An overview: PM$_{2.5}$ concentration levels in urban residential buildings during the past two decades

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ABSTRACT

The public has become increasingly aware of the critical effect of fine particle matter (PM$_{2.5}$) on indoor air quality. Urban residents spend more than half of their time at home. Therefore, monitoring PM$_{2.5}$ concentrations in residential settings is critical. This paper presents a review of studies on PM$_{2.5}$ concentrations in the living rooms of urban residential buildings. We included studies measuring indoor PM$_{2.5}$ concentrations across different regions worldwide and then summarized the measured concentrations. Factors contributing to differences in indoor concentrations were identified and explained. The review results revealed that most of the included studies were conducted in Asia and in Europe, and some were conducted in North
America and Africa. Moreover, the mean daily PM$_{2.5}$ concentration ranged from 17.3 $\mu$g m$^{-3}$ in North America to 68.6 $\mu$g m$^{-3}$ in Asia. Factors influencing PM$_{2.5}$ concentrations were as follows: indoor activities, ventilation type and air cleaner (AC) use, building type and performance, ambient environment and season. Smoking and cooking considerably increased PM$_{2.5}$ concentrations in the living rooms, even in measurements conducted over a short time. The use of an AC could reduce indoor PM$_{2.5}$ concentration in an average of 60%. Regarding building type, PM$_{2.5}$ concentration in multifamily apartment buildings had higher PM$_{2.5}$ concentrations than did single-room residences. Moreover, severe outdoor particle pollution increased indoor PM$_{2.5}$ concentrations by up to 142% in low-energy residential buildings.

**Keywords:**

PM$_{2.5}$, concentration, residential building, indoor activity, ventilation, ambient environment

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1 INTRODUCTION

Urban residents spend most of their time in indoor environments. Investigations of people’s activity patterns have indicated that more than half of the time in a day is spent in residential buildings (Kornartit et al., 2010; de Kluizenaar et al., 2017). The National Human Activity Pattern Survey of the United States reported that on average, people spend 16.6 h per day in average in residential buildings (Klepeis 2001). Baxter et al. (2013) observed that people spend 16.98 to 18.05 h per day in residential buildings in New Jersey, the United States. The Canadian Human Activity Pattern Survey indicated that adult Canadians spend 15.83 to 16.0 h per day in homes (Leech et al., 2002, Matz et al., 2014; Matz et al., 2015). According to one exposure assessment study, children spend 16.1 to 17.35 h per day at home in Windsor, Ontario (Van Ryswyk et al., 2014). Moreover, reports indicate that on average, people spend 13.95 h per day at home in seven European cities (Schweizer et al., 2007). In Germany, Belgium and Denmark, people spend approximately 15.7 (Brasche and Bischof, 2005), 15.84 (Dons et al., 2011) and 17.3 h (Bekő et al., 2015) per day at home, respectively. These figures clearly indicate that people spend considerable time in residential buildings. Therefore, special attention should be paid to residential indoor environments.

Air pollution is a key factor influencing residential environments. Among all forms of air pollutants, particle matter (PM) has received the most extensive research attention because of its adverse effects on health (Wu et al., 2018; Zhu et al., 2018). In particular, fine particle matter (PM$_{2.5}$, aerodynamic diameter less than 2.5 μm) causes severe morbidity and mortality because it is easily absorbed by the lungs and distributed throughout the human body (Hofmann 2011; Achilleos et al., 2017; Li et al., 2017). Toxicological and epidemiological
studies have indicated that PM$_{2.5}$ concentrations in various environments are strongly associated with several adverse health outcomes such as respiratory and cardiovascular diseases (Anderson et al., 2012; Wyzga and Rohr, 2015). Regarding urban outdoor environments, Cakmak et al. (2018) analysed the association between exposure to ambient PM$_{2.5}$ and disease-related mortality across Canada; their research indicated that an increase of 10 μg m$^{-3}$ in long-term PM$_{2.5}$ exposure resulted in a hazard ratio of 1.26 for lung cancer mortality. You et al. (2017) evaluated PM exposure and element deposition distributions in the human respiratory system by using data collected alongside a highway in Singapore. Perrone et al. (2013) assessed the chemical composition of PM by using data collected from Italian urban sites. Furthermore, Zwozdziak et al. (2017) estimated the inhaled dose of ambient PM in an urban area of southern Poland, and they reported the PM deposition fractions. Martuzevicius et al. (2008) estimated traffic-induced PM$_{2.5}$ concentrations near major highways in Cincinnati, the United States. Chen et al. (2017) determined the chemical components of regional PM$_{2.5}$ and the corresponding source contributors in Guangzhou, China.

Regarding urban indoor environments, Bai et al. (2020) assessed the health risks of polycyclic aromatic hydrocarbons (PAHs) attached in PM$_{2.5}$ in an office environment. Marta et al. (2019) reported that exposure to PM and PAHs was strongly associated with the risk of asthma, pulmonary infections, and allergies in school children. Chen et al. (2018) also investigated the associations between PM$_{2.5}$ and asthmatic or allergic diseases in Chinese preschool children. In South Asia, exposure to indoor PM emissions from anthropogenic activities engenders considerable health risks (Junaid et al., 2018). Zhao et al. (2019) collected samples of PAHs from cooking emissions for health risk assessment in residential settings. Although numerous
studies have reported the effects of outdoor PM, indoor particles have only recently started attracting research attention (Butler and Madhavan, 2017). Therefore, addressing the problem of indoor PM$_{2.5}$ is crucial.

Building envelopes separate residents from the outdoor environment, leading to an accumulation of indoor particles. Previous reviews have demonstrated that PM$_{2.5}$ pervades in indoor environments. Diaz and Siegel (2018) conducted a review of indoor environment air quality in European and American buildings, and observed that smoking led to high concentrations of PM$_{2.5}$. Morawska et al. (2017) reviewed the exposure pathways of airborne particles of outdoor origin in home, school, office and aged care facility environments. Other scholars have also conducted reviews of air pollutants in office environments (Wolkoff, 2013; Al Horr et al., 2016; Nezis et al., 2019). However, these reviews have neither summarized PM$_{2.5}$ concentrations nor identified the influential factors in urban residences. Additionally, people spend considerable time in residential buildings, especially in the living room. Hence, a thorough investigation of PM$_{2.5}$ concentrations in living rooms is necessary for effective indoor air quality control. Accordingly, we present a review of PM$_{2.5}$ concentrations in urban residential buildings, particularly studies predominantly focusing on the living room. Detailed analyses of the factors influencing PM$_{2.5}$ concentrations are also presented.

2 METHODS

2.1 Search Strategy

In this review, we included studies on PM$_{2.5}$ concentrations in the living rooms of urban home environments over the past two decades. The following search terms were used: “indoor environment” OR “indoor air quality”, “indoor PM$_{2.5}$” OR “indoor fine particulate matter” OR
“indoor particles”, and “urban dwellings” OR “urban residential buildings” OR “urban homes”. The inclusion criteria were as follows: 1) being searchable on the Web of Science Core Collection, 2) being published up to 2020, 3) being written in English, and 4) reporting on PM$_{2.5}$ concentrations in the living rooms of urban homes. Studies reporting on specific health outcomes, source apportionment, or the chemical species or composition of particles were excluded.

2.2 Literature Collection

Data from the selected studies were organized into tables and figures presenting PM$_{2.5}$ concentrations. Fig. 1 illustrates the number of studies selected in this review. In the graph showing the number of publications each year, an increase in the volume of research on this topic can be observed.

![Graph showing the number of publications each year](image)

**Fig. 1.** Reference amount in this review.

3 RESULTS AND DISCUSSION

3.1 Indoor PM$_{2.5}$ Measurements

We found that indoor PM$_{2.5}$ monitoring is predominantly performed with mobile
sampling instruments. Professional devices and low cost sensors are widely used in indoor environment measurements. Professional and accurate instruments are available for real-time monitoring. Particle number concentrations are measured using optical particle counter. Particle size distribution can be monitored by scanning mobility particle sizers. Particle mass concentrations are monitored by tapered element oscillating microbalance, continuous aerosol mass monitor, nephelometer and nanoparticle surface monitor. Moreover, due to the advantage of small dimension and low power demand, use of low cost sensors in indoor PM$_{2.5}$ monitoring is continuously increasing. The accuracy of low cost sensors can be improved by proper calibration techniques (Gozzi et al., 2016).

3.2 PM$_{2.5}$ Concentrations

We collected PM$_{2.5}$ concentrations from published articles to provide a review of PM$_{2.5}$ concentrations in households. As listed in Table S1, most studies reporting household PM$_{2.5}$ concentrations were conducted in Asia and in Europe, and some studies were conducted in North America and in Africa. The earliest studies that reported PM$_{2.5}$ measurements in living environments were conducted in North America and in Europe. Later studies were conducted in Asia, and few were conducted in Africa. Factors influencing PM$_{2.5}$ concentrations were as follows: 1) continent and country, 2) indoor activities, 3) ventilation type and air cleaner (AC) use, 4) building type and performance, 5) and ambient environment and season.

3.2.1 Mean PM$_{2.5}$ Concentration

We reviewed the mean daily household PM$_{2.5}$ concentrations measured by the included studies in different regions. Fig. 2 illustrates box plots of the mean daily PM$_{2.5}$ concentrations worldwide. In Europe, the mean daily PM$_{2.5}$ concentrations ranged from 6.0 $\mu$g m$^{-3}$ in
Colchester, the United Kingdom (Nasir and Colbeck, 2013), to 46.0 μg m⁻³ in Rome, Italy (Romagnoli et al., 2016). In North America, indoor PM₂.₅ concentrations varied from 6.5 μg m⁻³ in Edmonton, Canada (Kearney et al., 2014) to 45.4 μg m⁻³ in California, the United States (Sawant et al., 2004). In Asia, indoor PM₂.₅ concentrations ranged from 11.7 μg m⁻³ in Harbin, China (Liu et al., 2020) to 207.3 μg m⁻³ in Wuhan, China (Yin et al., 2017). In Africa, indoor PM₂.₅ concentrations ranged from 45.0 μg m⁻³ in Alexandria, Egypt (Abdel-Salam, 2015) to 74.0 μg m⁻³ in Accra, Ghana (Zhou et al., 2014). Typically, the mean daily PM₂.₅ concentrations measured in Asia were higher than those measured in Europe and North America. Similar concentrations were observed among European and North American countries. The mean daily PM₂.₅ concentrations measured in Europe, North America, Asia and Africa were 18.7, 17.3, 68.6 and 60.1 μg m⁻³, respectively.

![Box plot of mean daily PM₂.₅ concentration worldwide.](image)

We also reviewed the mean PM₂.₅ concentrations measured using different monitoring intervals, namely 1-, 3-, 5-, 6-, 10-, 15- and 30-min intervals. The mean PM₂.₅ concentrations measured using 30-min intervals ranged from 10.0 μg m⁻³ in Bologna, Italy (Zauli Sajani et al.,...
2015) to 64.9 μg m⁻³ in the Yangtze River Delta of China (Wang et al., 2016). The mean PM₂.₅ concentrations measured using 10-min intervals were 8.7 μg m⁻³ in Switzerland (Meier et al., 2015) up to 107.7 μg m⁻³ along a roadside in Nablus, Pakistan (Jodeh et al., 2017). Regarding shorter monitoring intervals, the mean PM₂.₅ concentrations measured using 1-min intervals were 8.4 μg m⁻³ in Edinburgh and Lothian, the United Kingdom (Steinle et al., 2015); 28.6 μg m⁻³ in winter in Seoul, Korea (Hwang and Lee, 2018); and 69.7 μg m⁻³ along a roadside in Hong Kong, China (Cao et al., 2005). In addition, the mean PM₂.₅ concentrations measured using short intervals were considerably higher in some Asian countries, particularly in environments involving smokers and during the heating season. Remarkably, the highest mean PM₂.₅ concentration measured in 1-min sampling intervals was 572.0 μg m⁻³, recorded under conditions of severe outdoor air pollution in Tianjin, China (Zhou et al., 2016).

3.2.2 Maximum PM₂.₅ concentration

We reviewed the maximum daily PM₂.₅ concentrations measured by the included studies in different regions worldwide, with our review revealing remarkable differences in the maximum daily PM₂.₅ concentrations among different sampling sites. In North America, the maximum daily PM₂.₅ concentration was 74.9 μg m⁻³ in Boston, the United States (Baxter et al., 2007). In Europe, the maximum daily PM₂.₅ concentration was 109.9 μg m⁻³ in Colchester, the United Kingdom (Nasir and Colbeck, 2013). However, the maximum daily PM₂.₅ concentrations measured in Africa and Asia were considerably higher; the concentration was 218.0 μg m⁻³ in Durban, South Africa (Gumede and Savage, 2017) and 368.0 μg m⁻³ in Lanzhou, China (Li et al., 2016). Higher PM₂.₅ concentrations were observed in some Asian and African countries under conditions of severe ambient air pollution (Zhou et al., 2016; Li et
This observation was likely influenced by high PM$_{2.5}$ concentrations in the outdoor environment. As displayed in Fig. 3, the maximum daily PM$_{2.5}$ concentrations were higher in Asia and Africa than in Europe and North America.

![Box plot of maximum daily PM$_{2.5}$ concentration worldwide.](image)

Fig. 3. Box plot of maximum daily PM$_{2.5}$ concentration worldwide.

Notably, a monitoring campaign conducted in France reported a maximum PM$_{2.5}$ concentration of 568.0 $\mu$g m$^{-3}$ (Langer et al., 2016). This high concentration was attributed to indoor smoking. In most regions, relatively high maximum PM$_{2.5}$ concentrations were observed in the vicinity of particle emission sources despite the use of short sampling intervals. For example, in Prague, Czech Republic, the maximum PM$_{2.5}$ concentration measured using a 5-min interval reached 2,282.0 $\mu$g m$^{-3}$ (Braniš and Kolomazníková, 2010). In Tianjin, China, the maximum PM$_{2.5}$ concentration measured using a 1-min interval was 1,370.0 $\mu$g m$^{-3}$ (Zhou et al., 2016); this was measured in an environment involving group smoking. This extremely high PM$_{2.5}$ concentration was primarily caused by considerable indoor activities over the short sampling period.

### 3.3 Factors Influencing PM$_{2.5}$ Concentrations

The PM$_{2.5}$ concentrations measured by the included studies are listed in Table 1. As
mentioned, factors influencing PM$_{2.5}$ concentrations were indoor activities, ventilation type and AC use, household type, ambient environment, and season. The effects of these factors on PM$_{2.5}$ concentrations are discussed in the following sections.

### 3.3.1 Indoor activities

Because tobacco smoking often occurs in the living room, it is an indoor activity that considerably elevates PM$_{2.5}$ concentrations. PM$_{2.5}$ concentrations measured in smoking households were compared with those measured in non-smoking ones, as illustrated in Fig. 4. In general, the mean daily PM$_{2.5}$ concentration observed in smoking households (36.7 $\mu$g m$^{-3}$) was higher than that observed in non-smoking ones (15.0 $\mu$g m$^{-3}$) by 2.5-fold. In smoking households, the daily PM$_{2.5}$ concentrations ranged from 16.0 to 109.0 $\mu$g/m$^{3}$ (Nasir and Colbeck, 2013). In Helsinki, Finland, the mean PM$_{2.5}$ concentrations in households of active smokers (31.1 $\mu$g m$^{-3}$) were higher than those in households of non-smokers (9.9 $\mu$g m$^{-3}$) by more than threefold (Kimmo, 2001). The mean PM$_{2.5}$ concentrations observed in some Asian countries were considerably higher than those observed in other countries. In a Chinese household, the mean PM$_{2.5}$ concentration measured within 1 min was 549.0 $\mu$g m$^{-3}$; when the household involved smoking, the maximum PM$_{2.5}$ concentration reached 1,317.0 $\mu$g m$^{-3}$ (Zhou et al., 2016). These results indicate that during this period, the maximum PM$_{2.5}$ concentration was higher than the mean PM$_{2.5}$ concentration by more than twofold. In conclusion, cigarette smoking causes a significant increase in PM$_{2.5}$ concentrations in the living room, particularly peak PM$_{2.5}$ concentrations measured using a short sampling interval.
Fig. 4. Mean daily PM$_{2.5}$ concentration in non-smoking and smoking households.

Domestic cooking is another major source of particles in residential environments. Our included studies extensively reported high concentrations of cooking-generated PM$_{2.5}$ in Europe (Abdullahi et al., 2013; Kosonen et al., 2006), North America (Olson and Burke, 2006) and Asia (Cao et al., 2017; Wang et al., 2020; Liu et al., 2020). These studies indicated that the influence of cooking-generated particles was not limited to the kitchen but instead spread to other sections of the living environment; this is because opening kitchen and interior doors leads to PM$_{2.5}$ diffusion throughout the living environment. A study performed a field measurement of PM$_{2.5}$ concentration during cooking in an apartment in Korea and indicated that the PM$_{2.5}$ concentration in the living room was higher than that in background areas by more than 12-fold (Kim et al., 2018). In addition, a monitoring campaign conducted in a Chinese style residence reported that cooking led to a peak PM$_{2.5}$ concentration of 365.0 µg
m$^{-3}$ in the living room, whereas the PM$_{2.5}$ concentration in background areas was 15.0 $\mu$g m$^{-3}$ (Liu et al., 2020). In a Korean residence with an open kitchen, the PM$_{2.5}$ concentration in the living room could reach up to 1,000.0 $\mu$g m$^{-3}$ (Kang et al., 2019). Furthermore, Zhao and Zhao (2020) conducted PM$_{2.5}$ measurements in a household with an open kitchen design and reported that cooking in the kitchen led to PM$_{2.5}$ concentrations ranging between 282.0 $\mu$g m$^{-3}$ and 1,187.0 $\mu$g m$^{-3}$ in the living room. These findings demonstrate that cooking in a household’s kitchen elevates PM$_{2.5}$ concentrations in the living room, especially in households with open kitchens.

### 3.3.2 Ventilation type and AC use

The most common types of ventilation in residential buildings are natural/normal ventilation (NV) with or without an AC and mechanical ventilation (MV) with an air filtration unit. We reviewed PM$_{2.5}$ concentrations measured in Chinese households with these types of ventilation, as presented in Fig. 5. In Harbin, China, the mean daily and maximum daily PM$_{2.5}$ concentrations measured in households with NV in winter were 88.0 and 261.0 $\mu$g m$^{-3}$, respectively. However, the mean daily and maximum daily PM$_{2.5}$ concentrations measured in households with an AC in winter were 51.0 and 131.0 $\mu$g m$^{-3}$, respectively (Xue et al., 2020). Therefore, the use of an AC reduced the mean daily and maximum daily PM$_{2.5}$ concentrations in this region by 42.0% and 49.8%, respectively. In addition, in Beijing, China, the use of an AC reduced the mean daily PM$_{2.5}$ concentration from 87.0 to 63.0 $\mu$g m$^{-3}$ and reduced the maximum daily PM$_{2.5}$ concentration from 223.0 to 116.0 $\mu$g m$^{-3}$ (Deng et al., 2017). Therefore, the mean and maximum PM$_{2.5}$ concentrations were reduced by 27.6% and 48.0%, respectively. Moreover, studies conducting measurements in the Yangtze River Delta region by using a
30-min interval revealed that the mean and maximum PM$_{2.5}$ concentrations were 26.0 and 63.0 μg m$^{-3}$, respectively, in households using both MV and an AC. Nevertheless, in households using only NV, the mean and maximum PM$_{2.5}$ concentrations were up to 64.9 and 165.0 μg m$^{-3}$, respectively (Wang et al., 2016). Therefore, see the use of both MV and an AC reduced the mean and maximum PM$_{2.5}$ concentrations by 60.0% and 61.8%, respectively.

**Fig. 5.** PM$_{2.5}$ concentration in Chinese households with natural/normal ventilation (NV), mechanical ventilation (MV) and use of AC.

### 3.3.3 Building type and performance

We reviewed the mean PM$_{2.5}$ concentrations measured in different building types and building performance levels, as displayed in Fig. 6. For different building types in European countries, single-room residences in Colchester, the United Kingdom, had the lowest mean daily PM$_{2.5}$ concentration (6.0 μg m$^{-3}$) (Nasir and Colbeck, 2013), followed by single-family houses in France (8.7 μg m$^{-3}$) (Derbez et al., 2018), multifamily apartment buildings in
Finland (9.0 μg m⁻³) (Du et al., 2015), and retrofitted multifamily apartment buildings in France (14.6 μg m⁻³) (Derbez et al., 2018). Multifamily houses in France had a higher mean daily PM₂.₅ concentration (32.0 μg m⁻³) than did other building types (Derbez et al., 2018). These results thus demonstrate that multifamily apartment buildings had higher mean PM₂.₅ concentrations than did single room residences. Notably, higher indoor PM₂.₅ concentrations were reported in winter than that in summer for most regions. One possible reason is that higher ambient PM₂.₅ concentrations in winter contributed to higher indoor concentrations.

We noted remarkable differences in PM₂.₅ concentration between Chinese households. Specifically, measurement conducted during heating season in Harbin revealed that the mean daily PM₂.₅ concentration was 51.0 μg m⁻³ in conventional households and 38.0 μg m⁻³ in passive households (Xue et al., 2020). A measurement campaign of PM₂.₅ concentration in different building types revealed that the concentration in conventional households was higher than those observed in passive households by 1.79-folds (Wang et al., 2018). Furthermore, the mean PM₂.₅ concentrations in energy-saving and passive residential buildings were lower than those in conventional households. The low concentration was predominately attributed to the good building performance.
3.3.4 Ambient environment and season

Ambient environmental factors that affect PM$_{2.5}$ concentrations include roadside conditions outside the household (proximity to a roadside with vehicular traffic, proximity to an urban area with no vehicular traffic, or proximity to industrial facilities), weather conditions (clear or hazy conditions), and climate zone and season. Household mean PM$_{2.5}$ concentrations under different ambient conditions are illustrated in Fig. 7. In typical residences without substantial outdoor pollution, the mean daily household PM$_{2.5}$ concentration was 56.2 μg m$^{-3}$. However, in residences located along roadsides with high traffic volumes or located in proximity to industrial facilities, the mean daily PM$_{2.5}$ concentrations were 73.5 and 73.4 μg m$^{-3}$, respectively (Huang et al., 2007). These results thus indicate that the mean daily PM$_{2.5}$ concentration in residences close to vehicular traffic and industrial facilities increased by 30.6%. In Nablus, Pakistan, the mean daily PM$_{2.5}$ concentration was 84.2 μg m$^{-3}$ in households located in urban areas and 107.7 μg m$^{-3}$ in households located along roadsides (Jodeh et al.,...
These results demonstrate that compared with the mean PM$_{2.5}$ concentration in households located in urban areas, the mean PM$_{2.5}$ concentration in households located along roadsides increased by 27.9%. A similar trend was also observed in Hong Kong, China (Cao et al., 2005) and Agra, India (Massey et al., 2012), where the mean PM$_{2.5}$ concentration was higher in households located along roadsides than in those located in urban areas with no vehicular traffic. The higher household PM$_{2.5}$ concentrations were attributed to the elevated concentrations in the ambient environment.

Weather conditions also considerably influence household PM$_{2.5}$ concentrations. During days involving severe haze pollution, high indoor PM$_{2.5}$ concentrations can be explained by the severe outdoor PM$_{2.5}$ pollution. Zhou et al. (2016) conducted indoor and outdoor
measurements in households with slightly open windows during periods of severe particle pollution in the ambient environment by using a sampling time of 1 min; they observed that the mean indoor and outdoor PM$_{2.5}$ concentrations were 572.0 and 723.0 µg m$^{-3}$, respectively. When windows and doors were adequately sealed, the mean indoor PM$_{2.5}$ concentration could still reach up to 246.0 µg m$^{-3}$, with the mean outdoor PM$_{2.5}$ concentration ranging from 254.0 to 403.0 µg m$^{-3}$. In addition, they reported that under conditions of low wind speed, the mean indoor and outdoor PM$_{2.5}$ concentrations were 290.0 and 580.0 µg m$^{-3}$, respectively; however, under conditions of high wind speed, the mean indoor and outdoor PM$_{2.5}$ concentrations were 65.0 and 33.0 µg m$^{-3}$, respectively (Zhou et al., 2016). A possible reason for the reduction in household PM$_{2.5}$ concentrations is the dilution effect of wind speed on the ambient pollutant concentration.

Concentrations varied with seasons. The mean daily PM$_{2.5}$ concentrations in different seasons in the various regions are presented in Fig. 8. In Bologna, Italy, the mean daily household PM$_{2.5}$ concentrations in spring, summer, and winter were 6.6, 8.4, and 15.1 µg m$^{-3}$, respectively, and the mean daily outdoor PM$_{2.5}$ concentrations were 10.8, 13.7, and 31 µg m$^{-3}$, respectively (Zauli Sajani et al., 2015). In Rome, Italy, the mean daily PM$_{2.5}$ concentrations in indoor and outdoor environments were 27.3 and 12.8 µg m$^{-3}$, respectively, in summer and 31.4 and 32.8 µg m$^{-3}$, respectively, in winter (Perrino et al., 2016). By contrast, higher PM$_{2.5}$ concentrations were reported in some Asian countries, particularly in winter. Specifically, in Lanzhou, China, the mean daily PM$_{2.5}$ concentrations in indoor and outdoor environments were 119.0 and 328.0 µg m$^{-3}$, respectively, in winter and 80.0 and 80.0 µg m$^{-3}$, respectively, in summer (Li et al., 2016). The remarkable increases in both indoor and outdoor PM$_{2.5}$
concentrations in winter were attributed to heating. In residences along roadsides in Agra, India, the peak mean PM$_{2.5}$ concentration in winter was 207.0 μg m$^{-3}$ in indoor environments and 212.0 μg m$^{-3}$ in outdoor environments. However, in summer, the mean PM$_{2.5}$ concentration in household was 119.0 μg m$^{-3}$ (Massey et al., 2012). These results demonstrate that in most households in Asian countries, the mean indoor PM$_{2.5}$ concentration in winter was higher than that in summer by approximately twofold. The increase in PM$_{2.5}$ concentration in winter can be attributed to indoor space heating and increased ambient concentrations. Except for the studies by Kearney et al. (2014) and Pekey et al. (2010), the other studies included in this review reported consistently higher PM$_{2.5}$ concentrations in winter than in summer in the various regions.

As illustrated in Fig. 8, the mean indoor and outdoor PM$_{2.5}$ concentrations in Shanghai,
China, were 69.9 and 77.1 μg m\(^{-3}\) in the cold season, respectively, 46.1 and 39.8 μg m\(^{-3}\) in the transitional season, respectively, 32.3 and 31.6 μg m\(^{-3}\) in the hot season, respectively. Similar household indoor and outdoor PM\(_{2.5}\) concentrations were observed during different seasons in the hot summer climate zone. The mean PM\(_{2.5}\) concentrations measured by Dai et al. (2018) in households in different climate zones in China are indicated by the box plot in Fig. 9. The PM\(_{2.5}\) concentrations differed considerably among the seasons across the climate zones. Specifically, the mean PM\(_{2.5}\) concentration in winter was considerably higher than those in the other seasons. The household PM\(_{2.5}\) concentrations ranged from 75.0 μg m\(^{-3}\) in the mild zone to 163.0 μg m\(^{-3}\) in the cold zone in winter. By contrast, the mean PM\(_{2.5}\) concentrations ranged from 32 μg m\(^{-3}\) in the mild zone to 56 μg m\(^{-3}\) in the cold zone (Dai et al., 2018). Notably, higher PM\(_{2.5}\) concentrations were observed in the cold climate zone across the various seasons. The mean PM\(_{2.5}\) concentration was 24.8 μg m\(^{-3}\) in the severe cold climate zone, 43.0 μg m\(^{-3}\) in the cold climate zone, 35.5 μg m\(^{-3}\) in the hot-summer and cold-winter climate zone, 13.5 μg m\(^{-3}\) in the mild zone and 27.0 μg m\(^{-3}\) in the hot-summer and warm-winter climate zone. The highest mean PM\(_{2.5}\) concentration was observed in the cold climate zone, whereas the lowest was observed in the mild climate zone.
4 CONCLUSIONS

We present a review of studies on PM$_{2.5}$ concentrations in urban residential buildings. We reviewed PM$_{2.5}$ concentrations that were measured using 1- to 30-min intervals in various regions worldwide. The findings indicate that PM$_{2.5}$ concentrations across the world varied considerably. The mean daily PM$_{2.5}$ concentrations in Asia and Africa were higher than those in Europe and North America by more than threefold. Similar concentrations were observed between European and North American countries. In some Asian countries, the PM$_{2.5}$ concentrations measured using intervals of several minutes were up to $>1,000$ µg m$^{-3}$. In regions with considerable particle pollution, the use of different sampling intervals is likely to engender variations in the measured concentrations. For example, the use of long sampling intervals during periods of high concentration could lead to biased measurements of average concentrations. Therefore, we recommend the use of uniform sampling intervals across different monitoring campaigns to facilitate comparisons future studies.
On the basis of the findings of the included studies, we can conclude that different indoor activities, ventilation type and AC use, building type and building performance, ambient environment, and seasons can explain the large discrepancies in indoor PM$_{2.5}$ concentrations between countries and regions. The main indoor particle sources that lead to large PM$_{2.5}$ concentration variations in residential environments are smoking and cooking. The mean daily PM$_{2.5}$ concentration in smoking households was higher than that in non-smoking households by 2.5-fold. Smoking led to a significant PM$_{2.5}$ concentration increase in the living rooms within short periods. Regarding measurements conducted for Chinese households with different ventilation types, the mean PM$_{2.5}$ concentrations were much lower in households with MV and ACs than in those with NV. The use of ACs could reduce the mean daily PM$_{2.5}$ concentration and mean maximum PM$_{2.5}$ concentration by 27.6%-60.0% and by 48.0%-61.8%, respectively.

We also observed differences in PM$_{2.5}$ concentrations among different building types and building performance levels. The mean PM$_{2.5}$ concentration in multifamily apartment buildings was higher than that in single-room residences in Europe. In China, the mean PM$_{2.5}$ concentration in passive households was lower than that in conventional residential buildings. Severe outdoor particle pollution could increase indoor PM$_{2.5}$ concentrations. The mean indoor PM$_{2.5}$ concentration in winter was higher than that in summer by approximately twofold for most households in Asian and African countries. Regarding the measurements made in the different climate zones of China, nearly identical indoor and outdoor household PM$_{2.5}$ concentrations were reported for different seasons in the hot summer climate zone. The mean household PM$_{2.5}$ concentration in the cold zone was higher than that in the mild zone by more
than threefold.

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REFERENCES


Bai, L., Chen, W., He, Z., Sun, S., Qin, J. (2020). Pollution characteristics, sources and health risk assessment of polycyclic aromatic hydrocarbons in PM$_{2.5}$ in an office building in


Relationship of Indoor/Outdoor PM$_{2.5}$ at Residential Homes in Guangzhou City, China.


Schembari, A., Triguero-Mas, M., de Nazelle, A., Dadvand, P., Vrijheid, M., Cirach, M., Martinez, D., Figueras, F., Querol, X., Basagaña, X., Eeftens, M., Meliefste, K.,


