# Supplementary Materials: Concentration Characteristics, Source Analysis, and Health Risk Assessment of Water-Soluble Heavy Metals in $PM_{2.5}$ during Winter in Taiyuan, China

**Qingyu Hu[1], Chao Zhang[1], Yang Chen[1], Nan Pei[1], Yufeng Zhao[1], Lijuan Sun[2], Jie Lan[2], Fengxian Liu[1,3,*], Ziyong Guo[1,*], Ling Mu[1], Jiancheng Wang[1], Xinhui Bi[4]**

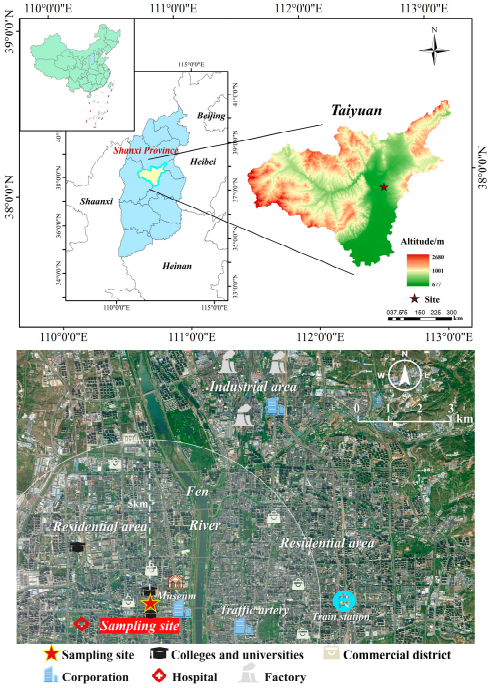


**Figure S1.** The location of the sampling points and their surrounding environment. Within a 5 km radius of the sampling points is a cultural, educational, and residential area, including schools, museums, hospitals, shopping malls, major transportation routes, and train stations. To the north is an industrial area, including the First and Second Power Plants, Taiyuan Iron and Steel Plant, and Taiyuan Heavy Machinery Plant.

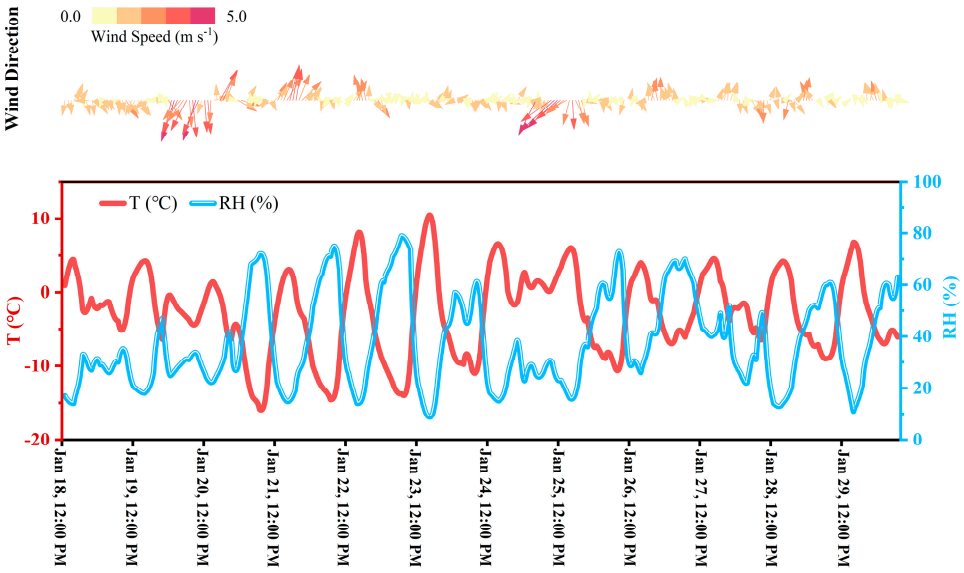


**Figure S2.** Meteorological parameters during the winter sampling period in Taiyuan.

**Table S1.** Meaning and value of calculate parameters for daily average exposure of heavy metals.

| Parameters | Meaning | Unit | Value | | Reference |
|---|---|---|---|---|---|
| | | | Child | Adult | |
| C | Concentration | mg $m^{-3}$ | - | - | |
| EF | Exposure Frequency | d $a^{-1}$ | 90[a] | 90[a] | This study |
| ED | Exposure Duration | a | 6 | 30 | [93] |
| $AT_{Car/Non-car}$ | Average exposure time | d | 90×ED(non-carcinogenic)<br>365×70(carcinogenic) | | [21]<br>This study |
| BW | Body Weight | kg | 15 | 60 | [93] |
| CF | Conversion Factor | kg $mg^{-1}$ | $1\times10^{-6}$ | $1\times10^{-6}$ | [21] |
| IngR | Ingestion Rate | mg $d^{-1}$ | 200 | 100 | [93] |
| InhR | Inhalation Rate | $m^3$ $d^{-1}$ | 7.6 | 20 | [93] |
| SA | exposed skin area | $cm^2$ | 1800 | 4350 | [93] |
| SL | skin adherence factor | mg $cm^{-2}$ | 0.2 | 0.07 | [93] |
| ABS | dermal absorption factor | unitless | 0.001(non-carcinogenic)<br>0.01(carcinogenic) | | [94] |
| PEF | Particle Emission Factor | $m^3$ $kg^{-1}$ | $1.36\times10^9$ | $1.36\times10^9$ | [59] |

[a] Exposure Frequency (EF)

EF represents the number of days of exposure in a year. Our 12-day intensive sampling captured water-soluble heavy metals in Taiyuan during winter. We used the sampling data from this study to represent the frequency of exposure during winter in Taiyuan throughout the year. Therefore, EF was set at 90 d $a^{-1}$.

**Table S2.** RfD and SF for different exposure of heavy metals.

| Elements | RfD (reference dosage) | | | SF(Slope of carcinogenicity factors) | | |
|---|---|---|---|---|---|---|
| | Ingestion | Dermal contact | Inhalation | Ingestion | Dermal contact | Inhalation |
| Mn | 4.70E-02 | 2.40E-03 | 1.40E-05 | - | - | - |
| Co | 2.00E-02 | 1.60E-02 | 5.71E-06 | - | - | 9.8 |
| Ni | 2.00E-02 | 1.00E-03 | 2.06E-02 | - | - | 0.84 |
| Cu | 3.70E-02 | 1.90E-03 | 4.02E-02 | - | - | - |
| Zn | 3.00E-01 | 6.00E-02 | 3.01E-01 | - | - | - |
| As | 3.00E-04 | 1.23E-04 | 3.01E-04 | 1.5 | - | 15.1 |
| Cd | 1.00E-03 | 5.00E-05 | 1.00E-03 | 0.38 | 6.1 | 6.3 |
| Pb | 3.50E-03 | 5.25E-04 | 3.52E-03 | 8.50E-03 | - | 8.50E-03 |
| Se | 5.00E-03 | - | - | - | - | - |
| Sn | 2.00E-01 | - | - | - | - | - |
| Sb | 4.00E-04 | - | 2.00E-04 | - | - | - |
| Ba | 2.00E-01 | 1.40E-02 | 2.00E-01 | - | - | - |

* Data from [95], and existing studies [93, 94, 59]

**Table S3.** Mass concentrations of WSHMs in Taiyuan and other regions.

| Sampling information | | | | WSHMs (ng m$^{-3}$) | | | | | | | | | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Representative | | Time | Zn | Fe | Mn | Ba | Cu | Se | As | Sb | Sn | Pb | Ni | V | Ti | Cd | Co | Total | |
| Taiyuan | Urban | Mean $PM_{2.5}$ | 2019. win | 87.01 ± 103.15 | 57.80 ± 47.88 | 28.73 ± 11.93 | 10.07 ± 8.44 | 5.64 ± 3.84 | 4.67 ± 2.43 | 4.48 ± 1.98 | 3.43 ± 1.95 | 1.5 ± 0.76 | 1.48 ± 1.29 | 1.45 ± 0.98 | 1.03 ± 0.55 | 1.09 ± 1.38 | 0.58 ± 0.54 | 0.2 ± 0.11 | 209.17 ± 187.21 | This study |
| | | HD, $PM_{2.5}$ | | 148.73 ± 116.26 | 60.46 ± 24.11 | 36.66 ± 11.51 | 11.63 ± 6.21 | 8.15 ± 2.07 | 6.36 ± 2.27 | 5.63 ± 1.67 | 4.39 ± 1.78 | 1.95 ± 0.64 | 2.19 ± 1.54 | 1.55 ± 0.76 | 1.24 ± 0.47 | 0.97 ± 0.51 | 0.90 ± 0.62 | 0.21 ± 0.03 | 291.01 ± 170.64 | |
| | | MD, $PM_{2.5}$ | | 24.08 ± 29.49 | 28.25 ± 11.66 | 19.79 ± 5.37 | 4.25 ± 1.96 | 2.15 ± 3.01 | 2.79 ± 1.02 | 2.68 ± 0.41 | 1.90 ± 1.13 | 0.83 ± 0.30 | 0.66 ± 0.18 | 0.89 ± 0.50 | 0.59 ± 0.10 | 0.41 ± 0.10 | 0.26 ± 0.12 | 0.12 ± 0.01 | 89.61 ± 55.36 | |
| | | SD, $PM_{2.5}$ | | 31.43 | 189.55 | 25.81 | 29.83 | 8.09 | 3.97 | 6.63 | 5.38 | 2.14 | 1.32 | 3.68 | 2.00 | 5.25 | 0.30 | 0.51 | 315.88 | |
| Guang-zhou | Coastal city | Mean | 2020 Win | 127 ± 70 | 53 ± 19 | 16 ± 8.4 | 6.3 ± 3.7 | 7.9 ± 5.1 | 2.4 ± 1.0 | 4.0 ± 2.9 | 1.4 ± 0.5 | 0.6 ± 0.2 | 7.6 ± 3.2 | 0.8 ± 0.5 | 0.5 ± 0.4 | 0.9 ± 0.3 | 1.0 ± 0.5 | - | 229.4 ± 115.7 | [23] |
| | | $PM_{2.5}$ > 75 μg m$^{-3}$ | | 250 ± 84 | 82 ± 14 | 31 ± 3.6 | 11 ± 3.9 | 15 ± 6.3 | 2.1 ± 0.7 | 4.7 ± 5.9 | 2.0 ± 0.4 | 0.8 ± 0.1 | 8.9 ± 4.5 | 1.1 ± 0.4 | 0.6 ± 0.4 | 1.1 ± 0.1 | 1.1 ± 0.7 | - | 411.4 ± 125.0 | |
| | | 35> $PM_{2.5}$ < 75 μg m$^{-3}$ | | 55 ± 11 | 34 ± 13 | 8.0 ± 3.1 | 3.4 ± 2.2 | 2.9 ± 1.5 | 1.7 ± 0.7 | 2.9 ± 1.8 | 0.9 ± 0.4 | 0.4 ± 0.2 | 5.3 ± 1.9 | 0.4 ± 0.3 | 0.2 ± 0.2 | 0.7 ± 0.5 | 0.6 ± 0.2 | - | 224.5 ± 60.2 | |
| | | $PM_{2.5}$ 35 μg m$^{-3}$ | | 121 ± 28 | 53 ± 12 | 16 ± 5.3 | 6.3 ± 3.2 | 7.9 ± 3.5 | 2.7 ± 1.0 | 4.2 ± 2.2 | 1.4 ± 0.4 | 0.6 ± 0.1 | 8.0 ± 2.9 | 0.8 ± 0.5 | 0.5 ± 0.4 | 0.9 ± 0.3 | 1.2 ± 0.4 | - | 116.4 ± 37.0 | |
| Yantai | Coastal city | | 2016 Spr | 153.4 ± 105.7 | 213.0 ± 141.5 | 38.4 ± 18.1 | - | 28.0 ± 15.4 | 6.2 ± 4.4 | - | - | - | 8.2 ± 6.2 | 3.8 ± 1.5 | 10.4 ± 4.3 | - | 0.9 ± 0.5 | 1.1 ± 0.6 | 463.4 ± 298.2 | [36] |
| | | | 2015 Sum | 46.1 ± 33.3 | 92.0 ± 58.1 | 14.5 ± 12.1 | - | 7.0 ± 7.2 | 5.1 ± 2.4 | - | - | - | 5.2 ± 3.9 | 3.7 ± 2.7 | 14.1 ± 6.9 | - | 0.4 ± 0.3 | 0.3 ± 0.2 | 188.4 ± 127.2 | |
| | | | 2015 Aut | 108.9 ± 84.1 | 83.1 ± 65.0 | 21.2 ± 13.6 | - | 17.5 ± 17.9 | 6.3 ± 3.8 | - | - | - | 5.7 ± 6.4 | 2.9 ± 2.5 | 10.6 ± 8.0 | - | 0.8 ± 0.6 | 0.2 ± 0.2 | 257.2 ± 202.1 | |
| | | | 2015 Win | 178.7 ± 241.7 | 145.0 ± 102.3 | 38.2 ± 28.1 | -- | 45.2 ± 49.4 | 8.6 ± 5.5 | -- | -- | -- | 7.7 ± 5.1 | 3.9 ± 3.6 | 10.5 ± 7.1 | -- | 1.4 ± 1.3 | 1.1 ± 1.5 | 440.3 ± 445.6 | |
| Tianjin | Coastal city | | 2016 Spr | 229.7± 176.4 | 41.3±34. 5 | 22.4 ± 8.7 | - | 27.2 ± 26.7 | - | - | - | - | 1.1 ± 0.8 | 1.5 ± 1.2 | - | - | 1.0 ± 0.8 | 0.2 ± 0.1 | 324.4 ± 249.2 | [36] |
| | | | 2015 Sum | 153.3± 129.7 | 24.5 ± 15 | 13.5 ± 6.2 | - | 17.9 ± 21.3 | - | - | - | - | 0.9 ± 0.7 | 2.2 ± 1.4 | - | - | 0.5 ± 0.5 | 0.1 ± 0.1 | 212.9 ± 174.9 | |
| | | | 2015 Aut | 321.8 ± 267.5 | 48.4 ± 28.3 | 25.1± 12 | - | 32.6 ± 29.2 | - | - | - | - | 2.0 ± 1.4 | 1.6 ± 0.7 | - | - | 1.6 ± 1.6 | 0.2 ± 0.1 | 433.3 ± 340.8 | |
| | | | 2015 Win | 363.2 ± 292.3 | 82.2 ± 48 | 33.6 ± 17.4 | - | 27.9 ± 35.9 | - | - | - | - | 3.6 ± 5.2 | 2.2 ± 1.2 | - | - | 2.1 ± 1.5 | 0.4 ± 0.2 | 515.2 ± 401.7 | |

| Sampling information | | | WSHMs (ng m$^{-3}$) | | | | | | | | | | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Representative | Time | Zn | Fe | Mn | Ba | Cu | Se | As | Sb | Sn | Pb | Ni | V | Ti | Cd | Co | Total | |
| Jinzhou | Coastal city | 2016 Spr | 113.8 ± 90.9 | 182.2±218.5 | 31.4± 18.8 | - | 6.8 ± 4.5 | 4.4 ± 2.9 | - | - | - | 10.7 ± 7.6 | 1.9 ± 1.2 | 8.8 ± 3.8 | - | 1.8 ± 1.3 | 0.3 ± 0.1 | 362.1 ± 349.6 | [36] |
| | | 2015 Sum | 90.0 ± 66.6 | 23.1±15.8 | 22.5± 17.1 | - | 3.6 ± 2.1 | 4.9 ± 3.6 | - | - | - | 2.3 ± 2.3 | 1.9 ± 0.8 | 6.8 ± 4.2 | - | 1.9 ± 1.4 | 0.1±0.0 | 157.0 ± 113.9 | |
| | | 2015 Aut | 168.9 ± 132.4 | 58.3±34.6 | 41.3± 39.9 | - | 8.5 ± 6.1 | 5.3 ± 4.1 | - | - | - | 3.8 ± 2.2 | 2.6 ± 2.0 | 6.2 ± 2.5 | - | 1.6 ± 1.3 | 0.3 ± 0.2 | 296.8 ± 225.3 | |
| | | 2015 Win | 128.7 ± 125.5 | 64.6±51.9 | 29.6± 15.9 | - | 6.1 ± 3.3 | 4.7 ± 3.8 | - | - | - | 5.3 ± 4.5 | 1.4 ± 1.2 | 6.9 ± 4.9 | - | 1.6 ± 1.7 | 0.3 ± 0.1 | 249.2 ± 212.8 | |
| Xiamen | Coastal city | 2021 Aut | 76.5 | 36.42 | 12.33 | 10.54 | 6.8 | 1.67 | 1.71 | - | - | 3.3 | 3.75 | 1.69 | - | 0.33 | - | 155.04 | [72] |
| | Island | 2020. Sum | 63.8 | 27.57 | 7.99 | 5.06 | 6.51 | 1.31 | 1.72 | - | - | 7.21 | 6.77 | 2.95 | - | 0.31 | - | 131.20 | [31] |
| Sanmen-xia | Urban | 2018 Win | 63.6 | 82.32 | 21.99 | - | 9.53 | - | 6.42 | 3.48 | - | 29.62 | 0.95 | - | - | 1.67 | - | 219.58 | [63] |
| Beijing | Urban | 2011 Win | 412.81 | - | 30.82 | - | 7.84 | 2.53 | 8.42 | 5.87 | 0.36 | 49.27 | 0.30 | 1.43 | - | 3.18 | 0.16 | 522.99 | [41] |
| HongKong | Coastal city | 2012 Win | 301.54 | 92.92 | 16.94 | | 32.88 | - | | | | 73.79 | 1.93 | 5.68 | - | 2.11 | - | 527.79 | [64] |
| Singa-pore | Urban | 2006 | 34.1 ± 19.4 | 18.2 ± 2.4 | 1.1 ± 0.4 | | 1.2 ± 0.7 | - | 0.8 ± 0.3 | | | 1.92 ± 1.2 | 5.6 ± 2.1 | 20.1 ± 5.6 | - | 0.17 ± 0.02 | 0.06 ± 0.01 | 83.25 ± 32.13 | [67] |
| Mega-lopolis | Small city | 2016 Win | 51.7 | 8.51 | 1.28 | - | 0.94 | - | 0.25 | - | - | 2.90 | 2.06 | 0.25 | 0.54 | 1.50 | 0.04 | 69.97 | [34] |
| Patra | Coastal city | | 163 | 11.9 | 1.25 | | 2.67 | - | 0.24 | | | 3.16 | 4.92 | 1.33 | 14.7 | 4.98 | 0.11 | 208.26 | |
| Iasi | Urban | 2016 Sum | 29.45 ± 18.50 | 52.92 ± 52.42 | 10.70 ± 7.97 | 1.59 ± 0.70 | 11.63 ± 6.17 | 7.33 ± 3.60 | 7.46 ± 5.42 | - | - | 2.02 ± 1.96 | - | 0.48 ± 0.20 | - | 0.26 ± 0.15 | 0.02 ± 0.03 | 123.86 ± 97.12 | [45] |
| | | 2016 Win | 33.94 ± 20.34 | 90.76 ± 76.44 | 9.06 ± 8.11 | 2.44 ± 1.04 | 7.70 ± 5.04 | 5.97 ± 3.19 | 5.70 ± 5.89 | - | - | 1.99 ± 1.39 | - | 0.41 ± 0.24 | - | 0.33 ± 0.22 | 0.09 ± 0.18 | 158.39 ± 122.08 | |
| Los An-geles | Urban | 2021. Win | 12.9 ± 3.79 | 8.44 ± 2.61 | 1.19 ± 0.22 | 10.57 ± 8.19 | 5.59 ± 3.36 | - | - | - | - | 0.27 ± 0.07 | 0.21 ± 0.08 | 0.15 ± 0.04 | 0.18 ± 0.06 | - | - | 39.5 ± 18.42 | [20] |
| Hanoi | Urban | 2019 Dry season | 363 ± 446 | 60.9 ± 27.5 | 11.9 ± 7.7 | - | 6.78 ± 9.78 | - | 3.35 ± 2.42 | 1.45 ± 0.75 | - | 56.0 ± 84.6 | 0.67 ± 0.29 | 1.73 ± 0.91 | | 1.60 ± 1.34 | 0.11 ± 0.05 | 507.79 ± 581.29 | |
| | | 2018 Wet season, | 231 ± 159 | 44.6 ± 13.8 | 5.44 ± 2.25 | - | 5.22 ± 5.67 | - | 1.12 ± 0.86 | 1.39 ± 1.33 | - | 29.0 ± 40.9 | 0.70 ± 0.37 | 2.29 ± 1.31 | 0.40 ± 0.14 | 0.59 ± 0.48 | 0.05 ± 0.02 | 321.80 ± 226.13 | [25] |
| Ho Chi Minh | Urban | 2019 Dry season | 142 ± 135 | 47.0 ± 14.4 | 5.06 ± 2.38 | - | 3.66 ± 3.06 | - | 0.32 ± 0.15 | 0.87 ± 1.30 | - | 9.6 ± 7.4 | 1.13 ± 0.47 | 3.53 ± 1.54 | 0.56 ± 0.17 | 0.28 ± 0.18 | 0.07 ± 0.03 | 214.08 ± 166.08 | |

| Sampling information | | | WSHMs (ng $m^{-3}$) | | | | | | | | | | | | | | | Refer-ence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Representative | Time | Zn | Fe | Mn | Ba | Cu | Se | As | Sb | Sn | Pb | Ni | V | Ti | Cd | Co | Total | |
| | | 2018 Wet season | 592 ± 646 | 51.7 ± 17.2 | 16.1 ± 9.4 | - | 4.24 ± 2.31 | - | 3.76 ± 2.53 | 1.34 ± 0.68 | - | 56.0 ± 35.5 | 0.60 ± 0.23 | 1.03 ± 0.39 | 0.60 ± 0.22 | 1.69 ± 1.33 | 0.08 ± 0.02 | 729.14 ± 715.81 | |

* Values represent average ± standard deviation