Environmental Science and Pollution Research (2021) 28:68134–68143
https://doi.org/10.1007/s11356-021-15244-z

RESEARCH ARTICLE

Evaluation of life expectancy loss associated with submicron and fine particulate matter (PM_1 and $PM_{2.5}$) air pollution in Nanjing, China

Hao Zheng[1] · Weizhuo Yi[2,3] · Zhen Ding[1] · Zhiwei Xu[4] · Hung Chak Ho[5,6] · Jian Cheng[2,3] · Mohammad Zahid Hossain[7] · Jian Song[2,3] · Yinguang Fan[2,3] · Jing Ni[2,3] · Qingqing Wang[1] · Yan Xu[1] · Jing Wei[8,9] · Hong Su[2,3]

Received: 5 May 2021 / Accepted: 28 June 2021 / Published online: 15 July 2021

Abstract

Particulate matters with an aerodynamic diameter ≤1 μm (PM_1) significantly increased mortality risk, and the effect of PM_1 was even greater than that of $PM_{2.5}$ (aerodynamic diameter ≤2.5 μm). But the quantitative impact of PM_1 on life expectancy was unknown. We aim to examine the extent to which that people's life expectancy was shortened by PM_1 and $PM_{2.5}$. We obtained daily data on deaths, PM_1 and $PM_{2.5}$ records, and weather variables during 2016–2017 in Nanjing, China. Years of life lost (YLLs) were calculated by matching each decedent's age and sex to the Chinese life table. The fitted nonlinear dose-response associations of YLLs with PM_1 and $PM_{2.5}$ were estimated by utilizing a generalized additive model with a Gaussian link that controlled for confounding factors including meteorological variables, day of week, and long-term trend and seasonality. The effect estimates were presented as the YLLs when PM_1 and $PM_{2.5}$ concentrations fell in different ranges. Life expectancy losses attributable to PM_1 and $PM_{2.5}$ were calculated. Stratified analyses were also performed by age, sex, and death causes. Significant PM-YLL associations were observed, with greater increases in YLLs associated with PM_1 (68.9 thousand). PM_1 was estimated to reduce life expectancy, which was greater than $PM_{2.5}$ (PM_1: 1.67 years; $PM_{2.5}$: 1.55 years). For PM_1, greater years of loss in PM-related life expectancy were found in the female group, ≥65 years group, and cardiovascular disease group. Exposure to PM_1 had a greater impact on life expectancy loss than did $PM_{2.5}$. Constant efforts are urgently needed to control PM_1 air pollution to improve people's longevity.

Keywords Particulate matter · PM_1 · YLL · Life expectancy · Air pollution · Responsible Editor: Lotfi Aleya

Hao Zheng, Weizhuo Yi and Zhen Ding contributed equally to this work.

Responsible Editor: Lotfi Aleya

✉ Jing Wei
weijing_rs@163.com

✉ Hong Su
suhong5151@sina.com

1 Department of Environmental Health, Jiangsu Provincial Center for Disease Control and Prevention, Nanjing 210009, China

2 Department of Epidemiology and Health Statistics, School of Public Health, Anhui Medical University, Hefei, Anhui, China

3 Inflammation and Immune Mediated Diseases Laboratory of Anhui Province, Hefei, China

4 School of Public Health, Faculty of Medicine, University of Queensland, Brisbane, Australia

5 Department of Urban Planning and Design, The University of Hong Kong, Hong Kong, China

6 School of Geography and Remote Sensing, Guangzhou University, Guangzhou, China

7 International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B), Dhaka, Bangladesh

8 Department of Chemical and Biochemical Engineering, Iowa Technology Institute, Center for Global and Regional Environmental Research, The University of Iowa, Iowa City, IA, USA

9 Department of Atmospheric and Oceanic Science, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA

Introduction

Exposure to air pollution, especially particulate matter (PM), can significantly increase mortality risk (Guo et al. 2013; Hayes et al. 2020; Huang et al. 2017). In China, the disability-adjusted life years (DALYs) from $PM_{2.5}$ (aerodynamic diameter ≤2.5 μm) pollution in 2017 ranked fourth among risk factors (Zhou et al. 2019). Studies have shown that $PM_{2.5}$ exposure can increase the death risk even below air quality standards concentrations (Cheng et al. 2021; Cohen et al. 2017; Di et al. 2017). At present, $PM_{2.5}$-related cause-specific mortality and morbidity have been widely investigated, mainly including cardiovascular diseases and respiratory diseases (Huang et al. 2019; Yin et al. 2020). Importantly, increasing studies suggested that the smaller the size fractions of PM such as PM_1 (aerodynamic diameter ≤1 μm) may have the greater impacts on human health (Hu et al. 2018; Kan 2017).

As a major component of $PM_{2.5}$, PM_1 has a greater surface area allowing it to carry more toxins and making it more easily to be absorbed into the blood through the alveoli (Kan 2017; Tian et al. 2019; Yang et al. 2018). At present, studies on PM_1 and population health are lacking due to the limited availability of routine surveillance data (Chen et al. 2019; Hu et al. 2018; Wang et al. 2021a, b, c; Yang et al. 2018). Previous studies have shown that PM_1 is associated with increased mortality and morbidity from multiple disease causes, as well as increased emergency department visits (Hu et al. 2018; Liu et al. 2021). However, taking morbidity and mortality as outcome indicators only cannot take into account the age difference of subjects, which may not truly reflect the disease damage. Year of life lost (YLL) is an important component of DALYs, which is a measure of the burden of disease based on life expectancy (Odhiambo Sewe et al. 2018). As a novel and precise indicator to measure disease burden, YLL has also been used as a supplement of morbidity and mortality in previous studies (Xu et al. 2014; Zhou et al. 2019). Compared with the traditional mortality indicator, YLL puts more weight on mortality among young people, which was commonly used to describe and determine the loss of life due to premature death. A recent study has indicated that $PM_{2.5}$ significantly shortened life expectancy and accounted for a great mortality burden in Hong Kong (Cheng et al. 2021). However, relevant analysis is urgent to be carried out in other cities due to regional differences in PM concentration. Besides, it remains unclear to what extent PM_1 affects YLL and whether the harm effect is greater than $PM_{2.5}$.

To fill in the knowledge gap above, a generalized additive model with a Gaussian link was used to investigate the associations between PMs (PM_1 and $PM_{2.5}$) and YLL in Nanjing, China. The attributable YLLs and related loss of life expectancy were estimated by age, sex, and major causes of death.

Materials and methods

Study setting

This study was conducted in Nanjing, the capital city of Jiangsu Province of China (Figure S1). Nanjing is a rapidly developing and highly dense city, with 8.3 million population living in an area of 6587.02 square kilometers (km^2) in 2017 (population density reached 1265 persons/km^2 in 2017). In Nanjing, PMs were reported to be the dominant major pollutants to poor air quality in recent years, exceeding the Chinese Ambient Air Quality Standard Grade I (Mao et al. 2020).

Data collection

Data on death and the calculation of YLL

Daily deaths in Nanjing from January 1, 2016, to December 31, 2017, were provided by Jiangsu Provincial Center for Disease Control and Prevention. The calculation of YLL used yearly life tables provided by World Health Organization. Consistent with previous studies (Cheng et al. 2021; Qi et al. 2020), YLLs for each death were calculated by matching age and sex to the life table. YLLs for all deaths within each day were summed up to create the time-series of daily YLLs in 2016–2017 for total population and subgroups (sex, age, and death causes). Deaths for two major diseases, including cardiovascular disease (ICD-10: I00-I99) and respiratory disease (ICD-10: J00-J99), were extracted for analysis.

Data on air pollution and meteorological variables

Regarding air pollution exposure data, we obtained daily satellite remote sensed PM_1 data with a spatial resolution of 1 km from previous studies (Wang et al. 2021a, b, c; Wei et al. 2019 2021). Briefly, the remote sensing technique was used to collect daily information of PM_1 from China Atmosphere Watch Network (CAWNET) and interpolated the processed spatial time-series data (resolution: 1 km) based on CAWNET (dataset is available at https://weijing-rs.github.io/product.html). To derive the daily estimation of PM_1 data, an ensemble learning model was established based on air quality information from 153 stations of CAWNET, topographic characteristics, Multi-Angle Implementation of Atmospheric Correction (MAIAC) aerosol optical depth (AOD) product, land use information, road network, MEIC emission data, and nighttime light (Wei et al. 2019, 2021). During the study period, PM_1 prediction data had a high consistency with observed data. Other air pollution data including $PM_{2.5}$ and NO_2 were obtained from ground monitoring stations, which was provided by the National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/). Besides, we collected daily meteorological variables including maximum, mean, and minimum temperatures and relative humidity during 2016–2017 from the China Meteorological Data Sharing System (http://data.cma.cn).

Statistical analysis

A two-stage approach was conducted to investigate the relationship between PM_1 and $PM_{2.5}$ and YLL in this study. In the first stage, we found that YLL follows a normal distribution (Figure S2); a generalized additive model with a Gaussian link was used to fit the dose-response associations of PM_1-YLL and $PM_{2.5}$-YLL, respectively (Huang et al. 2012; Wei et al. 2021; Zhu et al. 2017). The effects of PM_1 and $PM_{2.5}$ in different subgroups (sex, age) were further investigated to identify vulnerable subpopulations. Then, we estimated total YLLs and reduced life expectancy attributable to PM_1 and $PM_{2.5}$ under different percentile range based on fitted nonlinear associations.

Firstly, to capture the nonlinear dose-response associations of PM_1-YLL and $PM_{2.5}$-YLL, a natural cubic spline with three degrees of freedom (*dfs*) was used for the 0–2-day moving average of PM variables based on the generalized cross-validation (GCV) score. Consistent with previous studies (Cheng et al. 2021; Guo et al. 2013), the potential confounders controlled in the model mainly included meteorological variables, day of week (DOW, controlled for as a categorical variable), and long-term trend and seasonality. The mean temperature, diurnal temperature range, and relative humidity (0–21-day moving average) with a natural cubic spline with three *dfs* were adjusted for their nonlinear and lagged effects. We controlled for the long-term trend and seasonality of YLL by using a natural cubic spline with seven *dfs* per year for calendar time.

The effect estimates were presented as the YLLs when PM_1 and $PM_{2.5}$ concentrations fell in different ranges (≥25th percentile, ≥50th percentile, and ≥75th percentile, full range) in this study. Stratified analysis was further carried out based on demographic characteristics (sex and age). Sex was divided into male and female, and age was divided into 0–64 years old and ≥65 years old. Stratified analyses for respiratory and cardiovascular diseases were also performed.

Secondly, based on fitted nonlinear dose-response associations both in total population and subgroups, the YLLs attributable to PM_1 and $PM_{2.5}$ during the study period were the sum of the daily YLLs associated with PMs in different ranges (≥25th percentile, ≥50th percentile, and ≥75th percentile, full range). As described in previous studies (Qi et al. 2020; Xu et al. 2014), the average loss of life expectancy was calculated by dividing the attributable YLLs by the total number of deaths during the study period.

To test for the robustness of the model, sensitivity analysis was conducted by changing *dfs* (2 to 6) of mean temperature, diurnal temperature range, and relative humidity. All statistical analyses were conducted in R software (version 3.4.0).

Results

Descriptive statistics

Table 1 and Figure S3 present the descriptive statistics of death counts, YLLs, air pollution, and meteorological variables in Nanjing during 2016–2017. Overall, the average daily deaths and YLLs were 113 and 1406, respectively. The death counts and YLLs in males and deaths aged ≥65 years were greater than those in females and those aged 0–64 years. The average concentration of PM_1 was 32.0 $\mu g/m^3$, and $PM_{2.5}$ was 45.9 $\mu g/m^3$.

Dose-response associations of PM_1-YLL and $PM_{2.5}$-YLL

In Fig. 1, we observed significant nonlinear dose-response relationships between PM_1-YLL and $PM_{2.5}$-YLL in the total population, respectively. YLL changes were steeper for both PM_1 and $PM_{2.5}$ at low concentration level (<25th percentile) and remained steady with increasing concentrations. Besides, the estimated changes in years of life lost associated with PM_1 and $PM_{2.5}$ at different concentration cut-offs were compared, indicating that the effect of PM_1 on YLL has no significant difference from that of $PM_{2.5}$ ($P = 0.136$) (Table S1).

Figure 2 presents a nonlinear dose-response relationship for subgroups by sex, age, and death causes. In general, the dose-response curves of PM_1-YLL and $PM_{2.5}$-YLL in subgroups were similar to those in the total population except for the respiratory disease group. No significant dose-response relationship was found between PM_1 and YLL in the male group.

Attributable YLLs associated with PM_1 and $PM_{2.5}$

As presented in Fig. 3a, a total of 68.9 thousand and 63.6 thousand YLLs per year were attributed to PM_1 and $PM_{2.5}$, accounting for 13.40% and 12.37% of all YLLs, respectively. Both in total population and in each subgroup, the YLLs attributable to PM_1 per year were higher than those attributable to $PM_{2.5}$ in different percentile ranges (≥25th, ≥50th, ≥75th, full range) (Figs. 3a and 4). A total of 38.3 thousand YLLs per year were attributed to PM_1 in females, while no YLLs were attributed to PM_1 in males (Fig. 4a, b). The YLLs attributable to PM_1 and $PM_{2.5}$ in the ≥65 years group were greater than those in the 0–64 years group in different percentile ranges (Fig. 4c, d). The YLLs associated with PM_1 and $PM_{2.5}$ in the respiratory disease group were much lower than those in the cardiovascular disease group (Fig. 4e, f).

Table 1 Summary statistics of daily deaths, years of life lost, air pollutants, and weather conditions in Nanjing, China, 2016–2017

	Minimum	25th percentile	Mean	50th percentile	75th percentile	Maximum
Death counts						
Total	69	101	113	111	124	180
Male	35	56	63	63	70	103
Female	27	43	49	48	55	91
0–64 years	8	19	22	22	26	40
≥65 years	49	79	90	88	100	147
Years of life lost (years)						
Total	795	1252	1406	1384	1547	2374
Male	394	719	823	812	917	1407
Female	258	493	583	574	658	1166
0–64 years	192	542	650	633	750	1210
≥65 years	395	672	757	745	839	1210
Air pollutants						
PM_1 (μg/m^3)	11.9	23.0	32.0	28.4	38.8	84.3
$PM_{2.5}$ (μg/m^3)	6.7	24.5	45.9	39.0	58.2	219.9
NO_2 (μg/m^3)	16.0	33.0	45.7	42.0	56.0	126.0
Weather variables						
Mean temperature (°C)	−6.7	9.1	16.9	17.1	24.2	34.7
Diurnal temperature range (°C)	0.7	5.2	7.8	7.9	10.0	19.2
Relative humidity (%)	32.0	62.5	72.4	73.0	84.0	100.0

PM_1, particulate matter with aerodynamic diameter ≤1 μm; *$PM_{2.5}$*, particulate matter with aerodynamic diameter ≤2.5 μm; *NO_2*, nitrogen dioxide

Loss of life expectancy

The losses of life expectancy caused by PM_1 and $PM_{2.5}$ were 1.67 and 1.55 years, respectively (Fig. 3b). The life expectancy losses associated with PM_1 were similar to those associated with $PM_{2.5}$ in different percentile ranges (≥25th, ≥50th, ≥75th, full range). For example, there would be 1.35 and 1.05 years gains of life expectancy if PM_1 and $PM_{2.5}$ concentrations were below the 50th percentile, respectively. In Fig. 5, the losses of life expectancy associated with PM_1 and $PM_{2.5}$ in the female group, the ≥65 years group, and the cardiovascular disease group were greater than those in the male group, the 0–64 years group, and the respiratory disease group, respectively.

Sensitivity analysis

By adjusting for the *dfs* of mean temperature, diurnal temperature range, and relative humidity, we found that the fluctuation of the models and dose-response curves was slight, indicating that the models were robust enough (Table S2). Besides, a double-pollutant model was established by controlling NO_2, generating a similar dose-response curve with the single-pollutant model (Figure S4).

Discussion

To our knowledge, this study is the first time-series study to investigate the association between PM_1 and YLL. It is found that the losses of life expectancy associated with PM_1 and $PM_{2.5}$ were 1.67 years and 1.55 years, respectively, indicating that PM_1 has a greater impact on YLL than $PM_{2.5}$. Further studies of vulnerable populations showed that losses of life expectancy related to PMs in the female group, the ≥65 years group, and the cardiovascular disease group were higher than those in the male group, the 0–64 years group, and the respiratory disease group, respectively. This finding provides a reference for the formulation and evaluation of PM_1 and $PM_{2.5}$ air quality standards in the future.

The average concentration of $PM_{2.5}$ in this study was 45.9 μg/m^3, lower than the Chinese Ambient Air Quality Standard Grade II ($PM_{2.5}$ <75 μg/m^3). There have been many studies over the past few years indicating a significant association between $PM_{2.5}$ and life expectancy (Cheng et al. 2021; Jia et al. 2021; Moradi et al. 2021; Qi et al. 2021; Zallaghi et al. 2021; Zhu et al. 2017). Some of these studies have found nonlinear dose-response curves similar to this study (namely steep at low concentration and stable at high concentration). With the development of the air pollution warning system (Li and Zhu 2018; Mo et al. 2019), people's protection

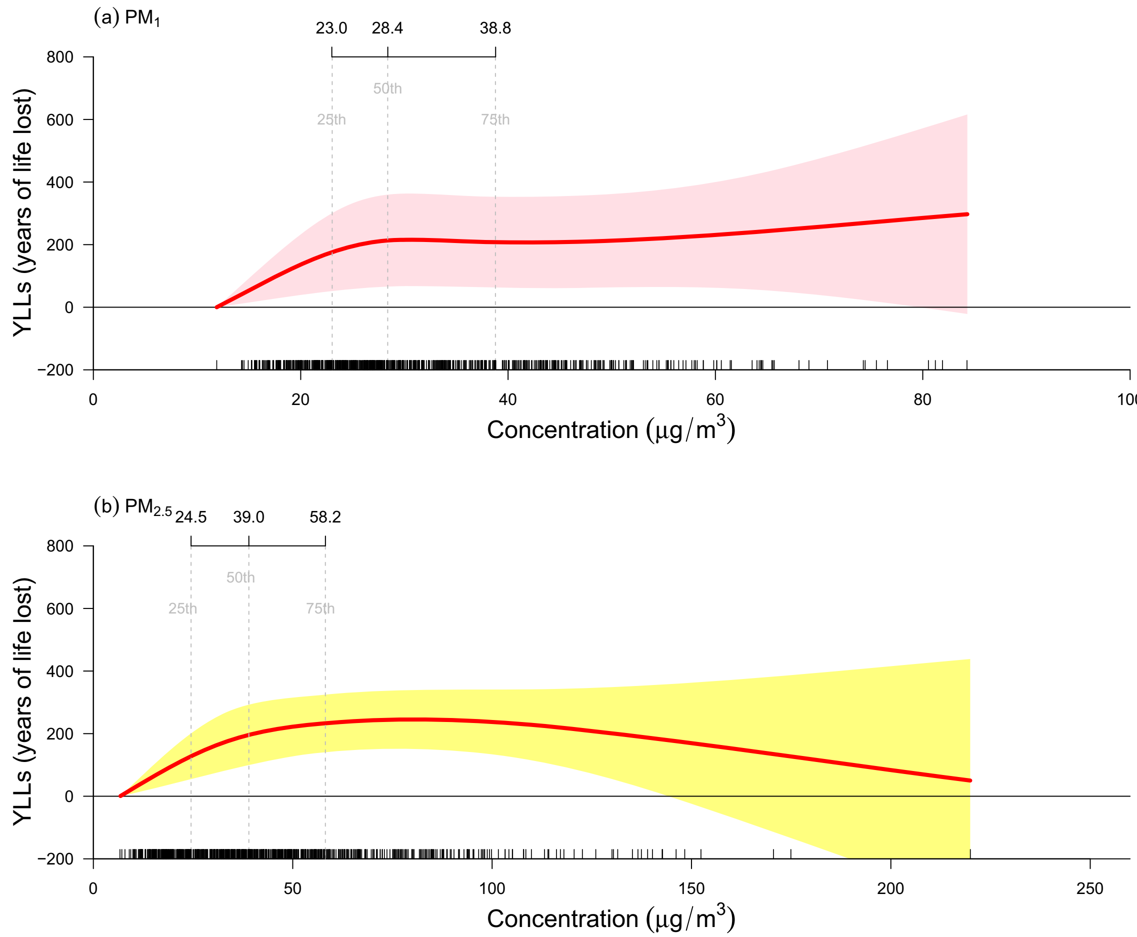

Fig. 1 Dose-response relationships between daily PM_1 and $PM_{2.5}$ concentrations and YLLs for the total population. (**a**) Relationship of PM_1-YLL; (**b**) relationship of $PM_{2.5}$-YLL. PM_1, particulate matter with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; YLLs, years of life lost

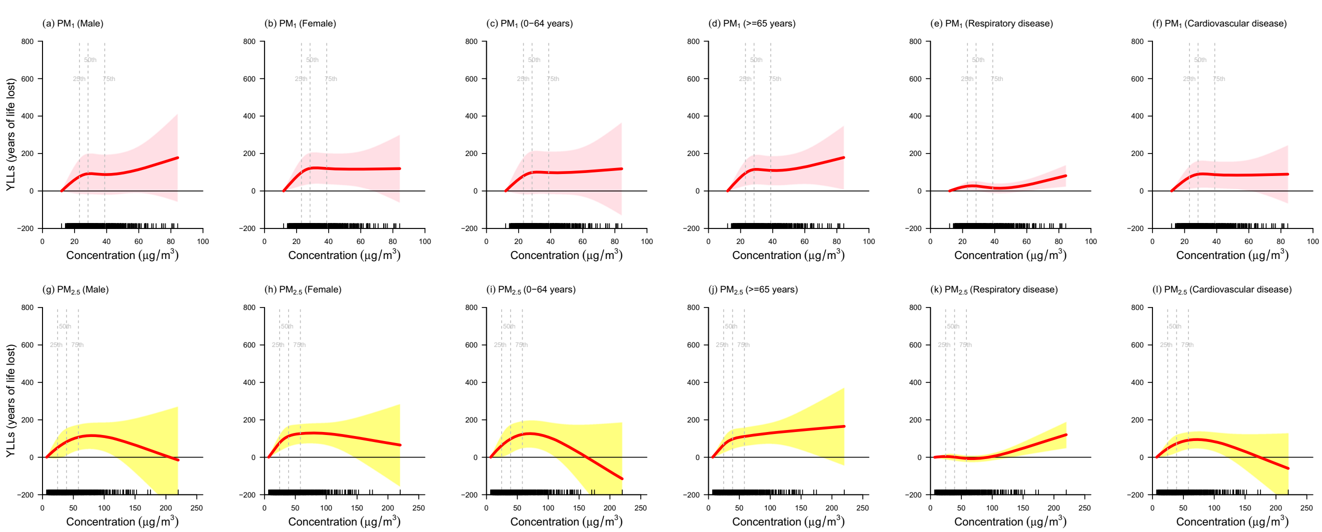

Fig. 2 Dose-response relationships between daily PM_1 and $PM_{2.5}$ concentrations and YLLs for the population by sex, age, and causes of death. (**a**–**f**) Relationship of PM_1-YLL; (**g**–**l**), relationship of $PM_{2.5}$-YLL. PM_1, particulate matter with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; YLLs, years of life lost

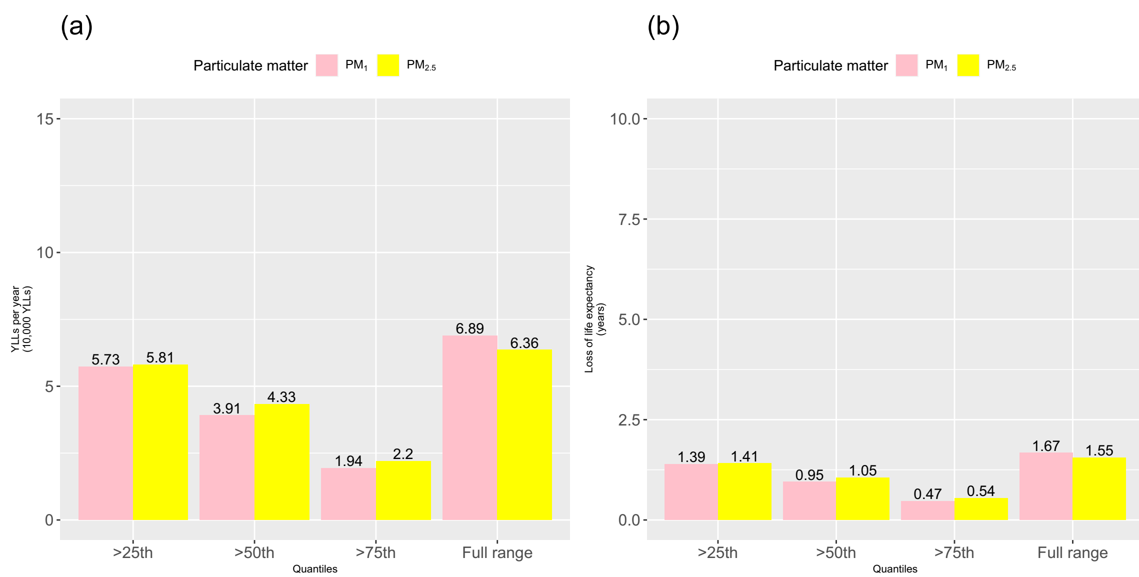

Fig. 3 YLLs per year and loss of life expectancy attributed to PM_1 and $PM_{2.5}$ in different percentile ranges for the total population. (**a**) YLLs per year attributed to PM_1 and $PM_{2.5}$. (**b**) Loss of life expectancy attributed to PM_1 and $PM_{2.5}$. PM_1, particulate matter with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; YLLs, years of life lost

consciousness is improving gradually in recent years (Qian et al. 2016). People would take effective measures (e.g., staying indoors, using air purifiers, and wearing anti-smog masks) during days with high air pollution levels, which may reduce PM-related YLLs. This may partly explain the nonlinear dose-response curves between PMs and YLL. In a word, previous studies, together with the present study, found that $PM_{2.5}$ at both high and low concentrations (even below air quality standards) can significantly increase YLLs, suggesting the need to re-evaluate the air quality standards for $PM_{2.5}$.

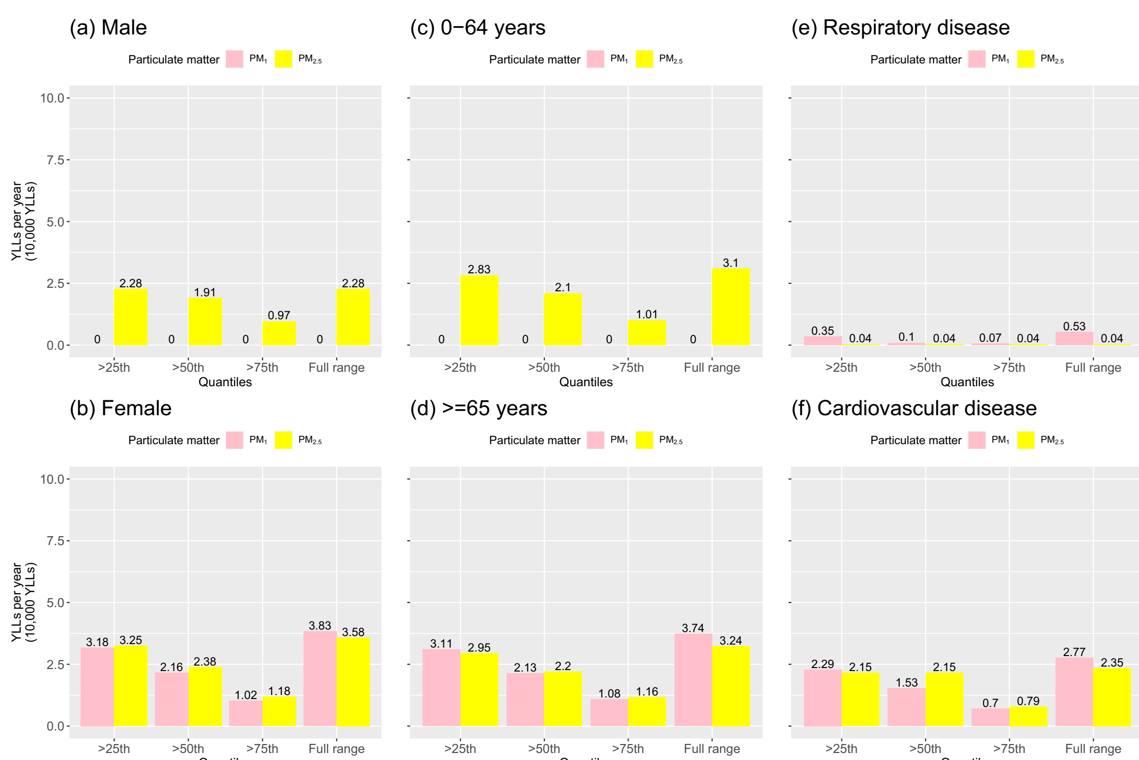

Fig. 4 YLLs per year loss of life expectancy attributed to PM_1 and $PM_{2.5}$ in different percentile ranges for the population by sex, age, and causes of death. (**a**, **b**) YLLs per year by sex; (**c**, **d**) YLLs per year by age; (**e**, **f**) YLLs per year by causes of death. PM_1, particulate matter with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm; YLLs, years of life lost

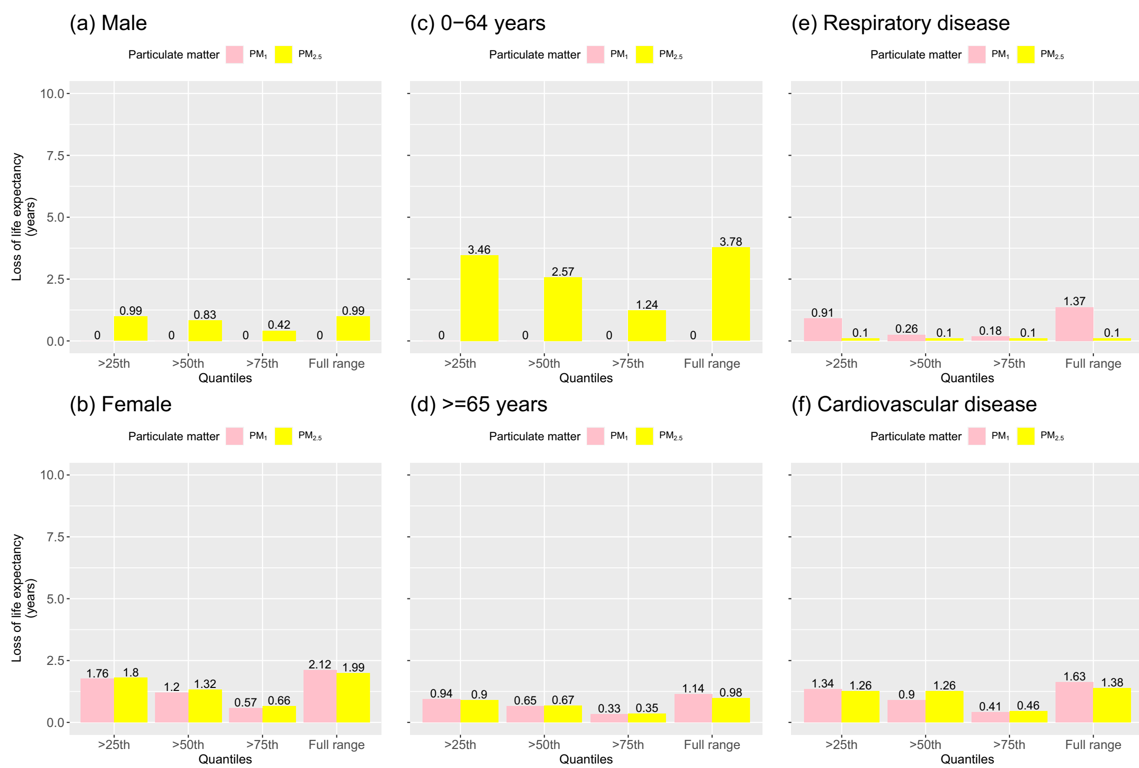

Fig. 5 Loss of life expectancy attributed to PM_1 and $PM_{2.5}$ in different percentile ranges for the population by sex, age, and causes of death. (**a**, **b**) Loss of life expectancy by sex; (**c**, **d**) loss of life expectancy by age; (**e**, **f**) loss of life expectancy by causes of death. PM_1, particulate matter with aerodynamic diameter ≤1 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤2.5 μm

Besides, PM_1 has a smaller particle size and can carry more toxic substances. And assessing the association between PM_1 and YLL may emphasize its potential as an indicator of air quality monitoring. In recent years, with the progress of monitoring technology and the improvement of sampling equipment, the research focus has gradually changed from large particle size (PM_{10} and $PM_{2.5}$) to small particle size (PM_1). However, the association between PM_1 and YLL remains largely unknown in China, partly due to the lack of availability of PM_1 monitoring data. A previous study in Zhejiang Province, China, found that PM_1 significantly increased the relative risk of all-cause death (Hu et al. 2018; Wang et al. 2021a, b, c). Besides, PM_1 has also been shown to be associated with emergency room visits and the risk of death from certain diseases such as cardiovascular disease (Chen et al. 2019; Liu et al. 2021; Yang et al. 2019a; Zhu et al. 2021). These results may support our finding, namely short-term exposure to PM_1 may increase the burden of death.

In this study, there were greater PM_1-related YLLs than $PM_{2.5}$, which is consistent with the previous hypothesis of the smaller particle size and the greater health effect. Compared with $PM_{2.5}$, PM_1 had a smaller particle size and larger surface area and carries more toxic substances (Chen et al. 2017; Wang et al. 2021a, b, c; Wu et al. 2020), which may result in a stronger permeability and a larger deposition area of PM_1 in the lung. The sources of PMs are complex, and the size of health impact varies according to the toxic characteristics of the components they carry (Buczyńska et al. 2014; Filep et al. 2016; Martins et al. 2020; Samek et al. 2017). A study has indicated that the concentrations of mineral and marine elements increased with increasing PM size, while anthropogenic elements were the opposite (Martins et al. 2020). This suggests that the benefits would be greater if anthropogenic sources of PM_1 are controlled. The components of PMs include heavy metals, polycyclic aromatic hydrocarbons, nitrates, and bacteria, which will be absorbed directly or indirectly through the alveoli into the blood circulation and can further cause inflammation and activation of oxidative stress (Hassanvand et al. 2015; Lin et al. 2016; Samek et al. 2018; Wang et al. 2015). For instance, animal studies have shown that the level of serum malondialdehyde (MDA), nitric oxide (NO), and nitric oxide synthase (NOS) increased in lung lavage fluid, and the activity of superoxide dismutase (SOD) decreased, which indicated that both $PM_{2.5}$ and PM_1 can cause oxidative damage in the body (Wang et al. 2021a, b, c). In conclusion, a better understanding of the exact mechanism by which PMs harm human health does not only help to identify the sources of air pollution (coal-burning, vehicle exhaust, power generation emissions, etc.) for intervention (Gao et al. 2018; Huang et al. 2020) but also of great significance for the personal protection and early warning for the whole population, especially the susceptible population.

Subgroup analysis by sex and age indicated that greater losses of life expectancy were found in the female group and the ≥65 years group. Current findings on the association between $PM_{2.5}$ and YLL by sex were mixed, which may be caused by differences in $PM_{2.5}$ exposure periods and characteristics of the study regions (Bennett et al. 2019; Cheng et al. 2021; Moradi et al. 2021; Zhu et al. 2017). However, studies from Hong Kong and Wuxi, China, also indicated that the YLLs associated with short-term $PM_{2.5}$ exposure were higher in females, which is consistent with our finding (Cheng et al. 2021; Zhu et al. 2017). As for age, the losses of life expectancy associated with $PM_{2.5}$ were greater in people aged 0–64 years in this study possibly because the elderly themselves have much less life expectancy than the younger people. This may result in lower losses of life expectancy in the elderly than that in the younger group, though the elderly were more sensitive to PM (Zhu et al. 2017). Considering that the death counts of the elderly in this study were much higher than those of the younger group, it is also necessary to invest enough health resources into the personal protection of the elderly population in the future.

A study based on 48 major cities in China and a study in Iran both indicated that $PM_{2.5}$ could significantly increase the YLL of cardiovascular disease (Chen et al. 2020; Li et al. 2020), the same with our findings. Evidence for the association between PM_1 and YLLs of cardiovascular disease is lacking, though the study has indicated that long-term PM_1 exposure was positively related to cardiovascular disease prevalence (Yang et al. 2019b). In this study, the deaths of YLLs caused by cardiovascular diseases accounted for about one-third of the total YLLs. Meanwhile, we found that YLLs attributable to PM_1 and $PM_{2.5}$ for respiratory diseases were significantly lower than those for cardiovascular diseases possibly because cardiovascular diseases such as acute myocardial infarction have higher short-term mortality than the respiratory disease. Future researches should include other disease-burden indicators such as DALYs, which might capture some of the life lost from the nonfatal disease.

Some limitations must be acknowledged in this study. First, the sources of data on PMs were heterogeneous. Exposure data for PM_1 and $PM_{2.5}$ were obtained through geographic interpolation technology and fixed monitoring stations on the ground, respectively, which limited the comparisons of results. Future studies should collect exposure measurements from the same air quality monitoring platform to compare the impacts of different particle sizes. Besides, similar to many other time-series studies, the exposure measurements of the two kinds of PMs may not accurately reflect individual exposure. So, exposure misclassification cannot be excluded. Second, this study only used the single-city data from Nanjing, and our findings should be tested in other regions because the PM exposure characteristics of each city such as particle composition and population characteristics are different. Therefore, it should be cautious in extrapolating our findings to other regions. Third, we only measured the concentrations of PM_1 and $PM_{2.5}$, and there was no further detection of the components of particles or the toxic substances they carried.

This study has the following strengths. First, we innovatively linked PM_1 with YLL, highlighting the harmfulness of PM_1 by comparing it with the $PM_{2.5}$-YLL association. Since PM_1 is not a conventional monitoring indicator in China at present, the quantitative assessment of PM_1-YLL association in this study is helpful for policymakers to include PM with smaller particle sizes in the air quality monitoring system. Second, most of the previous studies on PM_1 and population health were based only on daily satellite remote sensed exposure data. And in this study, we weighted the spatial interpolation data with population density, which is more accurate than previous PM_1 data. Third, subgroup analysis was conducted by gender, age, and major death causes, which identified that females, the elderly (≥65 years), and those with cardiovascular disease suffered greater YLLs associated with PM_1 and $PM_{2.5}$, which can help to allocate public health resources more rationally and targeted in the future. In summary, our finding reinforces the severity of PMs (PM_1 in particular) for the burden of mortality in the population and suggests that future environmental and health policy adjustments should focus on the prevention and control of PM with the smaller size and reassess the potential expectancy benefits.

Conclusion

This study demonstrated a significant association between PM_1 and YLL, and the effect is greater than $PM_{2.5}$. PM_1 seemed to reduce more years in life expectancy in females, people ≥65 years, and those with cardiovascular disease. Substantial health benefits could be obtained by constantly monitoring and controlling PM_1 air pollution, and it should be considered to further evaluate the need to adjust China's current $PM_{2.5}$ air quality standards in Nanjing City.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-15244-z.

Author contribution All authors contributed to the final version of the manuscript and have approved the final article. Their contributions to the article were as follows. Hao Zheng, Weizhuo Yi, and Zhen Ding: conceptualization, methodology, data curation, formal analysis, writing—original draft, writing—review and editing. Zhiwei Xu, Hung Chak Ho, and Jian Cheng: formal analysis, writing—review and editing. Mohammad Zahid Hossain and Jian Song: formal analysis, writing—review and editing. Yinguang Fan and Jing Ni: data curation, validation. Qingqing Wang and Yan Xu: formal analysis, methodology, data curation. Jing Wei and Hong Su: supervision, conceptualization, validation, writing—original draft, writing—review and editing.

Funding This work was supported by the National Natural Science Foundation of China (No. 81773518) and the High-Level Scientific Research Foundation of Anhui Medical University (No. 0305044201).

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This study was approved by the Ethical Committee of Anhui Medical University (Hefei, Anhui, China).

Consent to participate Not applicable. (This study does not contain any individual person's data in any form.)

Consent for publication The authors declare that they agree with the publication of this paper in this journal.

Competing interests The authors declare no competing interests.

References

Bennett JE, Tamura-Wicks H, Parks RM, Burnett RT, Pope CA 3rd, Bechle MJ et al (2019) Particulate matter air pollution and national and county life expectancy loss in the USA: a spatiotemporal analysis. PLoS Med 16:e1002856

Buczyńska AJ, Krata A, Van Grieken R, Brown A, Polezer G, De Wael K et al (2014) Composition of $PM_{2.5}$ and PM_1 on high and low pollution event days and its relation to indoor air quality in a home for the elderly. Sci Total Environ 490:134–143

Chen G, Li S, Zhang Y, Zhang W, Li D, Wei X et al (2017) Effects of ambient PM_1 air pollution on daily emergency hospital visits in China: an epidemiological study. The Lancet Planetary Health 1: e221–e229

Chen G, Wang A, Li S, Zhao X, Wang Y, Li H et al (2019) Long-term exposure to air pollution and survival after ischemic stroke. Stroke 50:563–570

Chen D, Mayvaneh F, Baaghideh M, Entezari A, Ho HC, Xiang Q et al (2020) Utilizing daily excessive concentration hours to estimate cardiovascular mortality and years of life lost attributable to fine particulate matter in Tehran, Iran. Sci Total Environ 703:134909

Cheng J, Ho HC, Webster C, Su H, Pan H, Zheng H et al (2021) Lower-than-standard particulate matter air pollution reduced life expectancy in Hong Kong: a time-series analysis of 8.5 million years of life lost. Chemosphere 272:129926

Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K et al (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. Lancet 389:1907–1918

Di Q, Dai L, Wang Y, Zanobetti A, Choirat C, Schwartz JD et al (2017) Association of short-term exposure to air pollution with mortality in older adults. Jama 318:2446–2456

Filep Á, Fodor GH, Kun-Szabó F, Tiszlavicz L, Rázga Z, Bozsó G et al (2016) Exposure to urban PM_1 in rats: development of bronchial inflammation and airway hyperresponsiveness. Respir Res 17:26

Gao M, Beig G, Song S, Zhang H, Hu J, Ying Q et al (2018) The impact of power generation emissions on ambient $PM_{2.5}$ pollution and human health in China and India. Environ Int 121:250–259

Guo Y, Li S, Tian Z, Pan X, Zhang J, Williams G (2013) The burden of air pollution on years of life lost in Beijing, China, 2004–08: retrospective regression analysis of daily deaths. BMJ 347:f7139

Hassanvand MS, Naddafi K, Faridi S, Nabizadeh R, Sowlat MH, Momeniha F et al (2015) Characterization of pahs and metals in indoor/outdoor PM_{10}/$PM_{2.5}$/PM_1 in a retirement home and a school dormitory. Sci Total Environ 527-528:100–110

Hayes RB, Lim C, Zhang Y, Cromar K, Shao Y, Reynolds HR et al (2020) $PM_{2.5}$ air pollution and cause-specific cardiovascular disease mortality. Int J Epidemiol 49:25–35

Hu K, Guo Y, Hu D, Du R, Yang X, Zhong J et al (2018) Mortality burden attributable to PM_1 in Zhejiang province, China. Environ Int 121:515–522

Huang C, Barnett AG, Wang X, Tong S (2012) The impact of temperature on years of life lost in Brisbane, Australia. Nat Clim Chang 2: 265–270

Huang F, Pan B, Wu J, Chen E, Chen L (2017) Relationship between exposure to $PM_{2.5}$ and lung cancer incidence and mortality: a meta-analysis. Oncotarget 8:43322–43331

Huang K, Yang X, Liang F, Liu F, Li J, Xiao Q et al (2019) Long-term exposure to fine particulate matter and hypertension incidence in China. Hypertension 73:1195–1201

Huang Y, Unger N, Harper K, Heyes C (2020) Global climate and human health effects of the gasoline and diesel vehicle fleets. GeoHealth 4: e2019GH000240

Jia B, Gao M, Zhang X, Xiao X, Zhang S, Lam Yung KK (2021) Rapid increase in mortality attributable to $PM_{2.5}$ exposure in India over 1998–2015. Chemosphere 269:128715

Kan H (2017) The smaller, the worse? Lancet Planetary Health 1:e210–e211

Li C, Zhu Z (2018) Research and application of a novel hybrid air quality early-warning system: a case study in China. Sci Total Environ 626: 1421–1438

Li J, Zhang X, Yin P, Wang L, Zhou M (2020) Ambient fine particulate matter pollution and years of life lost from cardiovascular diseases in 48 large Chinese cities: association, effect modification, and additional life gain. Sci Total Environ 735:139413

Lin H, Tao J, Du Y, Liu T, Qian Z, Tian L et al (2016) Particle size and chemical constituents of ambient particulate pollution associated with cardiovascular mortality in Guangzhou, China. Environ Pollut 208:758–766

Liu L, Song F, Fang J, Wei J, Ho HC, Song Y et al (2021) Intraday effects of ambient PM_1 on emergency department visits in Guangzhou, China: a case-crossover study. Sci Total Environ 750:142347

Mao M, Sun H, Zhang X (2020) Air pollution characteristics and health risks in the Yangtze River Economic Belt, China during winter. Int J Environ Res Public Health 17

Martins V, Faria T, Diapouli E, Manousakas MI, Eleftheriadis K, Viana M et al (2020) Relationship between indoor and outdoor size-fractionated particulate matter in urban microenvironments: levels, chemical composition and sources. Environ Res 183:109203

Mo X, Zhang L, Li H, Qu Z (2019) A novel air quality early-warning system based on artificial intelligence. Int J Environ Res Public Health 16

Moradi M, Hadei M, Yazdani M, Goudarzi M, Baboli Z, Tahmasebi Birgani Y et al (2021) Effect of long-term exposure to $PM_{2.5}$ on years of life lost in a populated Middle Eastern city. Environ Geochem Health

Odhiambo Sewe M, Bunker A, Ingole V, Egondi T, Oudin Åström D, Hondula DM et al (2018) Estimated effect of temperature on years of life lost: a retrospective time-series study of low-, middle-, and high-income regions. Environ Health Perspect 126:017004

Qi J, Ruan Z, Qian ZM, Yin P, Yang Y, Acharya BK et al (2020) Potential gains in life expectancy by attaining daily ambient fine particulate matter pollution standards in mainland China: a modeling study based on nationwide data. PLoS Med 17:e1003027

Qi J, Chen Q, Ruan Z, Qian ZM, Yin P, Liu Y et al (2021) Improvement in life expectancy for ischemic heart diseases by achieving daily ambient $PM_{2.5}$ standards in China. Environ Res 193:110512

Qian X, Xu G, Li L, Shen Y, He T, Liang Y et al (2016) Knowledge and perceptions of air pollution in Ningbo, China. BMC Public Health 16:1138

Samek L, Furman L, Mikrut M, Regiel-Futyra A, Macyk W, Stochel G et al (2017) Chemical composition of submicron and fine particulate matter collected in Krakow. Poland Consequences for the aparic project Chemosphere 187:430–439

Samek L, Stegowski Z, Styszko K, Furman L, Fiedor J (2018) Seasonal contribution of assessed sources to submicron and fine particulate matter in a Central European urban area. Environ Pollut 241:406–411

Tian G, Wang J, Lu Z, Wang H, Zhang W, Ding W et al (2019) Indirect effect of PM_1 on endothelial cells via inducing the release of respiratory inflammatory cytokines. Toxicol Int J Pub Asso BIBRA 57: 203–210

Wang BY, Lang JD, Zhang LN, Fang JH, Cao C, Hao JM et al (2015) [Characterizing Beijing's airborne bacterial communities in $PM_{2.5}$ and PM_1 samples during haze pollution episodes using 16s rRNA gene analysis method]. Huan jing ke xue=. Huanjing Kexue 36: 2727–2734

Wang G, Xu Y, Huang L, Wang K, Shen H, Li Z (2021a) Pollution characteristics and toxic effects of $PM_{1.0}$ and $PM_{2.5}$ in Harbin, China. Environ Sci Pollut Res Int 28:13229–13242

Wang H, Yin P, Fan W, Wang Y, Dong Z, Deng Q et al (2021b) Mortality risk associated with short-term exposure to particulate matter in China: estimating error and implication. Environ Sci Technol 55:1110–1121

Wang X, Xu Z, Su H, Ho HC, Song Y, Zheng H et al (2021c) Ambient particulate matter (PM_1, $PM_{2.5}$, PM_{10}) and childhood pneumonia: the smaller particle, the greater short-term impact? Sci Total Environ 772:145509

Wei J, Li Z, Guo J, Sun L, Huang W, Xue W et al (2019) Satellite-derived 1-km-resolution PM_1 concentrations from 2014 to 2018 across China. Environ Sci Technol 53(22):13265–13274

Wei J, Li Z, Lyapustin A, Sun L, Peng Y, Xue W et al (2021) Reconstructing 1-km-resolution high-quality $PM_{2.5}$ data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens Environ 252

Wu QZ, Li S, Yang BY, Bloom M, Shi Z, Knibbs L et al (2020) Ambient airborne particulates of diameter ≤1 μm, a leading contributor to the association between ambient airborne particulates of diameter ≤2.5 μm and children's blood pressure. Hypertension 75:347–355

Xu Z, Hu W, Wang X, Huang C, Tong S (2014) The impact of temperature variability on years of life lost. Epidemiol 25:313–314

Yang M, Chu C, Bloom MS, Li S, Chen G, Heinrich J et al (2018) Is smaller worse? New insights about associations of PM_1 and respiratory health in children and adolescents. Environ Int 120:516–524

Yang BY, Guo Y, Markevych I, Qian ZM, Bloom MS, Heinrich J et al (2019a) Association of long-term exposure to ambient air pollutants with risk factors for cardiovascular disease in China. JAMA Netw Open 2:e190318

Yang BY, Guo Y, Morawska L, Bloom MS, Markevych I, Heinrich J et al (2019b) Ambient PM_1 air pollution and cardiovascular disease prevalence: insights from the 33 communities Chinese health study. Environ Int 123:310–317

Yin P, Guo J, Wang L, Fan W, Lu F, Guo M et al (2020) Higher risk of cardiovascular disease associated with smaller size-fractioned particulate matter. Environ Sci Technol Lett 7:95–101

Zallaghi E, Goudarzi G, Sabzalipour S, Zarasvandi A (2021) Effects of long-term exposure to $PM_{2.5}$ on years of life lost and expected life remaining in Ahvaz city, Iran (2008–2017). Environ Sci Pollut Res Int 28:280–286

Zhou M, Wang H, Zeng X, Yin P, Zhu J, Chen W et al (2019) Mortality, morbidity, and risk factors in China and its provinces, 1990–2017: a systematic analysis for the global burden of disease study 2017. Lancet 394:1145–1158

Zhu J, Zhang X, Zhang X, Dong M, Wu J, Dong Y et al (2017) The burden of ambient air pollution on years of life lost in Wuxi, China, 2012–2015: a time-series study using a distributed lag non-linear model. Environmental pollution 224:689–697

Zhu F, Chen L, Qian ZM, Liao Y, Zhang Z, McMillin SE et al (2021) Acute effects of particulate matter with different sizes on respiratory mortality in Shenzhen, China. Environ Sci Pollut Res Int