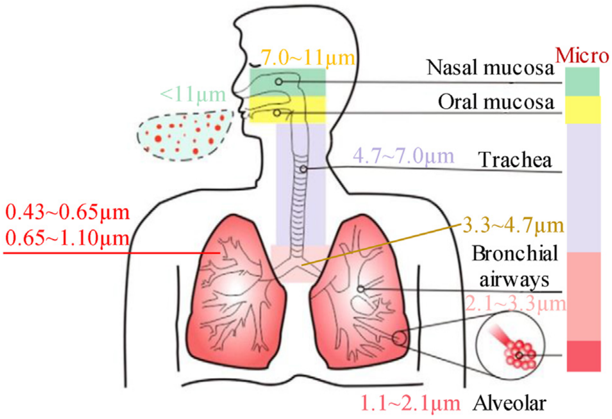

Figure 1. Schematic of human respiratory system and deposition of particle adapted from You et al. (2017).

composition, source apportionment and health outcomes in both ambient atmosphere and indoor environment. There are also indoor $PM_{2.5}$ studies concerned concentration level, spatial distribution and personal exposure in various microenvironments (Steinle et al., 2013). However, as listed in Table S1, urban people in most part of the world spent more percentage of time (from 60% to 90%) staying in indoor environment than outdoors. Meanwhile, the increasingly degradation of indoor air quality from particle pollution leads to much more public attention to indoor $PM_{2.5}$ recent years. Moreover, less studied are health effects of indoor $PM_{2.5}$ modifying factors such as type of indoor microenvironment, time-activity, exposure duration, individual physical characteristics and so forth (Hänninen et al., 2017; Lazaridis et al., 2017).

Traditionally, personal exposure data are obtained from ambient pollutant concentrations through outside monitoring sites in a large-scale population group rather than focuses on each individual in a small scale (Steinle et al., 2013). However, real $PM_{2.5}$ health effect varies with the microenvironment experienced by each individual rather than those recorded by outdoor air quality monitors. This traditional practice of measurements from ambient air monitoring sites as personal exposure surrogate in population have been challenged for individual health impact. As such, epidemiologic studies have consistently recommended $PM_{2.5}$ as a risk factor for adverse health effects (Zhou et al., 2018). As real health impact actually originated from personal exposure rather than from ambient concentration monitoring value, exposure plays an important role in adverse health effect explanation. Compared with general people, the susceptible population group (such as the elders, the sick, and pregnant) spend larger percentage of time (mostly more than 90%) in indoor environment. Therefore, personal exposure to $PM_{2.5}$ in indoor environment should be given much more attention as well as for the susceptible population groups.

The orientation of this review article is to offer summary literatures on personal exposure to $PM_{2.5}$ in urban dwellings. This article includes papers published from year of 2000–2021 relating to this topic. Specific search terms and study selection are illustrated in the second part to summarize development and current situation of personal exposure to $PM_{2.5}$ in urban dwellings. In the third part, factors affecting indoor $PM_{2.5}$ concentration, level as well as measurements and models are carefully investigated. The following part is personal exposure in terms of determinants factors and exposure models, including individual activity pattern behavior and microenvironment personal exposure model.

2. Literature search and selection

This literature review was collected from electronic databases in Web of Science, Google Scholar, and online publisher source of Elsevier, ScienceDirect, Springer, Wiley Online Library, SAGE publishing between January 2000 and December 2021. Articles were searched by applying the following criterion terms: "indoor air quality", "$PM_{2.5}$" and "home" for literature investigation. Based on title and abstract of literature, studies that (1) are not in urban, (2) are not in residences, and (3) are duplicates, were excluded. After full-text screening, studies that (1) are not accessible to indoor $PM_{2.5}$ mass concentration, (2) are for specific indoor activities (cooking, vacuuming, sweeping, making folds, etc. were excluded. Considering that kitchens in urban residential buildings are usually associated with rooms, sampling sites in kitchen, living room and bedroom were retained. In addition, "personal exposure", "microenvironment", "exposure model" for exposure studies, and "deposited dose", "dose simulation", "human respiratory tract" were searched for individual inhalation. However, the following specific term that contains "cardiopulmonary or cardiovascular disease", "ambulatory or arterial blood pressure", "autonomic and vascular dysfunction", "oxidative stress", "systemic inflammation response" were not included in this literature review. As such, "source apportionment", "chemical species or composition" and "risk assessment", "risk management", "exposure assessment" of $PM_{2.5}$ are neither not included.

11524 studies were obtained before searching criteria. After two rounds of screening, only 210 studies were chosen, as shown in Figure 2.

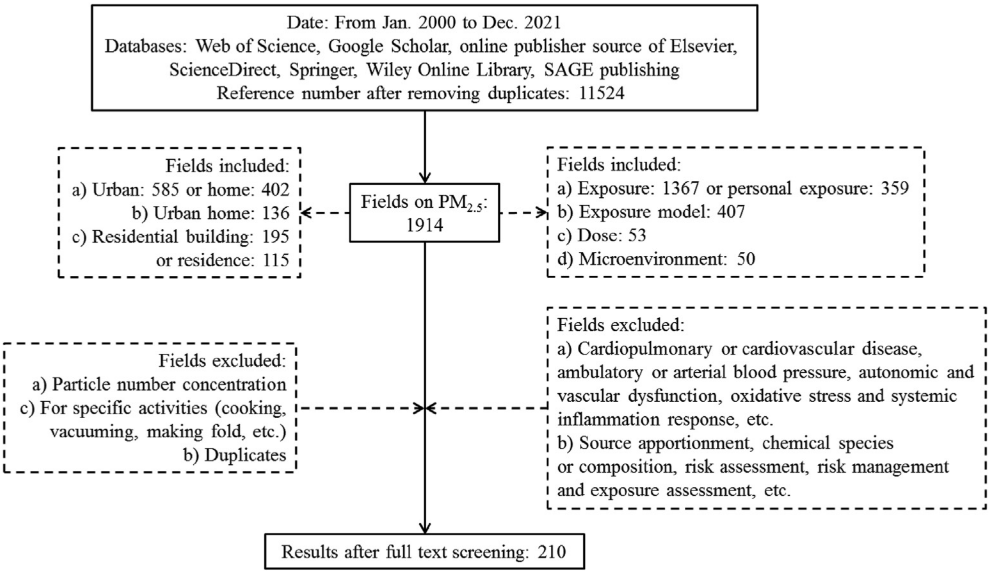

Figure 2. Flow chart of literature search and selection based on Page et al. (2021a and 2021b).

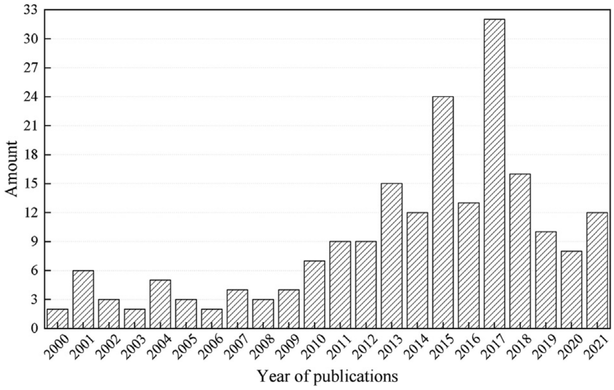

Figure 3. The amount of references in literature review.

Supplement valuable studies from references of these articles were also searched with inspection of titles and abstracts. Then these potential papers were looked through entirely, and relevant parts were inspected carefully to make sure whether they were suitable for collection as references in this literature review.

The amount of references in literature review is depicted in Figure 3. Collected paper per year before 2010 is less than six references. After year of 2010, the amount increases dramatically with peak of more than 30 in year of 2017. Study on $PM_{2.5}$ in residential buildings has given more and more attention in recent years.

3. Indoor $PM_{2.5}$

3.1. *Sources of indoor $PM_{2.5}$*

Several studies indicate that indoor PM can be attributed to both outdoor and indoor sources (Riley et al., 2002; Lim et al., 2011; Shrubsole et al., 2012; McGrath et al., 2014a,b; Serfozo et al., 2014; Chatoutsidou et al., 2015; Ranasinghe et al., 2015; Zauli Sajani et al., 2015; Zhao et al., 2015; Li et al., 2016, 2017b; Xu et al., 2016; Shi et al., 2017; Ye et al., 2017; Zhang et al., 2020). Indoor particles consist of transportation of outdoor origin $PM_{2.5}$ into indoors, primary emission from indoor sources and indoor secondary organic aerosols (SOA) that are the products of oxidative reactions with reactive organic gases (Ji and Zhao, 2015; Hodas et al., 2016).

As shown in Figure 4, indoor PM concentration level is affected by source emissions (such as cooking fume, fuel combustion, smoking and burning incenses), outdoor infiltration and penetration, indoor activities of occupants (vacuuming to clean room and walking) and SOA. The formation of SOA from reactions between oxidants and gas-phase compounds can also have impact on indoor $PM_{2.5}$ levels. Other parameters such as deposition effect and the external/internal air exchange could also affect the indoor PM concentration (Monn 2001; Lai et al., 2006; Géhin et al., 2008; Kornartit et al., 2010; Wan et al., 2011; Shrubsole et al., 2012; Abdullahi et al., 2013; Morawska et al., 2013; McGrath et al., 2014a,b; Serfozo et al., 2014; Ciuzas et al., 2015; Logue et al., 2015; Zauli Sajani et al., 2015; Ji and Zhao, 2015; Deng et al., 2017; Hussein, 2017; Li et al., 2017b). Latest research showed that $PM_{2.5}$ level in smoking area was significantly higher than that in non-smoking area and outdoor environment. The $PM_{2.5}$ concentration in heating season was dramatically higher than that in non-heating season. Personal exposure duration of high $PM_{2.5}$ concentration level in houses that facilitated clean energy applications was less than that in houses using coal and biomass fuel (Li et al., 2017b). Wang et al. (2017) concluded that PM concentrations were between 0.14 and 24.46 mg/cm^3 for various cooking emissions.

3.1.1. *Indoor origins*

Cooking-generated particles have been considered as the most remarkable indoor particle pollutants (Monn 2001; Lai 2004; Lim et al., 2011; Wan et al., 2011; Rim et al., 2012; Shrubsole et al., 2012; Abdullahi et al., 2013; Gao et al., 2013a,b,c; McGrath et al., 2014a,b; Poon et al., 2016; Amouei Torkmahalleh et al., 2017; Cao et al., 2017; Sharma and Jain, 2019). Cooking fume contains harmful substances suspended in the air with gaseous or particulate form. Exposure to high-concentration $PM_{2.5}$ can pose a direct health hazard to the homemakers who are subjected frequently to PM emissions during cooking. Du et al. (2017) measured the fume exposure during a typical Chinese domestic cooking process, reporting the $PM_{2.5}$ mass concentration ranging from 0.02 to 6.25μm in the breathing zone was 10.97 ± 9.53 mg/m^3 under normal ventilation situation, and insufficient exhaust of hood resulted in higher exposure level reaching 32.26 ± 31.18 mg/m^3. In addition, the vulnerable population group (particularly for infants, the very young children, the elders and the chronically ill) have a potential access to the pollutant (Zhang and Zhao, 2007; Shimada and Matsuoka, 2011; Chowdhury et al., 2012; Abdullahi et al., 2013; Li et al., 2017a; Wang et al., 2017; Martinez Vallejo et al., 2021). Cooking was investigated in terms of source emission and personal exposure. Large amount of investigations on PM emission during cooking were conducted from different viewpoints (Lai and Chen, 2007; Abdullahi et al., 2013; Gao et al., 2013a,b,c; Amouei Torkmahalleh et al., 2017; Wang et al., 2017), such as $PM_{2.5}$ concentrations during cooking in residential kitchen (Clark et al., 2010; Wan et al., 2011; Devakumar et al., 2014; Li et al., 2017b; Wang et al., 2017); particle concentrations and size distribution of cooking $PM_{2.5}$ (Yu et al., 2015; Patel et al., 2020). With respect to personal exposure, there are some research about exposure of homemaker and its potential health risk (Amouei Torkmahalleh et al., 2017; Cao et al., 2017; Du et al., 2017). However, there is little investigation on influence of other susceptible individuals in dwellings as the pollutant have access to them through airflow between the source and other room.

In addition, tobacco smoking is also one of the greatest indoor $PM_{2.5}$ sources that lead to a considerable increase in number/mass concentrations of indoor particles (Lim et al., 2011; Du et al., 2012; Shrubsole et al., 2012; Al-sarraf et al., 2013). Smoking of tobacco can temporarily raise local $PM_{2.5}$ concentrations up to 1000 mg/m^3 (Das et al., 2013). Li et al., 2016 figured the daily $PM_{2.5}$ concentrations were 137 ± 49 $\mu g/m^3$ in kitchen and 118 ± 51 $\mu g/m^3$ in bedroom respectively at the presence of smokers in dwellings. Sánchez-Soberón et al. (2015) figured indoor concentrations are highly affected by indoor human activities, reporting that mean $PM_{2.5}$ concentrations of 7.3 $\mu g/m^3$ with no emission sources that were up to 296 $\mu g/m^3$ when six cigarettes smoking exists, 289 $\mu g/m^3$ due to frying and 326 $\mu g/m^3$ as an incense stick burning.

3.1.2. *Outdoor infiltration and penetration*

Outdoor $PM_{2.5}$ stems from natural sources, vehicular exhaust emission (gasoline and diesel), biomass or fossil fuel combustion, industry activities (mining and smelting) and chemical reaction of primary particles in atmosphere (Monn, 2001; Abdullahi et al., 2013; Leung, 2015; Sánchez-Soberón et al., 2015; Li et al., 2017b; Zhao et al., 2021). The

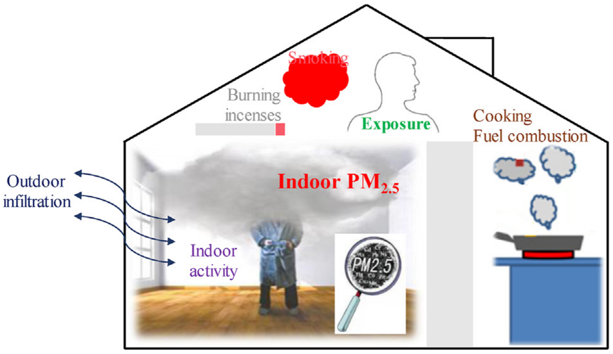

Figure 4. Sketch of indoor $PM_{2.5}$ source and exposure adapted from Li et al. (2017b).

contribution of outdoor PM source to the indoor PM level remains remarkable in comparison with indoor PM source. Due to air exchange between indoors and outdoors, chemical component of indoor $PM_{2.5}$ is associated with both indoor PM sources and outdoor sources (Monn, 2001; Abdullahi et al., 2013; Huang et al., 2015a, 2015b; Li et al., 2017b; Hossain et al., 2021; Liu et al., 2021). Leung (2015) found that the infiltration of outdoor air into buildings is an important factor in exposure assessment indoors. Air exchange rate (AER) is a key determinant in the infiltration of particle pollution in indoor residential environment. Baxter et al. (2016) concluded that AER varied widely in different urban areas due to diversities in building characteristics, seasonal meteorological conditions, and occupant behaviors such as the application of air conditioning or opening windows.

3.1.3. Other factors on indoor $PM_{2.5}$

Indoor $PM_{2.5}$ level has also relation with many other factors including building characteristics, housing location, outdoor meteorological parameters and seasonal variation, all of which influence the personal exposure to indoor $PM_{2.5}$ (Lai et al., 2006; Kornartit et al., 2010; Wan et al., 2011; Shrubsole et al., 2012; Abdullahi et al., 2013; Morawska et al., 2013; McGrath et al., 2014a,b; Ciuzas et al., 2015; Logue et al., 2015; Zauli Sajani et al., 2015; Li et al., 2017b; Abdel-Salam, 2021b). Li et al. (2017a) pointed that personal exposure to $PM_{2.5}$ in winter is much higher than that in summer. Inter-zonal airflows within dwellings strongly influence spatial variation of pollutant concentrations and personal exposure. Li et al., 2016 noticed that indoor $PM_{2.5}$ in different microenvironments varied significantly. A study in northwest Chinese residents demonstrated that the average $PM_{2.5}$ concentrations were 125 ± 51 $\mu g/m^3$ in kitchen and 119 ± 64 $\mu g/m^3$ in bedroom during heating season, 80 ± 67 $\mu g/m^3$ and 80 ± 50 $\mu g/m^3$ during non-heating season, respectively. Hänninen et al. (2017) pointed that for most general population, indoor exposures are dominant for exposure to PM. Butler and Madhavan (2017) pointed out that it is important to explore the contribution of ambient pollution outdoor and indoor sources to exposure indoors. It is also necessary to understand the amount of the exposure is under control by human, and the equilibrium in obtaining exposure reduction if people are to take effective actions. Indoor PM levels in developing countries are much higher than in developed countries owing to the less improvement in technology for activities in household and the rare application of cleaner fuels for cooking and heating (Abdullahi et al., 2013). Hwang and Lee (2018) figured that personal exposure to $PM_{2.5}$ could differ with season which was greater during winter compared with indoor and outdoor concentrations in residence. Greater PM concentrations during heating season was observed compared to non-heating season. The mean $PM_{2.5}$ exposure value was 27.8 ± 21.4 $\mu g/m^3$ in summer and 36.9 ± 28.7 $\mu g/m^3$ in winter in the population.

3.2. Standards of indoor $PM_{2.5}$

Limit $PM_{2.5}$ values have been set up for public human health protection. In 1997, US EPA developed a $PM_{2.5}$ concentration standard to control health effects. Following in 2013, revised annual $PM_{2.5}$ threshold value was in lowering the $PM_{2.5}$ concentration from 15 $\mu g/m^3$ to 12 $\mu g/m^3$ and a 24-hour standard of 35 $\mu g/m^3$ by the National Ambient Air Quality Standards. The European Union regulated an annual of 25 $\mu g/m^3$ and three years of 20 $\mu g/m^3$ in Air quality standard for $PM_{2.5}$ mass concentration (Wyzga and Rohr, 2015; Oprea et al., 2017). In China, the study of $PM_{2.5}$ is relatively later. Previous standards only provided limit value for PM_{10}. With the publishing of the Standard of the Measurement and Evaluation for Efficiency of Building Ventilation in 2013, that limits the daily average concentration of indoor $PM_{2.5}$ to <75 $\mu g/m^3$. The latest standard of ASHRAE62.1–201 released by the United States provides with a concentration <15 $\mu g/m^3$ for indoor $PM_{2.5}$ (Li et al., 2017a,b). However, McGrath et al. (2017) referred that there is also a link between short/long-term $PM_{2.5}$ exposures and mortality incidences under $PM_{2.5}$ concentration limits, such as the revised U.S. EPA standards and the European limits. There are no studies about identifying a threshold value below which individual suffered from adverse health effects.

Table 1. Standards and value of WHO, the United States, Directive 2008/50/EU and China for $PM_{2.5}$ ($\mu g/m^3$) adapted from Li et al. (2017b), Martins and Carrilho da Graça (2018).

		Annual mean concentration	24-h mean concentration
WHO	Air quality guideline	10	25
	Interim target-1	35	75
	Interim target-2	25	50
	Interim target-3	15	37.5
The United States[a]	Primary standards	12	35
	Second standards	15	35
Directive 2008/50/EU	Limit value	25	–
	Target value	20	–
China[b]	Primary standards	15	35
	Second standards	35	75

[a] Primary standards of the United States directed at public health protection, and second standards directed at social material wealth protection.

[b] Primary standards of China is aimed at nature reserves, scenic spots that are in need of special protection, and second standards is aimed at residential areas, commercial areas, transportation, cultural areas, industrial areas and rural areas.

Table 1 illustrates the $PM_{2.5}$ limit value of WHO, United States, European Union and China, including air quality guidelines of WHO and interim targets, $PM_{2.5}$ mass concentration limits in America national ambient air quality standards in 2012 and GB 3095-2012 of China. The table presented that WHO Air Quality Guideline was the strictest in all the standards, followed was the European Union. The table also showed that orientations of America and China were below WHO Interim target-1. Moreover, second standard of China was the same as WHO Interim targets-1, indicating that $PM_{2.5}$ limit value in China lagged behind America and WHO (Li et al., 2017b).

4. Personal exposure to $PM_{2.5}$

Exposure is defined as the contact of the substance in an environment. Personal exposure is defined as "person is present, and at the same time the concentration is present at the same location" (Dimitroulopoulou et al., 2001a,b; Kruize et al., 2003; Kornartit et al., 2010; Schembari et al., 2013; McGrath et al., 2017). The adoption of this term highlights that individual is the most important receptor of pollutant. This is a definition of a momentary contact between individual and pollutant. The term "average exposure" refers to the integrated exposure divided by the specified time. When considering the duration of exposure, the outcome is an "integrated exposure" by integrating the concentration (Monn, 2001; Shimada and Matsuoka, 2011; Steinle et al., 2013).

Personal exposure is sensitive to the individual activity pattern and interpersonal variability (Morawska et al., 2017; Mazaheri et al., 2018; Yang et al., 2019; Nazaroff, 2021). Personal exposure studies originate from population group in 1980s in the United States, and then spread to Europe countries and other part of the world. $PM_{2.5}$ concentration in the microenvironment can be determined through measurement or through application of various modelling techniques (e.g., multiple liner regression, mass balance equation) (Mölter et al., 2012; Hwang and Lee, 2018). Personal exposure measurements are considered as the best practice in actual exposure estimation. However, they are not feasible for its high costs or overburden to participants reported in many studies (Mölter et al., 2012). Consequently, many studies use indirect methods (such as mathematical models) to estimate exposure.

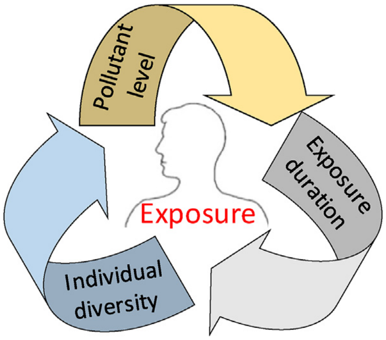

Figure 5. Key aspects influencing personal inhalation exposure to indoor $PM_{2.5}$.

4.1. Determinants on exposure to $PM_{2.5}$

It is obvious that factors influence personal inhalation exposure to $PM_{2.5}$ are the pollutant level, exposure duration and individual activity diversity shown in Figure 5 (Dimitroulopoulou et al., 2001a,b; Kornartit et al., 2010; Schembari et al., 2013; Hwang and Lee, 2018). Different individual activity profiles lead to various personal exposures. Numerous studies stressed variation of personal exposure as individuals move through a range of different microenvironments. The diversity of individual physiological state could have different impacts on personal exposure (Brian Broderick et al., 2015). Better understanding of personal inhalation exposure to $PM_{2.5}$ and their relationships to influence factors of exposure indoors are therefore imperative to the epidemiological studies as well as to create policies for efficient risk reduction (Kruize et al., 2003; Schembari et al., 2013). The residential environment is of great importance that determines the extent of personal exposure to $PM_{2.5}$, especially for the susceptible individuals (Nasir and Colbeck, 2013).

Studies have shown that personal inhalation exposure to particles vary by human activity. Different individual activities affect the timing, location and degree of exposure (Klepeis et al., 2001; Schweizer et al., 2007; Hwang and Lee, 2018). Shimada and Matsuoka (2011) estimated indoor $PM_{2.5}$ concentrations of personal exposure in developing countries and found that children and unemployed women suffered the highest exposure. A reasonable explanation is that these group of people stay much more time indoors than other population groups. McGrath et al. (2017) investigated the personal exposure to $PM_{2.5}$ in seven regions of Europe, reporting that more than 90% of the variance originated from diversity between subjects rather than between cities. Therefore, individual activity patterns should be taken into consideration in epidemiological analyses, personal exposure study and assessment.

Exposure can be measured or modeled with direct or indirect method (Kruize et al., 2003). Investigation methods of individual activity pattern and behavior are given in Table 2, including sampling or measurement, time-microenvironment-activity diary (TMAD), questionnaire and video record. Measurements were widely conducted in Africa (Abdel-Salam, 2013, 2015, 2021a), North America (Miller et al., 2009; Colton et al., 2014; Wang et al., 2016a; Singer et al., 2017; Singleton et al., 2017; Jeong et al., 2019), Europe (Derbez et al., 2014, 2018; Meier et al., 2015; Wyss et al., 2016; Salis et al., 2017; Ścibor et al., 2019) and Asia (Li and Chen, 2003; Cao et al., 2005; Massey et al., 2009, 2012; Yassin et al., 2012; Gurley et al., 2013; Sidra et al., 2015; Fan et al., 2016, 2018; Han et al., 2016; Wang et al., 2016b, 2018; Zhou et al., 2016; Shao et al., 2017; Weaver et al., 2017; Huang et al., 2018, 2019; Liu et al., 2018, 2020; Tang and Wang, 2018; Tong et al., 2018; Lawrence et al., 2019; Liu et al., 2020; Xue et al., 2020; Algari et al., 2021; Shen et al., 2021; Tran et al., 2021). However, direct measurements of personal exposure is hard to conducted, because it is expensive, labor intensive, invasive, and applicable only to samples (Dimitroulopoulou et al., 2001a,b; Kruize et al., 2003; McGrath et al., 2014a,b). However, TMAD study has become necessary component in exposure assessment and risk management. Moreover, a summary of some researches on personal exposure to air pollutants are summarized in Table S2.

4.2. Personal exposure models

Computational or mathematical modeling is recognized substitute for sampling or measurement in personal exposure evaluation (Table S3) (Dimitroulopoulou et al., 2001a,b; Kruize et al., 2003; McGrath et al., 2014a,b). McGrath et al. (2017) figured that although a number of models have been used to predict indoor pollutant concentrations, few studies have focused on predicting personal exposure in the residential environment. Meanwhile, limitations in physical pollutant models resulted in poor performance on estimation of indoor air pollutant exposure.

4.2.1. Microenvironment model

Duan introduced the term of “micro environments (MEs)” in 1982, which is defined as the “chunk of air space with homogeneous pollutant concentration” (Monn, 2001). The total average exposure (X) can be defined as Eq. (1).

$$X = \frac{\sum X_i t_i}{\sum t_i} \tag{1}$$

Where, X_i is the total exposure in the ith ME for a time interval t_i.

If the number of different MEs is J, integrated personal exposure (E) (Figure 6) can be calculated through Eq. (2).

$$E = \frac{\sum_{j=1}^{J} C_{ij} T_{ij}}{\sum t_{ij}} \tag{2}$$

Where, C_{ij} is the pollutant concentration in jth ME in which the individual stays during period t_{ij}.

An indirect way of modeling personal exposure is to use a micro environmental model. Dimitroulopoulou et al. (2001a,b) described a

Table 2. Methods of investigation on individual activity pattern and behavior (Wang et al., 2017).

Method	Advantage	Disadvantage	Application situation	Conduct
Sampling or measurement	More accuracy on data	Effected by GPS signal when recording the precise position	Low popularization and a new orientation	GPS, products such as activity trackers and smartwatches
Questionnaire	Simple, intuitive, directly, suitable for large-scale investigation	More subjectivity, coordinate, random error on uncertainties such as recalling bias	The most common approach in conducting individual activity investigations	Make record anytime and remember to fill out
Time-microenvironment-activity diary (*TMAD*)	More accuracy than questionnaire	Operation complexity, keep a diary anytime and recalling bias	One of the most common approach in conducting individual activity investigations in foreign countries	Telephone interview, survey in household
Video record	Present actually behavior of survey respondents	Cameraman might give perplex to the survey respondents	Infant In common use	With camera

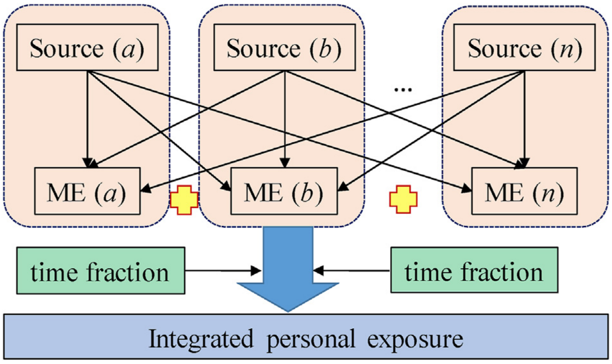

Figure 6. Concept of calculating personal exposure using time-activity data and pollutant levels in MEs.

modelling approach combining the description of physical processes and individual movement for personal NO_2 exposure prediction. However, this model does not associate ME concentrations with individual activity patterns, which is the most important determinant in exposure studies. This approach is unable to separate the role of indoor/outdoor sources, or to predict the effects of different indoors/outdoors emission rates. Afterward, Dimitroulopoulou et al. (2006) developed ME models to calculate indoor concentrations referring to building basic parameters, ambient concentrations, indoor source strength and pollutant physical properties. However, most of these models take only one pollutant into consideration with a deterministic approach.

4.2.2. Mathematical model

(1) *INDAIR*-Indoor Air model

Dimitroulopoulou et al. (2001a,b) first reported the outcomes of a deterministic two-compartment model in personal NO_2 exposure prediction. The model consists of two compartments as shown in Figure 7. Dimitroulopoulou et al. (2006) developed this model to Indoor Air (*INDAIR*) model further, which is a probabilistic model. This probabilistic model can predict the frequency concentration distributions as much as four kinds of air pollutants simultaneously. In the *INDAIR* model, three MEs (kitchen, lounge and bedroom) for the residential environment are involved as an extension of the two-compartment model developed (Dimitroulopoulou et al., 2001a,b). The developed *INDAIR* model was applied in providing inputs into a probabilistic exposure model for exposure assessment and policy evaluation. However, the *INDAIR* model has limitations that only two indoor sources are included. The omission of the established impact of re-suspension leads to underestimation of indoor concentrations (Dimitroulopoulou et al., 2006).

Terry et al. (2014) depicted a model called *INDAIR-CHEM* that combines a personal exposure model with a detailed chemistry model. *INDAIR-CHEM* links emissions of the major pollutants indoors with potential adverse health effects. Dimitroulopoulou et al. (2017) describe a state-of-art model titled *INDAIR-2/EXPAIR* that provides personal exposure frequency to NO_2 distribution prediction.

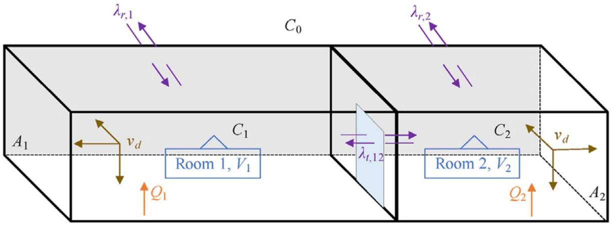

Figure 7. Diagrammatic representation of *INTAIR* model originated from Dimitroulopoulou et al. (2001a,b).

(2) *EXPAND*-Exposure model for Particulate matter and Nitrogen oxides

A mathematical model was developed for the determination of exposure to air pollution in an urban area by Soares et al. (2014). The deterministic modelling system titled Exposure Model for Particulate Matter and Nitrogen Oxides (*EXPAND*) that combines predicted concentrations, personal activity data and the position to assess the spatial and temporal variation of average urban population exposure to outdoor pollution in different microenvironments. The revised model can also be used for intake fraction predictions for various pollutants, source categories and population subgroups.

(3) *IAPPEM*-Indoor Air Pollutant Passive Exposure Model

Based on the *INDAIR* model developed by Dimitroulopoulou et al. (2006), the model titled Indoor Air Pollutant Passive Exposure Model (*IAPPEM*) is an advanced probabilistic model, which has the capacity to evaluate the contribution of both indoor and outdoor PM sources to indoors, including estimating personal PM exposure in a range of different microenvironments. Previous study has already illustrated that the effectiveness of *IAPPEM* in predicting indoor PM concentrations in a residential environment. McGrath et al. (2014a,b) pointed that the *IAPPEM* overcomes previous limitations in physical pollutant models, considering the assessment of variations in air pollutant concentrations due to variations and uncertainty in input parameters. McGrath (2014) and McGrath et al. (2017) combined of a physical pollutant model *IAPPEM* with a time-activity profile to create an air pollutant personal exposure model (Figure 8).

(4) *PALM*-Personal Activity and Location Model

Broderick et al. (2015) proposed the Personal Activity and Location Model (*PALM*) project published in EPA Research Program 2014–2020. This project was prepared by the US EPA, initiated by Trinity College Dublin and National University of Ireland Galway. The *PALM* project investigated methods for modelling an individual's personal exposure to air pollution, taking variations in their activity and location into consideration. The project developed a statistical model of the personal exposure of individuals in Dublin, and an improved version of the *IAPPEM*, aiming at the identification of the significance of indoor air quality for the health of a typical office worker. Differences between mean personal exposure measurements and ambient air quality exposure assessments were confirmed in this study, which provided implications for current policy on air quality management and epidemiological modelling investigations. Other related microenvironment personal exposure models are illustrated in Table S3.

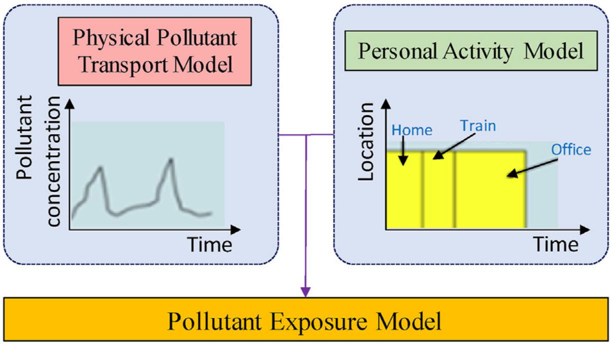

Figure 8. Diagram depicting how a pollutant exposure model is generated from a physical pollutant transport model and a personal activity profile designed from McGrath et al. (2017).

4.2.3. Stochastic model

Probabilistic modelling approaches were also taken to make simulation on personal exposure more accurately compared with conventional time–activity models. A population-based exposure model, Stochastic Human Exposure and Dose Simulation (*SHEDS*) model, applying a probabilistic method to estimate personal exposures for exposure simulation based on outdoor pollutant concentrations, residential AER, infiltration parameters and time spent in various microenvironments through database of activity diaries (Baxter et al., 2016). Derived from the European *EXPOLIS* study, *SHEDS-PM* model was applied to estimate population $PM_{2.5}$ exposure distributions in Philadelphia, PA, USA. For each individual in the simulation, input data were randomly sampled with two-dimensional Monte Carlo input distribution sampling. The predicted output includes inter-individual variability and uncertainty about the predicted population distribution percentile estimation (Burke et al., 2001; Han et al., 2015; Dimitroulopoulou et al., 2017; Hwang and Lee, 2018). As a stochastic model tool, Monte Carlo simulation has been widely used for pollutant concentrations prediction. Monte Carlo simulation was solved with appropriate distribution of multiple influencing factors to obtain indoor contaminant concentration (Johnson et al., 2011; McCreddin et al., 2015; Huang et al., 2018; Ji et al., 2018; Dai et al., 2019). Moreover, a summary of some researches on microenvironment personal exposure models to indoor air pollutant are illustrated in Table S3.

4.2.4. International Commission on Radiological Protection (ICRP) model

The International Commission on Radiological Protection (ICRP) model is the mostly widely used for modeling different size-range particles deposition fraction (DF) from 0.3 to 10 μm in different regions of human airway (Hussein et al., 2015, 2020; Li et al., 2016; Deepthi et al., 2019; Madureira et al., 2020; Mao et al., 2020; Vora et al., 2020; Nzazroff, 2021). However, inhaled deposited dose analysis of indoor aerosols have been given limited attention in many parts of the world (Hussein et al., 2020). Total lung DF and inhalable fraction (IF) was applied by Eqs. (3) and (4). Specifically, DF in three regions: head (HA) region, tracheobronchial (TB) region and alveolar (AL) region were estimated by Eqs. (5), (6), and (7), respectively (Rostami, 2009; Sharma and Jain, 2019).

$$DF = F\left(0.0587 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln d_p)} + \frac{0.943}{1 + \exp(0.503 + 2.58 \ln d_p)}\right) \tag{3}$$

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076dp^{2.8}}\right) \tag{4}$$

$$DF_{HA} = IF\left(\frac{1}{1 + \exp(6.84 + 1.183 \ln d_p)} + \frac{1}{1 + \exp(0.924 - 1.885 \ln d_p)}\right) \tag{5}$$

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)\left[\exp\left(-0.234(\ln d_p + 3.40)^2 + 63.9 \exp\left(-0.819(\ln d_p - 1.61)^2\right)\right)\right] \tag{6}$$

$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)\left[\exp\left(-0.416(\ln d_p + 2.84)^2 + 19.11 \exp\left(-0.482(\ln d_p - 1.362)^2\right)\right)\right] \tag{7}$$

Where d_p is particle size in μm.

4.2.5. Multiple Path particle Dosimetry (MPPD) model

Multiple Particle Path Dosimetry (MPPD) deposition patterns in different parts of the human respiratory tract (HRT), including extrathoracic (ET), tracheobronchial (TB) and pulmonary (PUL) (Hussein et al., 2015; Li et al., 2016; Deepthi et al., 2019; Mao et al., 2020). Dose rate (DR) was calculated for the regional inhaled deposited dose in particle diameter ranging from D_{p1} to D_{p2} in 1h exposure period in Eq. (8) (Hussein et al., 2020).

$$DR = \int_{D_{p1}}^{D_{p2}} V_E \cdot DF(D_p) \cdot n_N^0(D_p) \cdot fd \log(D_p) \tag{8}$$

Where V_E is volume of air breathed, $DF(D_p)$ is DF in a particular region of HRT, $n_N^0(D_p)$ is particle number size distribution (particles/cm^3, i.e., dN/dlog(D_p)) and f is a metric conversion for aerosol concentration.

4.2.6. Computational fluid dynamics simulation (CFD) simulation

Computational fluid dynamics (CFD) simulation can also be applied for calculation aerosol deposition in HRT. CFD simulation consists: (1) establishing physical model and discretized mesh, (2) specifying boundary condition and (3) solving equations for specified geometry. In modeling, lung morphometry, breathing pattern, properties of particles and gas/vapor need to be considered. Detailed information on CFD simulation can be found in Rostami (2009), Hofmann (2011), Hvelplund et al. (2019) and Madureira et al. (2020).

5. Conclusions

Careful investigations were performed on development of knowledge of personal exposure to $PM_{2.5}$ in residential buildings in past two decades. It is confirmed that personal exposure to indoor $PM_{2.5}$ is determined by spending time, concentration in the microenvironment and individual activity diversity. Mathematical methods, including physical model and stochastic model to predict personal exposure in previous researches are analyzed. Questionnaires are always as supplement tools for exposure assessment. ICRP model, MPPD model and CFD simulation are promising tools for estimating particle deposition in human airway but with great challenges.

Factors affecting individual time-activity patterns are still necessary in epidemiological analyses and exposure studies for accurate prediction. As the application of ambient measurement data to predict personal exposure to $PM_{2.5}$ is questionable, knowledge of assessment and prediction of personal exposure to indoor $PM_{2.5}$ need to be improved. Subsequently, more studies on role of indoor $PM_{2.5}$ concentration monitoring and total exposure assessment are encouraged in analysis of personal exposure. Data of actual exposure experienced by population subject to indoor $PM_{2.5}$ are scarce especially in many developing countries. Verifications of modeling approaches on its accuracy are necessary. There is a need for researchers to conduct further study of personal exposure to $PM_{2.5}$ in dwellings, including concentration monitoring and model development, which can have beneficial in personal exposure reduction and assessment.

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Author contribution statement

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Declaration of interests statement

The authors declare no conflict of interest.

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