# $PM_{2.5}$-Related Health Economic Benefits Evaluation Based on Air Improvement Action Plan in Wuhan City, Middle China

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## Supporting information

## **Section S1.** Ten Major tasks of Air Improvement Action Plan in Wuhan City

**Table S1.** Ten Major tasks of Air Improvement Action Plan in Wuhan City.

| No. | Major tasks | Concrete measures |
|---|---|---|
| 1 | Strengthen the pollution control of enterprises and reduce the emission of air pollutants | Implement major air pollutant emission reduction projects<br>Promote the upgrading of dust removal facilities in industrial enterprises<br>Strengthen the remediation of polluting enterprises<br>Strengthen the treatment of volatile organic compounds |
| 2 | Strengthen the prevention and control of mobile source pollution and reduce vehicle pollution emissions | Improve the quality of vehicle fuel<br>Strengthen environmental protection management of motor vehicles<br>Develop green transportation<br>Promote the prevention and control of non-road emission |
| 3 | Strengthen the fine management in urban and rural areas, reduce non-point source pollution emissions | Strictly control dust pollution at the construction sites<br>Strictly control road dust pollution<br>Control dust pollution of bare ground and storage yard<br>Strengthen the prevention and control of cooking fume pollution<br>Strictly supervise the burning of straw and other wastes<br>Strictly manage dust from sand and stone mining |
| 4 | Strictly require the access system of energy conservation and environmental protection and optimize industrial development structure | Strict environmental access for construction projects<br>Speed up the elimination of backward production capacity<br>Optimize industrial development layout<br>Establish ecological industrial parks |
| 5 | Accelerate the adjustment of energy structure and improve the utilization rate of clean energy | Strictly control coal consumption<br>Speed up the construction of high pollution fuel prohibition zone<br>Improve energy utilization efficiency |
| 6 | Optimize urban spatial layout and build green ecological barrier | Optimize the layout of urban ecological space<br>Vigorously promote urban greening construction |
| 7 | Improve the emergency system of monitoring and early warning and properly deal with heavy polluted weather | Improve the monitoring and early warning system<br>Improve the emergency capacity of air pollution<br>Actively promote joint prevention and control of regional air pollution |
| 8 | Improve the system of environmental protection laws and policies, and innovate the management mechanism of environmental protection | Improve local atmospheric environmental protection laws and regulations<br>Improve environment economic policy<br>Strengthen environmental supervision and law enforcement<br>Innovate environmental management system |
| 9 | Enhance scientific and technological supports, and strengthen environmental protection industry | Improve the scientific and technological support capacity of air pollution prevention and control<br>Strengthen the research, development and promotion of air pollution control technologies in key areas<br>Vigorously cultivate energy conservation and environmental protection industry |
| 10 | Strengthen information publicity and public opinion guidance, and expand public participation | Strengthening the publicity of government information<br>Strengthen disclosure of corporate information<br>Strengthen the guidance of public opinion including carrying out various forms of publicity and education, and popularizing the knowledge of air pollution prevention and control<br>Actively expand public participation |

In addition, at the government level, there are three safeguards to promote air quality improvement. Strengthen organizational leadership and improve working mechanism; establish assessment system and strengthen responsibility assessment, and increase investment in governance and provide financial guarantee [1].

## **Section S2** Guidelines to Calculate Air Quality index (AQI)

**Table S2.** Individual Air Quality index (IAQI) with corresponding pollutant concentrations.

| IAQI | Pollutant Concentrations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $SO_2$ (Daily average, μg/m³) | $SO_2$ (hourly average, μg/m³) [a] | $NO_2$ (Daily average, μg/m³) | $NO_2$ (hourly average, μg/m³) [a] | $PM_{10}$ (Daily average, μg/m³) | CO (Daily average, mg/m³) | CO (hourly average, mg/m³) [a] | $O_3$ (hourly average, μg/m³) | $O_3$ (8-hour moving average, μg/m³) | $PM_{2.5}$ (Daily average, μg/m³) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 50 | 150 | 40 | 100 | 50 | 2 | 5 | 160 | 100 | 35 |
| 100 | 150 | 500 | 80 | 200 | 150 | 4 | 10 | 200 | 160 | 75 |
| 150 | 475 | 650 | 180 | 700 | 250 | 14 | 35 | 300 | 215 | 115 |
| 200 | 800 | 800 | 280 | 1200 | 350 | 24 | 60 | 400 | 265 | 150 |
| 300 | 1600 | [b] | 565 | 2340 | 420 | 36 | 90 | 800 | 800 | 250 |
| 400 | 2100 | [b] | 750 | 3090 | 500 | 48 | 120 | 1000 | [c] | 350 |
| 500 | 2620 | [b] | 940 | 3840 | 600 | 60 | 150 | 1200 | [c] | 500 |
| Note | a. The hourly average concentration values of $SO_2$, $NO_2$ and CO are only used for real-time reporting, and the daily average concentration limits of corresponding pollutants need to be used in daily reports. b. If the hourly average concentration of $SO_2$ is higher than 800 μg/m³, its IAQI needn't to be calculated. The IAQI of $SO_2$ is reported based on the daily average concentration. c. If the 8-hour average concentration of $O_3$ is higher than 800 μg/m³, its IAQI needn't to be calculated. The IAQI of $O_3$ is reported based on the hourly average concentration. | | | | | | | | | |

AQI can be calculated according to Technical Regulation on Ambient Air Quality Index (HJ 633–2012) [2]. Based on the concentration limits of six pollutants in Table S1, the IAQI can be calculated by Equation (1).

$$\mathrm{IAQI_p} = \frac{\mathrm{IAQI_{Hi}} - \mathrm{IAQI_{Lo}}}{\mathrm{BP_{Hi}} - \mathrm{BP_{Lo}}}\left(\mathrm{C_p} - \mathrm{BP_{Lo}}\right) + \mathrm{IAQI_{Lo}} \quad (1)$$

where $\mathrm{IAQI_p}$ means the IAQI of pollutant p; $\mathrm{C_p}$ means the concentration of pollutant p; $\mathrm{BP_{Hi}}$ means the high value of limit value of pollutant concentration close to $\mathrm{C_p}$ in Table S1; $\mathrm{BP_{Lo}}$ means the low value of limit value of pollutant concentration close to $\mathrm{C_p}$ in Table S1; $\mathrm{IAQI_{Hi}}$ means the IAQI corresponding to $\mathrm{BP_{Hi}}$ in Table S1; $\mathrm{IAQI_{Lo}}$ means the IAQI corresponding to $\mathrm{BP_{Lo}}$ in Table S1.

Then, using Equation (2) to select the maximum value of $\mathrm{IAQI_p}$ as AQI.

$$\mathrm{AQI} = \mathrm{Max}\,\{\mathrm{IAQI_1}, \mathrm{IAQI_2}, \mathrm{IAQI_3}, \dots, \mathrm{IAQI_n}\} \quad (2)$$

where, IAQI means individual air quality index; n means different pollutants, such as $PM_{2.5}$, $PM_{10}$, $SO_2$, $NO_2$, $O_3$, CO.

Finally, the AQI level is determined according to the calculation result of Equation (2).

**Table S3.** AQI value and description.

| AQI value | Description | AQI value | Description |
|---|---|---|---|
| 0~50 | Excellent | 151~200 | Moderate pollution |
| 51~100 | Good | 201~300 | Heavy pollution |
| 101~150 | Mild pollution | > 300 | Serious pollution |

## **Section S3** Exposed population and all-cause mortality rate in Wuhan

**Table S4.** Exposed population and all-cause mortality rate in Wuhan.

| | Exposed population (person) | | | | |
|---|---|---|---|---|---|
| | 2013 | 2014 | 2015 | 2016 | 2017 |
| Jiang'an | 700,179 | 711,084 | 719,531 | 726,209 | 741,784 |
| Jianghan | 485,618 | 486,676 | 486,430 | 486,214 | 496,289 |
| Qiaokou | 528,649 | 527,593 | 526,494 | 524,620 | 528,604 |
| Hanyang | 567,230 | 576,536 | 585,373 | 595,834 | 631,185 |
| Wuchang | 1,086,411 | 1,076,733 | 1,056,137 | 1,041,746 | 1,044,072 |
| Qingshan | 442,347 | 438,525 | 433,676 | 428,816 | 426,289 |
| Hongshan | 927,275 | 936,139 | 948,785 | 964,851 | 1,073,545 |
| Dongxihu | 276,445 | 283,103 | 288,541 | 296,479 | 312,834 |
| Hannan | 111,562 | 112,889 | 113,189 | 113,891 | 114,288 |
| Caidian | 449,084 | 454,810 | 456,551 | 459,923 | 461,772 |
| Jiangxia | 583,623 | 588,943 | 590,510 | 598,280 | 611,436 |
| Huangpi | 1,112,543 | 1,121,602 | 1,124,832 | 1,132,828 | 1,133,207 |
| Xinzhou | 949,527 | 958,484 | 962,617 | 968,759 | 961,212 |
| Wuhan City | 8,220,493 | 8,273,117 | 8,292,666 | 8,338,450 | 8,536,517 |
| All-cause mortality rate (‰) | 4.98 | 4.97 | 5.75 | 5.44 | 11.62 |

## **Section S4** Relative Risk (RR) associated $PM_{2.5}$ exposure to all-cause mortality

**Table S5.** Epidemiological studies linking $PM_{2.5}$ exposure to all-cause mortality.

| RR (95% CI) (10 μg/m³) | Study area | Reference |
|---|---|---|
| 1.0036 (1.0010, 1.0061) | Shanghai, China | Kan et al., 2007 [3] |
| 1.0020 (1.0007, 1.0033) | Xi'an, China | Huang et al., 2012 [4] |
| 1.0088 (1.0030, 1.0416) | 5 urban city districts and 2 rural counties in Beijing, Tianjin, and Hebei Province, China | Zhou et al., 2015 [5] |
| 1.0090 (0.9970, 1.0180) | 31 cities of 16 provinces, China | Cao et al., 2011 [6] |
| 1.1300 (1.0400, 1.2300) | Six US cities | Dockery et al., 1993 [7] |
| 1.1600 (1.0700, 1.2600) | Six US cities | Laden et al., 2006 [8] |
| 1.1400 (1.0700, 1.2200) | Six US cities | Lepeule et al., 2012 [9] |
| 1.0600 (1.0400, 1.0800) | North America (America and Canada), Asia (China), Europe (Netherlands and Italy), Oceania (New Zealand) | Hoek et al., 2013 [10] |

By searching the studies on the health effects of atmospheric $PM_{2.5}$ at home and abroad, Table S4 summarizes the results of relatively representative studies on the relative risk (RR) of all-cause death related to $PM_{2.5}$. In China, there are few studies investigating the concentration-response relationship between $PM_{2.5}$ exposure and all-cause death, some of which were conducted for specific regions [3-5]. Since $PM_{2.5}$ was not monitored in China during the study's cohort period, Cao et al. converted $PM_{10}$ concentrations to $PM_{2.5}$ concentrations (conversion as $PM_{2.5}/PM_{10}\approx0.65$), and then analyzed the concentration-response between $PM_{2.5}$ exposure and health effect endpoints [6]. Hoek et al. conducted a multi-regional meta-analysis and the study had clear health effect endpoints, they reported that excess risk (ER) per 10 μg/m³ increase in $PM_{2.5}$ exposure was 6% (95% CI: 4,8%) increased for all-cause mortality [10]. That suggested a Relative Risk (RR) of 1.0600 with respect to all-cause mortality of long-term exposure to $PM_{2.5}$ [11]. Therefore, this study selects Hoek's findings and calculates the concentration-response coefficients (β) associated with $PM_{2.5}$ exposure based on equation (3) [12].

$$\beta = \frac{\ln(RR)}{\Delta PM} \quad (3)$$

where $\Delta PM_{2.5}$ is the air quality change. For example, if the epidemiological study reported result like "The excess risk (ER) per 10 μg/m³ increase in $PM_{2.5}$ exposure was 6% (95% CI: 4,8%) increased for all-cause mortality", that means △PM is 10 and the value of RR is 1.0600 (95% CI: 1.0400, 1.0800), so β is 0.005827.

## **Section S5** Highest and lowest values of $PM_{2.5}$ concentration in Wuhan

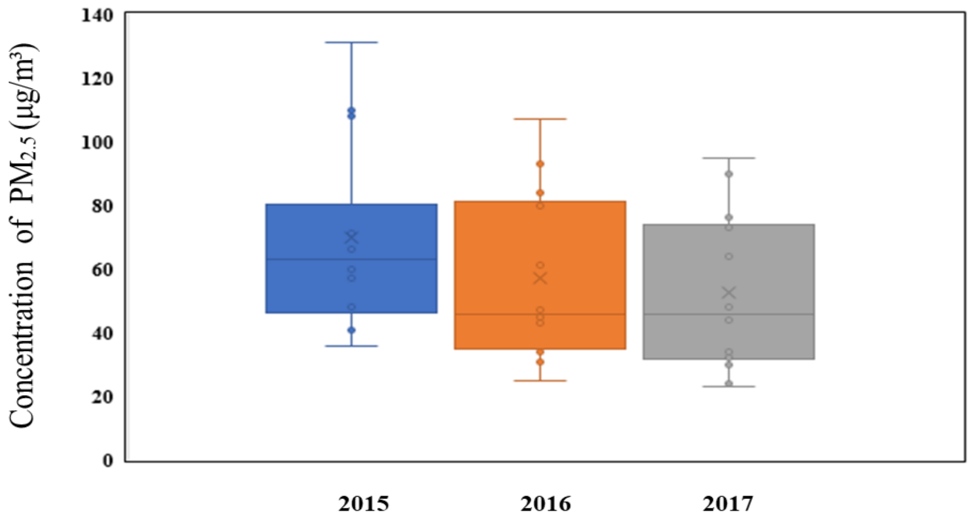


**Figure S1.** Highest and lowest values of monthly average concentration of $PM_{2.5}$ in Wuhan city during the period of 2015–2017.

## **Section S6** Impact of population structure on evaluating the long-term health economic benefits of controlling air pollution

**Table S6.** Total number of $PM_{2.5}$-related avoided premature deaths in Wuhan from 2013 to 2017 by annual estimation method (95% confidence interval).

| District | Time Periods | | | | |
|---|---|---|---|---|---|
| | 2013–2014 | 2014–2015 | 2015–2016 | 2016–2017 | Total |
| Jiang'an | 275 (188-359) | 268 (183-350) | 266 (182-349) | 96 (65-126) | 905 (618-1184) |
| Jianghan | 174 (119-228) | 160 (109-209) | 198 (135-259) | 99 (67-130) | 631 (431-826) |
| Qiaokou | 149 (102-196) | 190 (130-249) | 225 (154-294) | 100 (68-132) | 664 (454-870) |
| Hanyang | 175 (120-230) | 189 (129-247) | 261 (179-341) | 110 (74-144) | 735 (502-962) |
| Wuchang | 429 (294-561) | 316 (216-414) | 458 (314-599) | 179 (121-235) | 1382 (944-1809) |
| Qingshan | 150 (102-196) | 188 (129-245) | 177 (121-232) | 37 (25-49) | 552 (377-722) |
| Hongshan | 354 (242-463) | 344 (235-449) | 364 (248-476) | 80 (54-106) | 1142 (780-1494) |
| Dongxihu | 89 (61-117) | 111 (76-145) | 121 (83-159) | 40 (27-53) | 361 (247-473) |
| Hannan | 26 (17-34) | 26 (18-34) | 50 (34-65) | 4 (3-5) | 106 (71-138) |

| | | | | | |
|---|---|---|---|---|---|
| Caidian | 80 (54-105) | 156 (107-204) | 192 (131-251) | 30 (20-39) | 458 (312-599) |
| Jiangxia | 202 (138-264) | 189 (129-247) | 240 (164-314) | 54 (36-71) | 685 (467-896) |
| Huangpi | 408 (279-534) | 400 (273-523) | 450 (307-588) | 122 (83-161) | 1380 (942-1806) |
| Xinzhou | 366 (250-478) | 377 (258-492) | 371 (253-485) | 85 (57-112) | 1199 (818-1567) |
| Wuhan City | 2877 (1966-3765) | 2912 (1990-3808) | 3373 (2305-4412) | 1035 (702-1363) | 10,200 (6963-13,348) |

From 2013 to 2017, the avoided premature deaths in Wuchang District (1382 people), Huangpi District (1380 people), Xinzhou District (1199 people) and Hongshan District (1142 people) were all over 1000 people due to the decrease of $PM_{2.5}$ concentration. The number of avoided premature deaths in seven central urban districts was 6011 which was 1.43 times as those in the suburban districts. The total number of $PM_{2.5}$-related avoided premature deaths in Wuhan from 2013 to 2017 was added up to 10,200 (95% CI: 6963 to 13,348), these results were smaller than the estimation that setting 2013 as baseline scenario and 2017 as control scenario in this study (21,384, 95% CI: 15,004 to 27,255). Through continuous exploration, we found that the most likely cause of the problem lies in the great change of all-cause mortality rate in Wuhan in 2017, and the change was not only affected by the improvement of air quality, but also greatly influenced by the net migrating rate in Wuhan (Table S6). If the net migrating rate > 0, means the number of immigrating populations > the number of emigrating populations in a specific period of the area. Thanks to the city's talent introduction policies, compared with 2013–2016, the number of people who immigrated to Wuhan and became the registered population in 2017 had an obvious impact on the city's population structure (http://www.whzc.gov.cn/html/2017-07/61.html). The possibility is not ruled out that people who obtained household registration in Wuhan in 2017 also lived in the city from 2013 to 2016. Therefore, setting 2013 as baseline scenario and 2017 as control scenario could contribute to reduce the uncertainty caused by population migration in a particular period.

Combined with the premature deaths avoided by the decrease of $PM_{2.5}$ concentration from 2013 to 2017, the economic benefits obtained in all districts of Wuhan were calculated and were shown in Figure S2. The economic benefits of controlling $PM_{2.5}$ pollution in Wuhan was 30.70 billion RMB (95% CI: 20.95 to 40.17 billion), accounting for about 2.3% (95% CI: 1.6% to 3.1%) of the city’s GDP in 2017. The economic benefits gained in the central urban districts were 18.31 billion RMB, which was 5.92 billion RMB more than the benefits in suburban districts. Economic benefits in D5 (Wuchang District, 4.16 billion RMB), D12 (Huangpi District, 4.15 billion RMB), D13 (Xinzhou District, 3.61 billion RMB), D7 (Hongshan District, 3.44 billion RMB) and D1 (Jiang’an District, 2.72 billion RMB) were more than the average level in Wuhan (2.36 billion RMB).

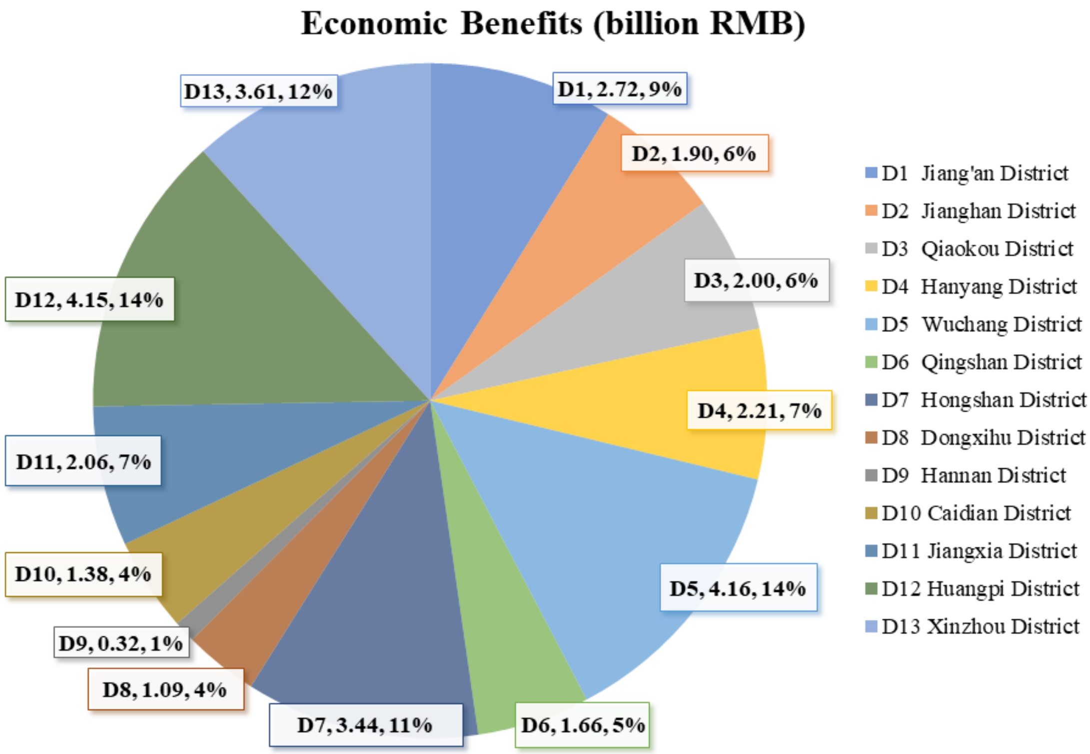


**Figure S2.** Economic benefits of $PM_{2.5}$ concentration reduction in Wuhan from 2013 to 2017 by annual estimation (billion RMB). D1, 2.72, 9% means that the economic benefit of Jiang'an District was 2.72 billion RMB, accounting for 9% of the total economic benefit of Wuhan.

## **Section S7** Comparison with other similar researches

**Table S7.** $PM_{2.5}$-related health economic benefits studies in China during 2013 to 2017.

| **Study Area** | **Evaluation period** | **$PM_{2.5}$ decline** | **Number of avoidable premature death** | **Economic benefits** | **Reference** |
|---|---|---|---|---|---|
| China | 2013–2017 | 39.5% | 214,821 | 210.14 billion US$ | [13] |
| China | 2013–2017 | Decline varied from province to province | 60,213 | 54.97 billion RMB | [14] |
| China | 2013–2017 | Decline varied from province to province | 718,000 | 3762 billion RMB | [15] |
| Pearl River Delta | 2013–2015 | 28% | 3800 | 1300 billion US$ | [16] |
| Shanghai | 2013–2017 | 38.3% (population-weighted annual average concentrations of $PM_{2.5}$) | 3439 | 11.841 billion RMB | [17] |
| This Study | 2013–2017 | 43.6% | 21,384 | 64.35 billion RMB | |

**Table S8. Population changes in Wuhan City from 2013 to 2017.**

| **Item** | **2013** | **2014** | **2015** | **2016** | **2017** |
|---|---|---|---|---|---|
| Exposed Population (person) | 8,220,493 | 8,273,117 | 8,292,666 | 8,338,450 | 8,536,517 |
| Number of Births (person) | 92,701 | 100,784 | 105,169 | 95,436 | 131,409 |
| Birth Rate (‰) | 11.28 | 12.22 | 12.70 | 11.48 | 15.57 |
| Number of Deaths (person) | 40,941 | 41,007 | 47,637 | 45,259 | 98,029 |
| All-cause Mortality Rate (‰) | 4.98 | 4.97 | 5.75 | 5.44 | 11.62 |
| Net Migrating Population (person) | -25,132 | 360 | -14,762 | -2430 | 166,922 |
| Net Migrating Rate (‰) | -3.06 | 0.04 | -1.78 | -0.29 | 19.55 |

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