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Indoor $PM_{2.5}$ concentrations in China: A concise review of the literature published in the past 40 years

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A R T I C L E I N F O

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A B S T R A C T

Fine particulate matter ($PM_{2.5}$) pollution is of national concern in China. Indoor $PM_{2.5}$ concentrations may contribute significantly to human exposure because people spend most of their time indoors. In this study, we systematically reviewed the level of indoor $PM_{2.5}$ concentrations in residences, offices, and schools in China. We looked for corresponding literature published between 1980 and 2019 in six major literature databases and finally obtained 118 articles. We then summarized the spatial distribution of indoor $PM_{2.5}$ concentrations in urban and rural areas, analyzed the indoor $PM_{2.5}$ concentrations in residences, offices, and schools in urban areas across three time periods, and compared the indoor $PM_{2.5}$ concentration levels in the urban and rural areas.

It was found that the urban areas considered are mainly distributed in the middle and eastern part of China, while the rural areas are mainly distributed in northeast, north, and southwest China. Indoor $PM_{2.5}$ concentrations have decreased significantly in the past decades. The mean ± SD value of indoor $PM_{2.5}$ concentration decreased from 127.5 ± 111.4 μg/m^3 prior to 2010 to 70.1 ± 35.2 μg/m^3 following 2015. The indoor $PM_{2.5}$ concentration in rural areas was much higher than that in urban areas. The mean ± SD value of indoor $PM_{2.5}$ concentrations in rural residences was up to 275.7 ± 326.4 μg/m^3, while that in urban residences was 95.4 ± 71.0 μg/m^3. A long-term national indoor $PM_{2.5}$ concentration measurement is suggested to obtain a more comprehensive and accurate indoor $PM_{2.5}$ concentration level.

1. Introduction

Fine particulate matter ($PM_{2.5}$) pollution in China is severe and poses a critical threat to human health. $PM_{2.5}$ contains toxic and harmful substances such as heavy metals and microorganisms. These substances can severely damage the respiratory system, including the lungs, when inhaled. In addition, $PM_{2.5}$ deposition in the lungs can cause lung sclerosis. Several studies have shown that $PM_{2.5}$ has a strong relationship with diseases including lung cancer, lower respiratory infections, chronic obstructive pulmonary disease, stroke, and ischemic heart disease [1,2].

As most people spend 80% of their time indoors [3], information on indoor $PM_{2.5}$ concentration is significant for assessing human exposure to $PM_{2.5}$ but is still relatively lacking. The indoor $PM_{2.5}$ concentration depends on both outdoor and indoor sources. With regard to outdoor sources, outdoor $PM_{2.5}$ mainly enters the room through indoor-outdoor

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air exchange, including infiltration and ventilation. Indoor sources include smoking, cooking, fuel burning, and secondary dust from housework, which generate $PM_{2.5}$ in a wide range of magnitudes. Both outdoor and indoor sources vary significantly spatiotemporally. The outdoor $PM_{2.5}$ concentration may decrease owing to air pollution prevention and control actions, while indoor $PM_{2.5}$ sources may vary across different regions owing to different human behaviors. Consequently, $PM_{2.5}$ concentrations in different regions and time periods vary significantly. However, current studies on indoor $PM_{2.5}$ concentration are often limited to certain cities or regions and a systematic review is required.

The purpose of this review is to summarize the measured $PM_{2.5}$ concentrations in residences, offices, and schools in China, as reported in published literature over the past 40 years. In this study, we first briefly review the measurement methods of indoor $PM_{2.5}$ concentration. We then summarize the spatial distribution of indoor $PM_{2.5}$ concentration in urban and rural areas, analyze the indoor $PM_{2.5}$ concentrations in residences, offices, and schools in urban areas, and compare the indoor $PM_{2.5}$ concentrations in urban and rural areas. We expect the results of this study to provide latest information on indoor $PM_{2.5}$ concentration in China, which is critical for the assessment of human exposure to $PM_{2.5}$, and for the estimation of related health risks.

2. Material and methods

2.1. Literature search and selection

We searched six databases, including Web of Science, PubMed, Engineering Village, China National Knowledge Infrastructure (CNKI), CQVIP, and Wan Fang, for published studies related to indoor $PM_{2.5}$ concentration in China between January 1980 and December 2019. In total, combinations of 27 search terms in Chinese and 38 search terms in English were used to search studies published in Chinese and English, respectively. The list of search terms is shown in Table A1 in the Supporting Information.

The retrieved search results were then screened twice. According to the title and abstract, studies that (1) are not in the field of indoor $PM_{2.5}$ concentration, (2) were not conducted in China, (3) were not conducted in residences, offices, and schools, and (4) were duplicates, were excluded. After the full-text screening, studies that (1) have no available measured data of indoor $PM_{2.5}$ concentration, (2) are for specific activities (e.g., cooking), and (3) are short-term measurements (measured only once and the measurement duration was less than 30 min), were excluded. For studies in rural residences, considering that kitchens in rural residences are generally connected with other rooms, the sampling sites in the following 5 cases were retained: only kitchen/heating room, kitchen and bedroom/living room, only bedroom/living room, NA (unspecified room type) and tent in pastoral area. The average measured $PM_{2.5}$ concentrations in these 5 cases are summarized in Table A2 in the Supporting Information. The average concentrations have little difference except the concentration in tent, which is extremely high due to burning yak dung with open stove. Some rural residents use stove in living room, which may result in similar $PM_{2.5}$ levels in living room and kitchen. Besides, the measuring durations in kitchen were all no less than 22 h except one measurement. This measurement lasted for 60–90 min each time but we only selected the $PM_{2.5}$ concentrations measured in the non-combustion cases. Thus, we think the $PM_{2.5}$ concentrations measured in the kitchen can reflect the concentration level of the entire house.

2.2. Search findings

Initially, 18527 studies were obtained after removing the duplicates. After two rounds of screening, only 118 [4–121] studies were obtained (Fig. 1), of which 81 were in Chinese and 37 were in English. A total of 100 studies were conducted in urban areas [4–103], and 19 were conducted in rural areas [21,104–121] (one study was conducted in both urban and rural areas [21]). Among studies conducted in urban areas, 60 were related to residences [4,7,15,16,19–21,31,32,36,38–87], 34 to offices [4–37], and 25 to schools [4,14,15,20,26,28,31,34,72,88–103] (six of them were related to both residence and office [7,16,19,21,32,36], one was related to both residence and school [72], four were related to both offices and schools [14,26,28,34], and four were related to the three building types [4,15,20,31]). Studies related to rural areas were all conducted in residences. The residence is the most studied building type, where people spend most of their time indoors. Most studies were conducted after 2010, when $PM_{2.5}$ pollution in China gained sufficient attention. In total, 28 and 20 areas were involved in studies conducted in urban and rural areas, respectively. These are labeled in Figs. 2 and 3. Among the studies conducted in urban areas, the studies for residences covered 23 areas, the studies for offices covered 12, and the studies for schools covered 11 as well. Beijing was the most extensively studied with 29 studies [4,6,7,13–15,20,24,25,31,34,45–48,50,55,61,64,66,76,77,82,84,87,90,91,97,98], owing to severe air pollution in Beijing in recent years. The 118 studies included in this review are summarized in Table A3 in the Supporting Information.

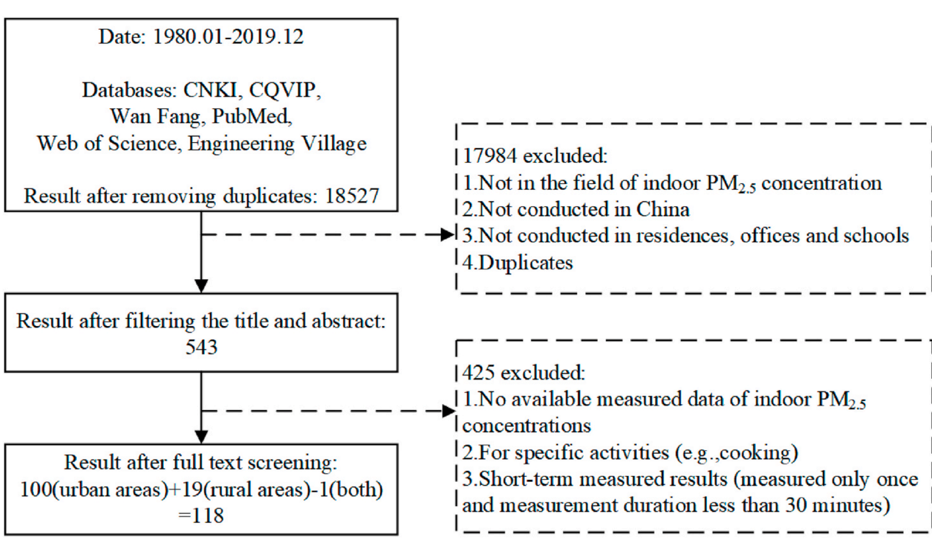

Fig. 1. Flow chart of the literature search and selection.

2.3. Statistical analysis

The analysis was based on the average value provided in the studies. The nonparametric Kruskal-Wallis test was applied to compare the differences among $PM_{2.5}$ concentration groups of indoor $PM_{2.5}$ concentration in different building types and time periods. Statistical analyses were performed using R (version 4.0.3). We considered a *p-value* less than 0.05 to suggest a statistically significant difference.

3. Results

3.1. Summary of measurement methods

According to the measuring principles, the $PM_{2.5}$ concentration measurement methods in the reviewed studies can be divided into four categories: light scattering, β-ray attenuation, aerodynamic particle size counting based on the time-of-flight, and weighing filtration membrane. Light scattering and weighing filtration membrane are the two main measurement methods. Detection instruments applying the first three methods were used for online measurements. The light scattering method is based on the principle that the intensity of the scattered light particles is proportional to their mass concentration, and it is used to measure particle concentrations. The light scattering measurement result has high uncertainty, which is affected by the structure of the instrument itself, the particle material, particle size distribution, environmental humidity, and other factors [122]. Therefore, calibration is necessary when applying this method. Twenty-four studies [8,10,11,16,17,24,25,32,33,40,50,54,55,67,73,82,86,89,93,98,99,104,114,118] applying the light scattering method referred to the calibration methods, of which the weighing filtration membrane method was predominantly used. In addition, other calibration methods were employed, such as the use of other instruments [10,54,82,104], manufacturers [17,99], authoritative departments [24] or government data [50]. For the β-ray attenuation method, which has a high accuracy, the particle concentration is calculated by measuring the energy attenuation of β-rays passing through the filter membrane, where the particles are deposited after the air passes through. Only one study reported a detection instrument (APS-3321) by applying aerodynamic particle size counting based on the time-of-flight. APS-3321 can measure the aerodynamic particle diameter in real-time using precise time-of-flight technology and convert it into mass concentration using its own software. Offline measurements mainly use the weighing filtration membrane method, in which samples with a quartz fiber or Teflon membrane are weighed to obtain the average $PM_{2.5}$ mass concentration. The measurement methods are presented in Table 1.

Table 1
Mechanisms of measuring indoor $PM_{2.5}$.

Detection mechanism	Number of literature	Online/ offline	Calibration method	References
Light scattering	64	Online	Weighing filtration membrane: 13	[16,25,32,33,40,55,67,86,89,93,98,114,118]
			Others: 8	[10,17,24,50,54,82,99,104]
			Did not indicate calibration method: 3	[8,11,73]
			NA: 40	[5,7,13–15,18,21,22,26,38,42,49,51,56,58,60,62–64,66,69,74,76,77,83,87,88,90–92,95,96,100–103,107,110,115,120]
β ray attenuation	1	Online	NA	[97]
Aerodynamic particle size counting based on time of flight	1	Online	NA	[65]
Weighing filtration membrane	52	Offline		[4,6,9,12,19,20,23,27–31,34–37,39,41,43–48,52,53,57,59,61,68,70–72,75,78–81,84,85,94,105,106,108,109,111–113,116,117,119,121]

NA: Did not indicate whether calibrated.

3.2. Spatial distribution of indoor $PM_{2.5}$ concentration in urban areas

Fig. 2a shows the spatial distribution of indoor $PM_{2.5}$ concentrations in urban areas [4–103]. The studied cities are mainly distributed in the middle and eastern part of China. Considering the following reasons: the indoor $PM_{2.5}$ concentration changes over time; the $PM_{2.5}$ pollution has aroused national attention since 2010; with the launch of Air Pollution Prevention and Control Action Plan in 2013 [123], the $PM_{2.5}$ pollution has improved significantly since 2015, the data of indoor $PM_{2.5}$ concentration were divided into three groups according to the test time: pre-2010, 2010–2015, and post-2015. The number of studied cities before 2010 was only six (residence: 5, office: 2, school: 1, one of them covered all the three building types), while the numbers of studied cities in the 2010–2015 and post-2015 periods were 16 and 18 respectively. The number of studied cities covering residences, offices, and schools between 2010 and 2015 were 13, 9, and 7 (four cities covered both residences and offices, two cities covered both residences and schools, one cities covered both offices and schools, and three cities covered all the three building types), respectively, and the corresponding number after 2015 was 16, 5, and 7 (three cities covered both residences and offices, three cities covered both residences and schools, and two cities covered all three building types), respectively. Overall, the indoor $PM_{2.5}$ concentration showed a downward trend. Beijing and Guangzhou were the only two cities with data for the three time periods. The indoor $PM_{2.5}$ concentration in these two cities decreased significantly. Other cities that contain data for the 2010–2015 and post-2015 periods show a decline in indoor $PM_{2.5}$ concentration. The city with the largest decline was Harbin, where the indoor $PM_{2.5}$ concentration dropped from 270.9 to 72.0 μg/m^3.

Prior to 2010, the indoor $PM_{2.5}$ concentration in Beijing was up to 296.1 μg/m^3, which was much higher than that in the other five cities. This was mainly attributed to the contribution of a study in the winter of 2000, which measured indoor $PM_{2.5}$ concentration in buildings with steel industrial base in the nearby area and bungalows that used soot equipment for cooking and heating [66]. The lowest indoor $PM_{2.5}$ concentration (23.7 μg/m^3) was in Taipei, which has stricter air quality standards [124]. During the 2010–2015 period, Harbin had the highest indoor $PM_{2.5}$ concentration (270.9 μg/m^3), which was due to the severe haze and burning of coal and straw during the heating season [21]. The lowest indoor $PM_{2.5}$ concentration (0.1 μg/m^3) was in Lhasa, which had the lowest outdoor $PM_{2.5}$ concentration. After 2015, the indoor $PM_{2.5}$ concentration in different cities was mainly in the range of 25–100 μg/m^3. Taian recorded the highest concentration (178.3 μg/m^3) as a result of heavy air pollution [95]. Changchun had the lowest concentration (29.9 μg/m^3) owing to less flow of people inside and outside the building and the effective air tightness of the building [51].

3.3. Spatial distribution of indoor $PM_{2.5}$ concentration in rural areas

The spatial distribution of indoor $PM_{2.5}$ concentrations in rural areas is shown in Fig. 3a [21,104–121]. The figure shows that the studied cities in rural areas are mainly distributed in the northeast (four cities),

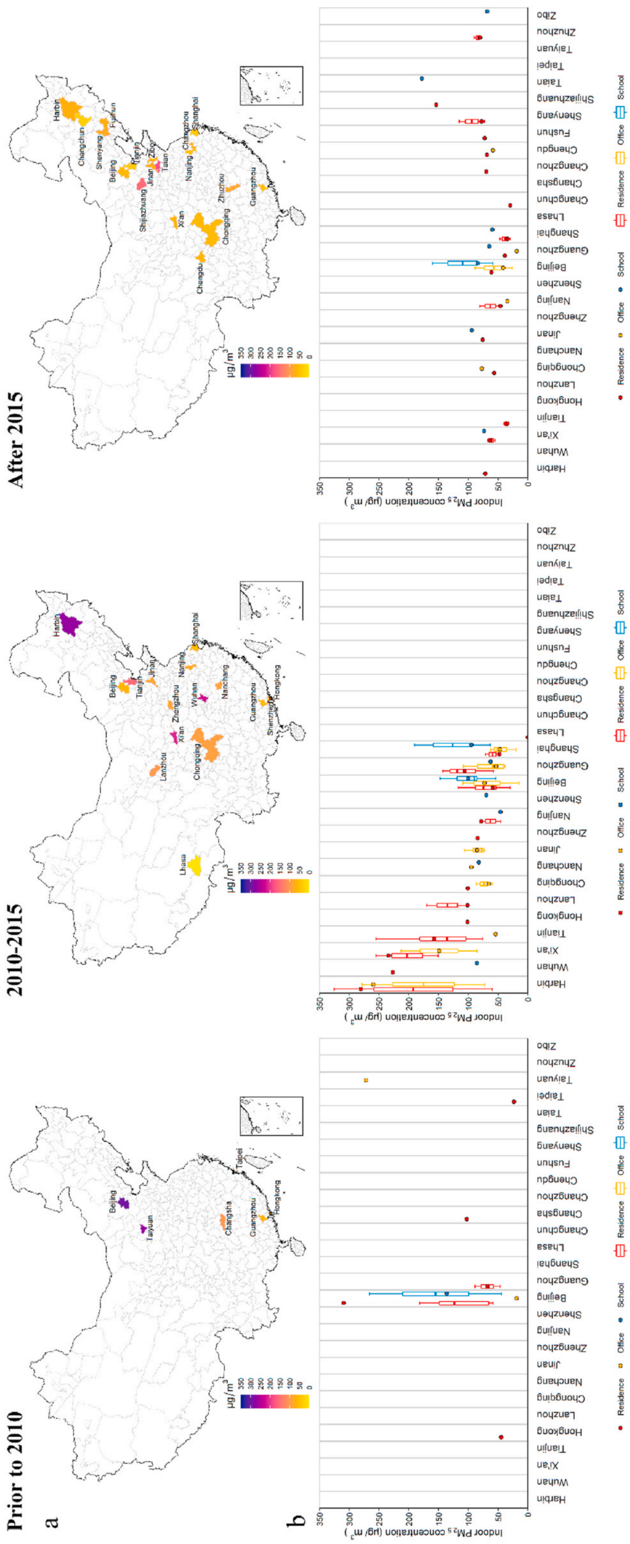

Fig. 2. Indoor $PM_{2.5}$ concentrations in urban areas. (a) spatial distribution of indoor $PM_{2.5}$ concentrations; (b) indoor $PM_{2.5}$ concentration levels of the three building types in different cities. The boxes in (b) represent the measured $PM_{2.5}$ concentrations in each included study case and the dots represent indoor $PM_{2.5}$ concentration levels of the three building types in different cities. Weighted average values of the number of tested buildings are used to represent the concentration levels. Corresponding sample sizes for each category are summarized in Table A4 in the Supporting Information. Only the dot is shown in (b) for the categories with only one sample size.

north (three cities), and southwest (seven cities) China. The indoor $PM_{2.5}$ concentrations in rural areas are relatively high, 65% of which are higher than 150 μg/m^3. The highest indoor $PM_{2.5}$ concentration in rural areas was 813.1 μg/m^3, which was measured in Lhasa. However, the indoor $PM_{2.5}$ concentration (28.2 μg/m^3) measured in Wuwei was the lowest because the study was conducted in a new type of residence with floor heating by a coal-fired boiler combined with a solar system [110], which is cleaner than the heating system of traditional rural residences. As in urban areas, the indoor $PM_{2.5}$ concentration data in rural areas were divided into three groups according to the test time: prior to 2010 (nine cities), 2010–2015 (ten cities), and after 2015 (five cities). The extremely high indoor $PM_{2.5}$ concentration (1668.0 μg/m^3) in Lhasa is a test result of four typical nomadic tents using open stoves that burn yak dung [109].

3.4. Indoor $PM_{2.5}$ concentrations in residences, offices and schools in urban areas

Fig. 4 shows the distributions of indoor $PM_{2.5}$ concentrations in residences, offices, and schools in urban areas and the average outdoor $PM_{2.5}$ concentrations of the corresponding cities with indoor $PM_{2.5}$ concentrations except Hongkong and Taipei. The outdoor concentrations are from 2013 to 2018 since the monitoring of outdoor $PM_{2.5}$ concentrations in Chinese mainland began in 2013 and only one study covered the first two months of 2019. Interestingly, the indoor $PM_{2.5}$ concentration decreased with time, but only the concentrations during the 2010–2015 and post-2015 periods showed a statistically significant difference ($p = 0.028$). We did not observe a statistically significant difference for the indoor $PM_{2.5}$ concentration prior to 2010 (a *p-value* of 0.677 for indoor $PM_{2.5}$ concentration comparison between the pre-2010 and 2010–2015 periods, and a *p-value* of 0.247 for indoor $PM_{2.5}$ concentration comparison between the pre-2010 and post-2015 periods, respectively), which may be due to the limited amount of pre-2010 data. With the Chinese government launching an Air Pollution Prevention and Control Action Plan in 2013 [123], the outdoor $PM_{2.5}$ concentration in China has decreased significantly. The significant decrease in outdoor $PM_{2.5}$ concentration may lead to a decrease in indoor $PM_{2.5}$, as indoor $PM_{2.5}$ concentration is strongly positively correlated with outdoor $PM_{2.5}$ concentration [125]. For each building type, indoor $PM_{2.5}$ concentrations in residences between the 2010–2015 and post-2015 periods showed a similar statistically significant downward trend ($p = 0.009$). The indoor $PM_{2.5}$ concentrations in offices and schools also decreased, except that the concentration in schools increased after 2015. The exception can be explained by the severe air pollution when the measurement was conducted in the studies reporting high values [91,95,96], for heavily-polluted outdoor air being the leading source of indoor $PM_{2.5}$ in naturally ventilated rooms. The classrooms in most Chinese schools are naturally ventilated. However, although the indoor $PM_{2.5}$ concentrations of offices and schools demonstrated more variations across different time periods than that of residences, the differences showed no statistical significance, because of the limited amount of data. A significant difference analysis could only be conducted for the indoor $PM_{2.5}$ concentrations reported between the 2010–2015 and post-2015 periods. However, we found no statistical significance (a *p-value* of 0.148 for indoor $PM_{2.5}$ concentration comparison in offices and a *p-value* of 0.606 for indoor $PM_{2.5}$ concentration comparison in schools) when comparing the indoor $PM_{2.5}$ concentrations between both periods.

3.5. Indoor $PM_{2.5}$ concentrations in rural areas

The indoor $PM_{2.5}$ concentration in rural areas is much higher than that in urban areas (see Fig. 5). The mean ± SD value of indoor $PM_{2.5}$ concentrations in rural area residences is 275.7 ± 326.4 μg/m^3 (median value = 182.3 μg/m^3) while that in urban areas is 95.4 ± 71.0 μg/m^3 (median value: 76.0 μg/m^3). The high indoor $PM_{2.5}$ concentrations in rural areas are generally attributed to the following two reasons: (1)

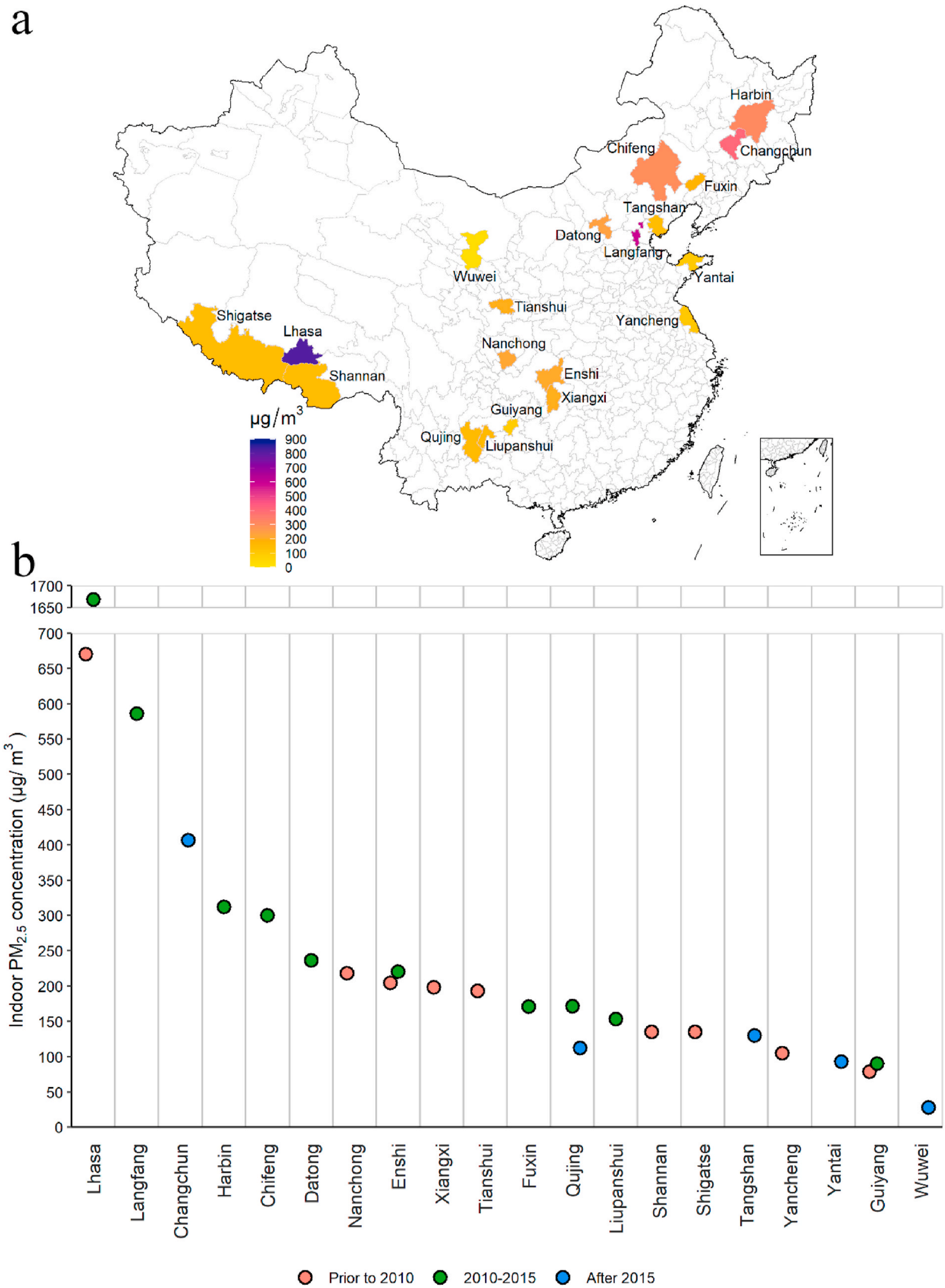

Fig. 3. Indoor $PM_{2.5}$ concentrations in rural areas. (a) spatial distribution of indoor $PM_{2.5}$ concentrations; (b) measured $PM_{2.5}$ concentrations in each of the included study cases. The weighted average values of the number of tested buildings were used to represent the concentration levels in (a). Each dot in (b) represents one sample size.

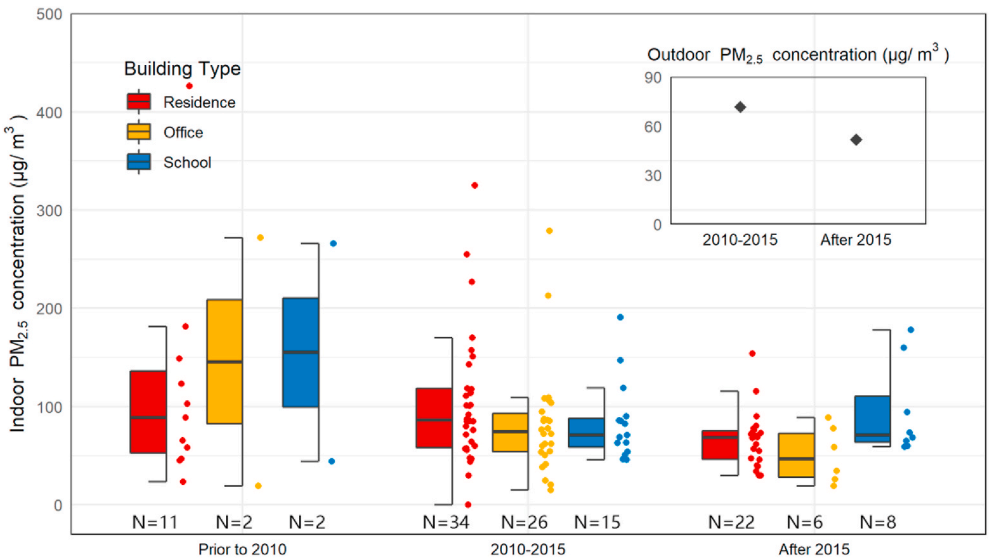

Fig. 4. Indoor $PM_{2.5}$ concentrations of residences, offices and schools in urban areas across different time periods. Corresponding sample sizes for each category are shown at the bottom. The outdoor $PM_{2.5}$ concentrations are the average concentrations of the corresponding cities with indoor $PM_{2.5}$ concentrations except Hongkong and Taipei from 2013 to 2018 [126–131]. The outdoor $PM_{2.5}$ concentration data of each city in each year are summarized in Table A5 in the Supporting Information.

most studies in rural areas were conducted in the season during which coal or biomass fuel are generally burned in stoves for heating in rural houses; (2) kitchens in rural residences are not well separated from other rooms; cooking and resting may even be done in the same rooms. In addition, most rural residences do not have smoke exhaust ventilators installed in their kitchens, which is different from urban residences.

4. Discussion

As the analyses were only based on the data from the reviewed studies, this study has some limitations. the measurement time in different studies varies considerably. For example, some studies sampled continuously for seven days, while others performed measurements for only 30 min. This leads to an uneven quality of data, which may

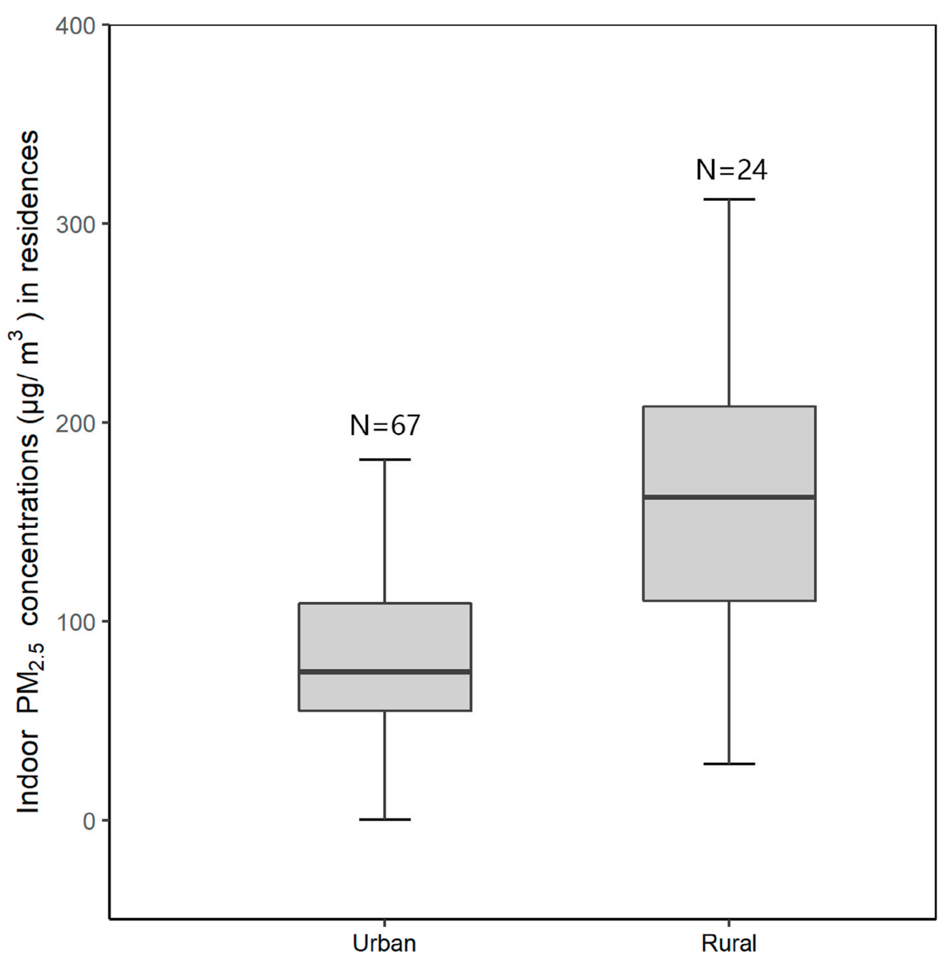

Fig. 5. Comparison of indoor $PM_{2.5}$ concentrations in urban and rural residences. Corresponding sample sizes for each category are shown in the figure.

inadequately reflect indoor $PM_{2.5}$ concentrations. More than half of the reviewed studies reported indoor $PM_{2.5}$ concentrations measured using the light scattering method, which has high uncertainty and generally requires calibration. However, many studies didn't indicate the calibration method or whether calibration was employed. Therefore, we suggest that future studies record detailed information on each measurement, including the outdoor $PM_{2.5}$ concentration during measurement, building location (e.g., near the road), ventilation type (natural ventilation or mechanical ventilation), human activity (e.g., smoking and cooking) and measurement process.

In addition, we did not analyze the influence of different factors on indoor $PM_{2.5}$ concentration owing to the lack of data and uneasy control of factors. More than half of the reviewed studies were conducted in winter when air pollution is usually severe in China. This may lead to a higher measured $PM_{2.5}$ concentration than the average annual level. The concentration data obtained from the studies were extremely limited, especially the data from offices and schools, which influenced the significant difference analysis among the three building types. Most of the studies were conducted in economically developed cities in eastern China, such as Beijing, and Guangzhou. Although indoor $PM_{2.5}$ concentrations in these cities are high, indoor $PM_{2.5}$ pollution may be more severe in western China and rural areas, but few studies have been conducted in those areas. It is therefore suggested that long-term national indoor $PM_{2.5}$ concentration measurements should be performed in the future to obtain more comprehensive and accurate indoor $PM_{2.5}$ concentrations.

5. Conclusions

By reviewing the measured indoor $PM_{2.5}$ concentrations in China reported in the literature published in the past 40 years, we draw the following conclusions:

(1) Light scattering and weighing filtration membrane are the two main methods used to measure indoor $PM_{2.5}$ concentrations in China.
(2) The urban areas considered are mainly distributed in the middle and eastern part of China, while the rural areas are mainly distributed in northeast, north, and southwest China. Prior to 2010, the highest indoor $PM_{2.5}$ concentration in urban areas was in Beijing (296.1 μg/m^3), while the lowest was in Taipei (23.7 μg/m^3). Between 2010 and 2015, the highest and lowest indoor $PM_{2.5}$ concentrations in urban areas were in Harbin (270.9 μg/m^3) and Lhasa (0.1 μg/m^3), respectively. Taian and Changchun recorded the highest (178.3 μg/m^3) and lowest (29.9 μg/m^3) indoor $PM_{2.5}$ concentrations, respectively, in urban areas after 2015. Regarding indoor $PM_{2.5}$ concentrations in rural areas, the highest and lowest indoor $PM_{2.5}$ concentrations were in Lhasa (813.1 μg/m^3) and Wuwei (28.2 μg/m^3), respectively.
(3) The indoor $PM_{2.5}$ concentrations in urban areas decreased significantly, mainly owing to the decline of outdoor $PM_{2.5}$ concentrations, caused by the air pollution prevention and control action plan that started in 2013 in China. The indoor $PM_{2.5}$ concentration decreased from 127.5 ± 111.4 μg/m^3 prior to 2010 to 70.1 ± 35.2 μg/m^3 following 2015.
(4) The indoor $PM_{2.5}$ concentration in rural areas was much higher than that in urban areas. The indoor $PM_{2.5}$ concentration in rural area residences was 275.7 ± 326.4 μg/m^3, while that in urban areas was 95.4 ± 71.0 μg/m^3. The higher indoor $PM_{2.5}$ concentrations in rural areas are generally due to the burning of coal or biomass fuel and the structure of rural residences where the kitchen is not well separated from other rooms.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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