Supplementary Materials

Field study on atmospheric emissions and profiles of heavy metal-containing nanoparticles from multiple full scale industrial sources in China

Qiuting Yang,[1,2,3] Yuxiang Sun,[2,3] Jianghui Yun,[2,3] Yujue Yang,[2,3] Junhao Tang,[2,4] Guorui Liu[1,2,3,4,*]

[1] *Zhejiang Key Laboratory of Digital Intelligence Monitoring and Restoration of Watershed Environment, College of Geography and Environmental Sciences, Zhejiang Normal University, Jinhua, 321004, China.*

[2] *State Key Laboratory of Environmental Chemistry and Ecotoxicology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, P.O. Box 2871, Beijing, 100085, China*

[3] *University of Chinese Academy of Sciences (UCAS), Beijing, 100049, China*

[4] *School of Environment, Hangzhou Institute for Advanced Study, UCAS, Hangzhou, 310024, China*

[*] Corresponding author, E-mail: liiugr@zjnu.edu.cn

Table of Contents

Supplementary Figures 1–3

Fig. S1 Distribution map of sampling sites for 132 industrial particulate matter samples. **Page 3**

Fig. S2 The standard curves for 10 heavy metal ions and Au ions **Page 4**

Fig. S3 (a) Mass detection limit and (b) size detection limit of HM-containing NPs for each sample **Page 5**

Supplementary Tables 1–12

Table S1. Detailed information on particulate matter samples from 132 industrial activities **Page 6-10**

Table S2 The toxicity coefficients (C_T) of heavy metals used for calculating the Toxicity Contribution Value (TCV) **Page 11**

Table S3 Source of production data for the 13 categories of industrial activities **Page 12**

Table S4 Activity data (thousand tons) of 13 industrial sources in China's provinces and cities* **Page13–14**

Table S5 Parameters for estimating the annual average $PM_{2.5}$ deposition rate for each province **Page 15**

Table S6 Steady-state concentrations of particulate matter emitted into the atmosphere from industrial activities **Page 16**

Table S7 Parameters for estimating adult and child exposure to HM-containing NPs in air **Page 17**

Table S8 Particle number concentrations (particles/g) of 10 HM-containing NPs emitted by 132 actual industrial process from thirteen industrial sectors **Page 18–19**

Table S9 Toxicity Contribution value of 10 HM-containing NPs emitted by 132 actual industrial process from thirteen industrial sectors **Page 20–21**

Table S10 Emission factors (particles/t) of HM-containing NPs for thirteen industrial sectors **Page 22**

Table S11 Atmosphere emissions (particles) of 10 HM-containing NPs from different industrial sources in China mainland **Page 21**

Table S12 The Lifetime Average Daily Dose (LADD) of HM-containing NPs for Adults and Children Through Inhalation and Dermal Exposure from 13 Industrial Sources **Page22**

Supplementary Method 1 Analysis Method for Particle Number Concentration (PNC) of HM-Containing Nanoparticles by ICP-TOF-MS **Page 23-25**

Supplementary Method 2 Quality Assurance and Quality Control **Page 26-27**

Reference **Page 28**

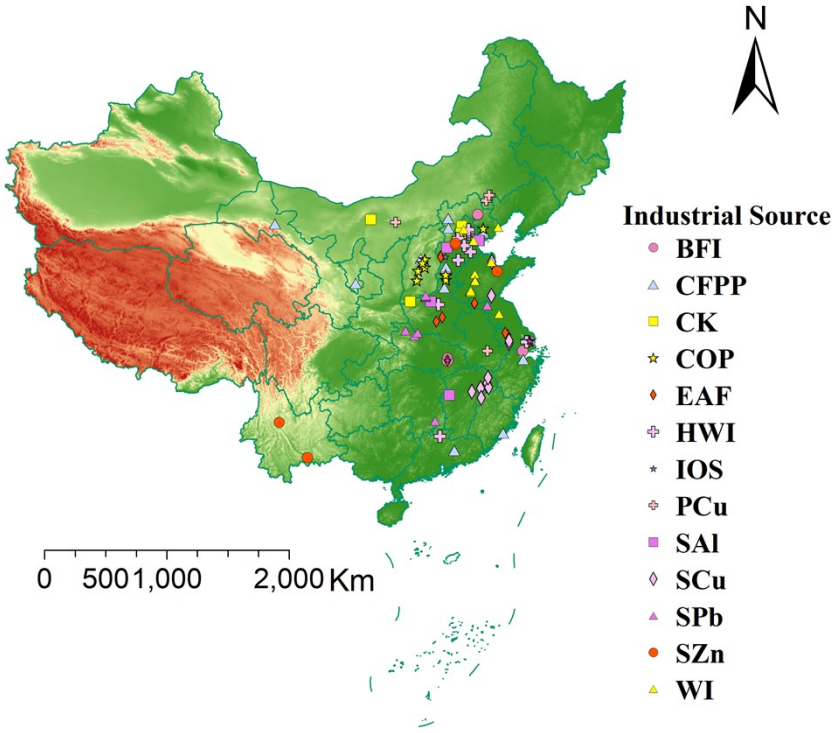

Fig. S1 Distribution map of sampling sites for 132 industrial particulate matter samples. The map is based on free vector data sourced from the "Database of National Catalogue Service for Geographic Information [GS (2020)4619]" (https://www.resdc.cn/DOI/doi.aspx?DOIid=122) and created using ArcGIS software. This sampling map also shown in our previous manuscript (Nature Sustainability 2024, DOI:10.1038/s41893-024-01388-6).

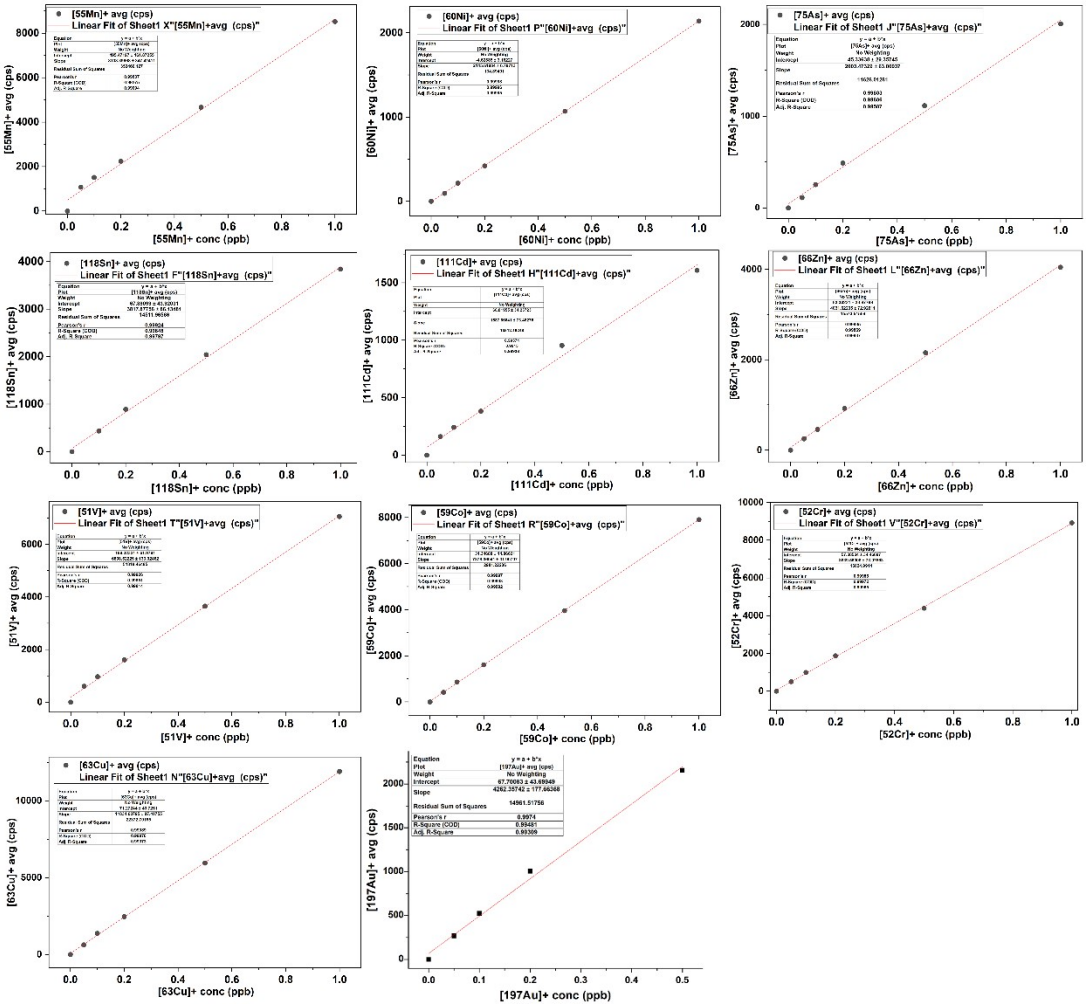

Fig. S2 The standard curves for 10 heavy metal ions and Au ions.

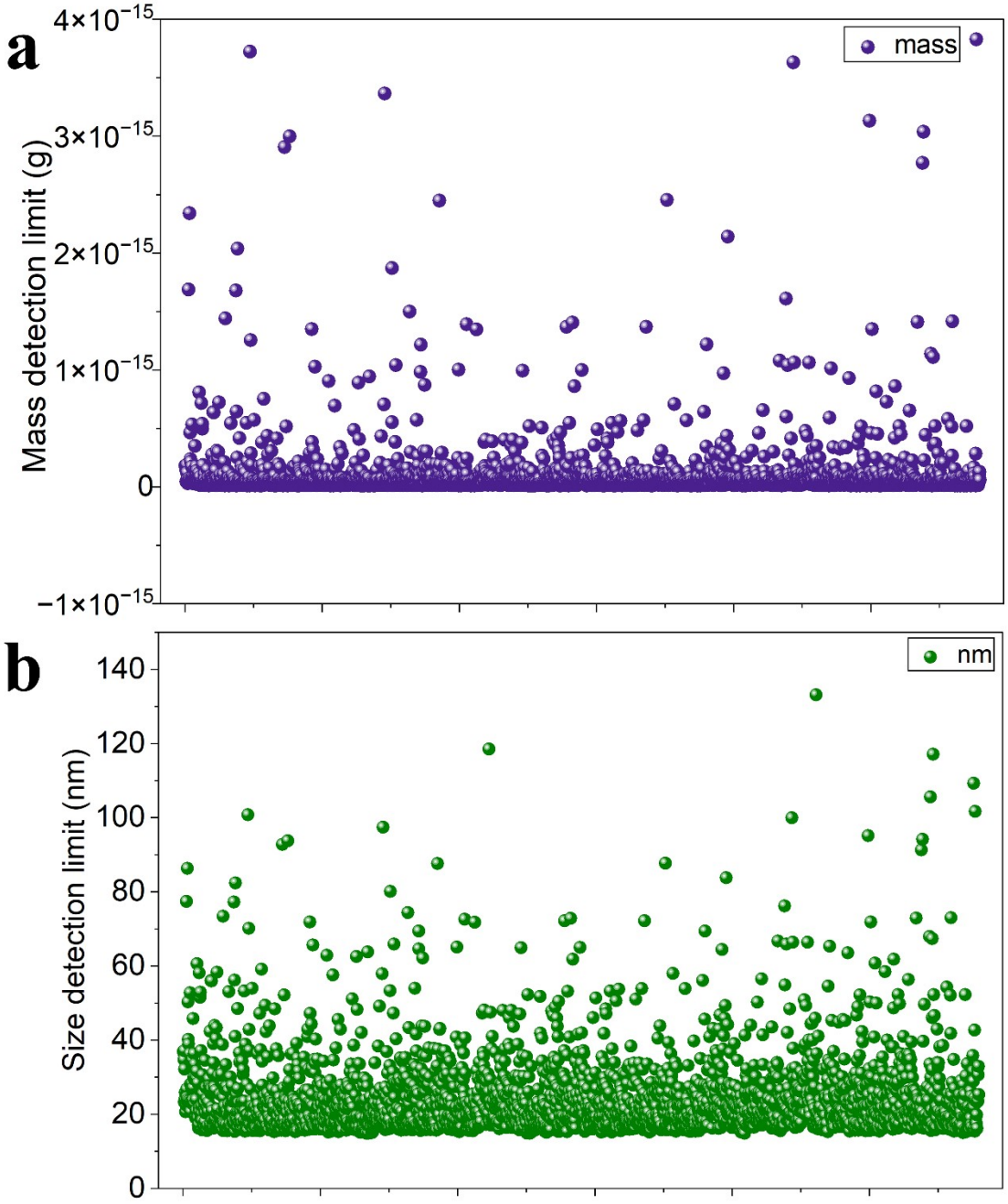

Fig. S3 (a) Mass detection limit and (b) size detection limit of HM-containing NPs for each sample

Table S1. Detailed information on particulate matter samples from 132 industrial activities

Number	Sample ID	Provinces	City/District	Industrial activities	Raw material	APCD
1	BFI1	Hebei	Chengde	blast furnace pig iron	Coke, hematite ore	BF
2	BFI2	Hebei	Chengde	blast furnace pig iron	Coke, hematite ore	BF
3	BFI3	Shanghai	Baoshan	blast furnace pig iron	Coke, hematite ore	BF
4	BFI4	Hubei	Wuhan	blast furnace pig iron	Coke, hematite ore	BF
5	BFI5	Zhejiang	Jiaxing	blast furnace pig iron	Coke, hematite ore	BF
6	BFI6	Hubei	Wuhan	blast furnace pig iron	Coke, hematite ore	BF
7	CFPP1	Hebei	Xingtai	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
8	CFPP2	Hebei	Zhangjiakou	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
9	CFPP3	Zhejiang	Jiaxing	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
10	CFPP4	Hebei	Xingtai	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
11	CFPP5	Hebei	Xingtai	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
12	CFPP6	Hebei	Tangshan	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
13	CFPP7	Hebei	Tangshan	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
14	CFPP8	Gansu	Jiayuguan	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
15	CFPP9	Shanxi	Gujiao	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
16	CFPP10	Ningxia	Guyuan	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
17	CFPP11	Guangdong	Heyuan	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
18	CFPP12	Hebei	Zhangjiakou	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
19	CFPP13	Hebei	Langfang	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
20	CFPP14	Henan	Hebi	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
21	CFPP15	Fujian	Quanzhou	Coal-Fired Power Plant	Bituminous coal, anthracite and lignite	BF
22	CK1	Beijing	Changping	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
23	CK2	Beijing	Changping	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
24	CK3	Beijing	Fangshan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
25	CK4	Beijing	Fangshan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
26	CK5	Beijing	Fangshan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
27	CK6	Inner Mongolia	Bayannur	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF

28	CK7	Henan	Sanmenxia	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
29	CK8	Beijing	Fangshan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
30	CK9	Chongqing	Hechuan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
31	CK10	Chongqing	Hechuan	Cement Kilns Coordinate the Disposal of Solid Waste	Solid Danger Waste	ESP&BF
32	COP1	Shanxi	Jiexiu	Coking Plant	Coal	BF
33	COP2	Shanxi	Taiyuan	Coking Plant	Coal	BF
34	COP3	Shanxi	Taiyuan	Coking Plant	Coal	BF
35	COP4	Shanghai	Baoshan	Coking Plant	Coal	BF
36	COP5	Hebei	Tangshan	Coking Plant	Coal	BF
37	COP6	Hebei	Tangshan	Coking Plant	Coal	BF
38	COP7	Shanghai	Baoshan	Coking Plant	Coal	BF
39	COP8	Hebei	Handan	Coking Plant	Coal	BF
40	COP9	Hebei	Handan	Coking Plant	Coal	BF
41	COP10	Hebei	Handan	Coking Plant	Coal	BF
42	COP11	Shanxi	Taiyuan	Coking Plant	Coal	BF
43	COP12	Shanxi	Taiyuan	Coking Plant	Coal	BF
44	COP13	Shanxi	Taiyuan	Coking Plant	Coal	BF
45	COP14	Shanxi	Taiyuan	Coking Plant	Coal	BF
46	COP15	Shanxi	Taiyuan	Coking Plant	Coal	BF
47	EAF1	Jiangsu	Zhenjiang	Electric Arc Furnace Steelmaking	Scrap	BF
48	EAF2	Jiangsu	Xuzhou	Electric Arc Furnace Steelmaking	Scrap	BF
49	EAF3	Henan	Luohe	Electric Arc Furnace Steelmaking	Scrap	BF
50	EAF4	Shanghai	Baoshan	Electric Arc Furnace Steelmaking	Scrap	BF
51	EAF5	Jiangsu	Zhenjiang	Electric Arc Furnace Steelmaking	Scrap	BF
52	EAF6	Jiangsu	Xuzhou	Electric Arc Furnace Steelmaking	Scrap	BF
53	EAF7	Henan	Luohe	Electric Arc Furnace Steelmaking	Scrap	BF
54	EAF8	Hebei	Shijiazhuang	Electric Arc Furnace Steelmaking	Scrap	BF
55	EAF9	Hebei	Shijiazhuang	Electric Arc Furnace Steelmaking	Scrap	BF
56	EAF10	Hubei	Wuhan	Electric Arc Furnace Steelmaking	Scrap	BF

57	HWI1	Guangdong	Shaoguan	hazardous waste incinerator	Hazardous waste such as medical waste	BF
58	HWI2	Hebei	Baoding	hazardous waste incinerator	Hazardous waste such as medical waste	BF
59	HWI3	Shanghai	Shanghai	hazardous waste incinerator	Hazardous waste such as medical waste	BF
60	HWI4	Shanghai	Shanghai	hazardous waste incinerator	Hazardous waste such as medical waste	BF
61	HWI5	Hebei	Cangzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
62	HWI6	Beijing	Tongzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
63	HWI7	Beijing	Tongzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
64	HWI8	Beijing	Tongzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
65	HWI9	Hebei	Hengshui	hazardous waste incinerator	Hazardous waste such as medical waste	BF
66	HWI10	Hebei	Cangzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
67	HWI11	Beijing	Tongzhou	hazardous waste incinerator	Hazardous waste such as medical waste	BF
68	HWI12	Henan	Xinzheng	hazardous waste incinerator	Hazardous waste such as medical waste	BF
69	IOS1	Hebei	Tangshan	Iron Ore Sintering	Iron Ore	ESP&BF
70	IOS2	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
71	IOS3	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
72	IOS4	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
73	IOS5	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
74	IOS6	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
75	IOS7	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
76	IOS8	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
77	IOS9	Shanghai	Baoshan	Iron Ore Sintering	Iron Ore	ESP&BF
78	IOS10	Hubei	Wuhan	Iron Ore Sintering	Iron Ore	ESP&BF
79	PCu1	Inner Mongolia	Baotou	Primary Copper Smelting	copper ore	ESP&BF
80	PCu2	Inner Mongolia	Chifeng	Primary Copper Smelting	copper ore	ESP&BF
81	PCu3	Inner Mongolia	Chifeng	Primary Copper Smelting	copper ore	ESP&BF
82	PCu4	Inner Mongolia	Chifeng	Primary Copper Smelting	copper ore	ESP&BF
83	PCu5	Anhui	Tongling	Primary Copper Smelting	copper ore	ESP&BF
84	PCu6	Anhui	Tongling	Primary Copper Smelting	copper ore	ESP&BF
85	SAl1	Tianjin	Tianjin	Secondary Aluminum Smelting	Waste Aluminium	ESP

86	SAl2	Tianjin	Tianjin	Secondary Aluminum Smelting	Waste Aluminium	ESP
87	SAl3	Jiangxi	Yichun	Secondary Aluminum Smelting	Waste Aluminium	ESP
88	SAl4	Hebei	Baoding	Secondary Aluminum Smelting	Waste Aluminium	ESP
89	SAl5	Henan	Gongyi	Secondary Aluminum Smelting	Waste Aluminium	ESP
90	SCu1	Jiangxi	Shangrao	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
91	SCu2	Jiangxi	Shangrao	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
92	SCu3	Jiangxi	Guixi	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
93	SCu4	Jiangxi	Fuzhou	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
94	SCu5	Jiangxi	Shangrao	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
95	SCu6	Jiangxi	Shangrao	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
96	SCu7	Shandong	Linyi	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
97	SCu8	Shandong	Dongying	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
98	SCu9	Jiangsu	Wuxi	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
99	SCu10	Jiangsu	Wuxi	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
100	SCu11	Jiangxi	Guixi	Secondary Copper Smelting	Waste Mixed Copper	ESP&BF
101	SPb1	Hunan	Bangzhou	Secondary Lead Smelting	Waste Lead	BF-coated film
102	SPb2	Henan	Jiyuan	Secondary Lead Smelting	Waste Lead	BF-coated film
103	SPb3	Henan	Jiyuan	Secondary Lead Smelting	Waste Lead	BF-coated film
104	SPb4	Henan	Jiyuan	Secondary Lead Smelting	Waste Lead	BF-coated film
105	SPb5	Henan	Jiyuan	Secondary Lead Smelting	Waste Lead	BF-coated film
106	SPb6	Hubei	Xiangyang	Secondary Lead Smelting	Waste Lead	BF-coated film
107	SPb7	Hubei	Xiangyang	Secondary Lead Smelting	Waste Lead	BF-coated film
108	SPb8	Jiangsu	Xuzhou	Secondary Lead Smelting	Waste Lead	BF-coated film
109	SPb9	Hubei	Xiangyang	Secondary Lead Smelting	Waste Lead	BF-coated film
110	SPb10	Hubei	Shiyan	Secondary Lead Smelting	Waste Lead	BF-coated film
111	SPb11	Zhejiang	Huzhou	Secondary Lead Smelting	Waste Lead	BF-coated film
112	SZn1	Yunnan	Yuanyang	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
113	SZn2	Yunnan	Dali	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
114	SZn3	Yunnan	Yuanyang	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film

115	SZn4	Hebei	Tangshan	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
116	SZn5	Shandong	Weifang	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
117	SZn6	Hebei	Baoding	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
118	SZn7	Hebei	Baoding	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
119	SZn8	Hebei	Baoding	Secondary Zinc Smelting	Waste Mixed Zinc	BF-coated film
120	WI1	Beijing	Haidian	Waste Incineration	Municipal soiled waste	BF
121	WI2	Hebei	Qinhuangdao	Waste Incineration	Municipal soiled waste	BF
122	WI3	Tianjin	Tianjin	Waste Incineration	Municipal soiled waste	BF
123	WI4	Shandong	Dongying	Waste Incineration	Municipal soiled waste	BF
124	WI5	Shandong	Taian	Waste Incineration	Municipal soiled waste	BF
125	WI6	Shandong	Taian	Waste Incineration	Municipal soiled waste	BF
126	WI7	Shandong	Jining	Waste Incineration	Municipal soiled waste	BF
127	WI8	Shandong	Jining	Waste Incineration	Municipal soiled waste	BF
128	WI9	Shandong	Jining	Waste Incineration	Municipal soiled waste	BF
129	WI10	Jiangsu	Huaian	Waste Incineration	Municipal soiled waste	BF
130	WI11	Shandong	Jinan	Waste Incineration	Municipal soiled waste	BF
131	WI12	Shandong	Jining	Waste Incineration	Municipal soiled waste	BF
132	WI13	Hong Kong	Hong Kong	Waste Incineration	Municipal soiled waste	BF

Note: Air pollution control equipment (APCD); ESP (electrostatic precipitator); BF (bag filter)

Part of these sample information were also shown in our previous study [1] (Nature Sustainability 2024, DOI:10.1038/s41893-024-01388-6).

Table S2. The toxicity coefficients (C_T) [2] of heavy metals used for calculating the Toxicity Contribution Value (TCV)

Heavy Metal	Toxicity Coefficients (C_T) [2]
V	2
Cr	2
Mn	1
Co	5
Ni	5
Cu	5
Zn	1
As	10
Cd	30
Sn	1

Table S3. Source of production data for the 13 categories of industrial activities

Industrial source	Abbreviation	Data Source
Waste Incineration	WI	https://www.mee.gov.cn/；https://databank.worldbank.org/；
Hazardous Waste Incineration	HWI	https://www.mee.gov.cn/；https://databank.worldbank.org/；
Secondary Metal Smelting	SeMetal	https://www.usgs.gov/centers/national-minerals-information center/international-minerals-statistics-and-information；
Primary Copper Smelting	PCu	https://icsg.org/；
Coal-Fired Power Plant	CFPP	https://www.mee.gov.cn/； https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html；
Cement Kiln	CK	https://worldcementassociation.org/；
Secondary Aluminum Smelting	SAl	https://international-aluminium.org/statistics/primary-aluminium-production/；
Secondary Lead Smelting	SPb	https://ila-lead.org/；
Electric Arc Furnace	EAF	https://www.worldsteel.org/；
Blast Furnace Pig Ironmaking	BFI	https://www.worldsteel.org/；
Coke production	COP	https://www.mee.gov.cn/；

Table S4 Activity data (thousand tons) of 13 industrial sources in China's provinces and cities*

Province	COP	CFPP (TWh)	CK	EAF	IOS	WI	BFI	PCu	SCu	SZn	SPb	SAl	HWI
Beijing	0.0	436	2034	0.0	1799	3997	0.0	0.0	0.0	0.0	0.0	1.0	263
Tianjin	1754	741	5295	2027	47338	1365	18184	0.0	19.1	0.0	0.0	155	717
Hebei	48255	2832	100339	23771	269169	3433	202030	0.0	34.3	26.7	0.0	337	4796
Shanxi	104937	3033	48446	5397	49033	1226	59884	193	0.0	0.0	0.0	31.5	3760
Inner Mongolia	42225	4841	35970	2312	22595	931	23474	333	4.4	0.0	93.9	82.4	6076
Liaoning	22971	1507	39109	6888	68991	0.0	70247	110	0.0	0.0	0.4	23.5	2034
Jilin	3687	750	17314	1207	13009	1322	13661	125	0.0	0.0	0.0	0.0	2454
Heilongjiang	10627	922	18811	776	5614	1005	8466	0	0.0	0.0	0.0	20.5	1155
Shanghai	5406	833	3696	1633	19833	3860	13910	31.3	2.7	0.0	0.0	198	1401
Jiangsu	13129	4434	142357	10443	121467	13287	100239	288	99.2	32.6	310	854	5746
Zhejiang	2132	2443	129537	1269	30487	9813	7948	235	116	29.0	0.0	345	5070
Anhui	12284	2556	142187	3110	31950	4203	29116	748	97.4	0.0	755	436	2335
Fujian	2235	1565	96929	2090	29159	5853	11452	319	0.0	2.4	0.0	202	1723
Jiangxi	6885	1167	89972	2504	25713	1138	23156	755	592	3.2	77.6	50.2	1847
Shandong	31626	5142	135225	7192	94278	11164	75244	1298	767	0.0	0.0	540	10082
Henan	18478	2515	114884	2898	36610	2075	27468	299	100	14.9	526	355	2827
Hubei	8012	1222	110562	3078	36499	4093	26244	334	151	0.0	206	123	1423
Hunan	6040	852	99984	2312	23747	3115	21774	0.0	100	125	73.2	87.6	2121
Guangdong	5970	3603	152264	2886	43376	12417	20536	0.0	106	12.4	0.0	605	5045
Guangxi	8118	1065	104265	2267	28909	1535	30153	489	0.0	18.3	17.7	79.2	4071
Hainan	0.0	213	16264	0.0	0.0	1337	0.0	0.0	0.0	0.0	0.0	0.0	193
Chongqing	2797	542	53211	639	11877	2569	6745	5.7	0.6	7.7	47.1	739	982
Sichuan	10742	528	130701	2406	28967	5582	20920	0.1	0.0	8.0	0	40.1	4976
Guizhou	4284	1332	64281	419	5543	1304	3754	0.0	0.0	12.0	33.3	12.1	744
Yunnan	10933	415	96937	1929	19407	2526	17116	536	55.9	169	2.4	45.6	3024
Tibet	0.0	4.1	7927	0.0	0.0	285	0.0	8.4	0.0	0.0	0.0	0.0	1.1
Shaanxi	48965	2038	65298	1181	14452	0.0	11363	1.4	0.0	189	0.0	33.6	2259
Gansu	5168	876	40478	804	8335	1090	7892	370	56.3	0.0	0.0	13.4	1782
Qinghai	1826	105	9785	138	1466	0.0	1542	21.3	0.0	0.0	1.6	81.0	1201
Ningxia	9208	1530	16675	253	2668	499	4576	0	0.0	8.5	0.0	13.4	1155

Xinjiang	22469	3263	38775	1158	13227	155	11476	116	0.0	0.0	0.0	0.0	3347
Total	471161	53303	2129512	92987	1105517	101179	868568	6614	2301	659	2143	5504	84612

Note: In addition to WI, HWI is the unit of waste disposal (thousand tons) and CFPP is coal-fired power generation (TWh), other industrial activities are production (thousand tons).

* (also shown in our previous study, doi: 10.1038/s41893-024-01388-6)

Table S5 Parameters for estimating the annual average $PM_{2.5}$ deposition rate for each province

Provinces	D_{dry} (m/s) [3]	D_{wet} (m/s) [4]	Rainy Days (Tp rain, d)*	Sunny Days (d)	Deposition Rate (Dp, cm/s)
Beijing			76.5	288.5	0.41
Tianjin			65.6	299.4	0.37
Hebei			71.3	293.7	0.39
Shanxi			72.3	292.7	0.39
Inner Mongolia			85.3	279.7	0.44
Liaoning			89.3	275.7	0.46
Jilin			95.4	269.6	0.48
Heilongjiang			91	274	0.46
Shanghai			120.8	244.2	0.58
Jiangsu			129	236	0.61
Zhejiang			143.6	221.4	0.66
Anhui			139.6	225.4	0.65
Fujian			127	238	0.6
Jiangxi			147.3	217.7	0.68
Shandong			74.6	290.4	0.4
Henan	0.12	1.38	84.9	280.1	0.44
Hubei			118.4	246.6	0.57
Hunan			170	195	0.76
Guangdong			149.2	215.8	0.68
Guangxi			173.2	191.8	0.77
Hainan			144.2	220.8	0.67
Chongqing			147.2	217.8	0.68
Sichuan			146.9	218.1	0.68
Guizhou			190.3	174.7	0.84
Yunnan			128.3	236.7	0.61
Tibet			92.8	272.2	0.47
Shaanxi			90.3	274.7	0.46
Gansu			87	278	0.45
Qinghai			96.1	268.9	0.48
Ningxia			45.2	319.8	0.29
Xinjiang			96.9	268.1	0.49

*Source: Weather Report, <https://www.weather-atlas.com/zh/china> (accessed January 10, 2026).

Table S6 Steady-state concentrations of particulate matter emitted into the atmosphere from industrial activities

Provinces	Area (A_p, m^2)*	Deposition Rate (D_p, m/s)	C_{Cu} in air (particles/m^3)	C_{Cd} in air (particles/m^3)	C_{Sn} in air (particles/m^3)	C_{Pb} in air (particles/m^3)
Beijing	1.70×10^{10}	0.0041	2.61×10^{4}	1.56×10^{2}	4.96×10^{4}	5.11×10^{5}
Tianjin	1.20×10^{10}	0.0037	7.68×10^{4}	1.07×10^{3}	1.85×10^{5}	1.58×10^{6}
Hebei	1.90×10^{11}	0.0039	2.29×10^{4}	1.12×10^{3}	1.12×10^{5}	4.98×10^{5}
Shanxi	1.60×10^{11}	0.0039	2.36×10^{4}	9.92×10^{2}	8.43×10^{4}	4.81×10^{5}
Inner Mongolia	1.20×10^{12}	0.0044	4.05×10^{3}	8.31×10^{1}	9.67×10^{3}	8.01×10^{4}
Liaoning	1.50×10^{11}	0.0046	1.18×10^{4}	5.16×10^{2}	4.88×10^{4}	2.44×10^{5}
Jilin	1.90×10^{11}	0.0048	4.10×10^{3}	1.70×10^{2}	1.54×10^{4}	7.91×10^{4}
Heilongjiang	4.60×10^{11}	0.0046	2.06×10^{3}	6.20×10^{1}	7.40×10^{3}	4.01×10^{4}
Shanghai	6.30×10^{9}	0.0058	1.00×10^{5}	1.54×10^{3}	2.21×10^{5}	2.07×10^{6}
Jiangsu	1.00×10^{11}	0.0061	3.86×10^{4}	1.61×10^{3}	1.69×10^{5}	7.46×10^{5}
Zhejiang	1.00×10^{11}	0.0066	2.13×10^{4}	1.20×10^{3}	1.19×10^{5}	3.76×10^{5}
Anhui	1.40×10^{11}	0.0065	1.70×10^{4}	1.21×10^{3}	9.72×10^{4}	3.04×10^{5}
Fujian	1.20×10^{11}	0.006	1.33×10^{4}	9.08×10^{2}	7.99×10^{4}	2.36×10^{5}
Jiangxi	1.70×10^{11}	0.0068	7.53×10^{3}	6.86×10^{2}	4.87×10^{4}	1.23×10^{5}
Shandong	1.60×10^{11}	0.004	4.21×10^{4}	2.05×10^{3}	1.67×10^{5}	7.80×10^{5}
Henan	1.70×10^{11}	0.0044	1.90×10^{4}	1.07×10^{3}	9.97×10^{4}	3.48×10^{5}
Hubei	1.90×10^{11}	0.0057	8.25×10^{3}	7.03×10^{2}	5.96×10^{4}	1.43×10^{5}
Hunan	2.10×10^{11}	0.0076	4.25×10^{3}	3.55×10^{2}	3.51×10^{4}	7.23×10^{4}
Guangdong	1.80×10^{11}	0.0068	1.59×10^{4}	6.91×10^{2}	7.93×10^{4}	2.90×10^{5}
Guangxi	2.40×10^{11}	0.0077	4.28×10^{3}	4.14×10^{2}	3.20×10^{4}	7.31×10^{4}
Hainan	3.40×10^{10}	0.0067	5.95×10^{3}	3.85×10^{2}	4.04×10^{4}	1.02×10^{5}
Chongqing	8.20×10^{10}	0.0068	7.06×10^{3}	5.41×10^{2}	5.38×10^{4}	1.19×10^{5}
Sichuan	4.90×10^{11}	0.0068	1.93×10^{3}	2.25×10^{2}	2.11×10^{4}	3.09×10^{4}
Guizhou	1.80×10^{11}	0.0084	4.86×10^{3}	2.37×10^{2}	2.61×10^{4}	8.77×10^{4}
Yunnan	3.90×10^{11}	0.0061	2.18×10^{3}	3.19×10^{2}	2.22×10^{4}	3.42×10^{4}
Tibet	1.20×10^{12}	0.0047	4.58×10^{1}	8.02×10^{0}	6.85×10^{2}	5.79×10^{2}
Shaanxi	2.10×10^{11}	0.0046	1.09×10^{4}	4.94×10^{2}	4.99×10^{4}	2.07×10^{5}
Gansu	4.30×10^{11}	0.0045	2.63×10^{3}	1.90×10^{2}	1.35×10^{4}	4.68×10^{4}
Qinghai	7.20×10^{11}	0.0048	2.18×10^{2}	1.88×10^{1}	1.68×10^{3}	3.72×10^{3}
Ningxia	6.60×10^{10}	0.0029	3.51×10^{4}	5.92×10^{2}	9.22×10^{4}	6.82×10^{5}
Xinjiang	1.70×10^{12}	0.0049	1.80×10^{3}	3.87×10^{1}	4.96×10^{3}	3.52×10^{4}

Table S7 Parameters [5] with for estimating adult and child exposure to HM-containing NPs in air

Parameters [5]	Adult	Child
Inhalation Rate (IR, m^3/day)	20	7.6
Inhalation Exposure Time (ET_{inh}, day)	1	1
Dermal Exposure Time (ET_{der}, s)	7200	7200
Exposure Area (EA, m^2)	0.52	0.28
Body weight (kg)	70	15

Table S8 Particle number concentrations (particles/g) of 11 HM-containing NPs emitted by 132 actual industrial process from thirteen industrial sectors

Industry	V (NPs/g)	Cr (NPs/g)	Mn (NPs/g)	Co (NPs/g)
EAF	8.9×10^{8}(1.4×10^{9},1.4×10^{8}-1.4×10^{9})	3.1×10^{10}(2.5×10^{10},9.5×10^{8}-8.4×10^{11})	2.4×10^{11}(3.0×10^{11},2.6×10^{9}-2.9×10^{12})	/
COP	2.9×10^{8}(1.4×10^{8},2.6×10^{7}-8.5×10^{8})	2.8×10^{8}(3.4×10^{8},2.7×10^{7}-1.6×10^{9})	1.9×10^{9}(2.3×10^{9},3.6×10^{8}-5.0×10^{9})	1.4×10^{8}(1.4×10^{8},2.7×10^{7}-1.4×10^{8})
CK	5.9×10^{8}(3.7×10^{8},2.7×10^{7}-1.7×10^{9})	3.5×10^{8}(2.8×10^{8},2.7×10^{7}-7.7×10^{8})	3.7×10^{9}(3.8×10^{9},1.1×10^{9}-6.3×10^{9})	1.4×10^{8}(1.3×10^{8},2.8×10^{7}-1.3×10^{9})
CFPP	1.6×10^{9}(1.0×10^{9},4.2×10^{8}-1.5×10^{10})	1.5×10^{9}(1.2×10^{9},1.4×10^{8}-1.7×10^{10})	2.9×10^{10}(1.9×10^{10},3.4×10^{9}-9.1×10^{10})	3.2×10^{9}(1.6×10^{9},1.3×10^{8}-1.7×10^{10})
PCu	8.0×10^{7}(8.0×10^{7},1.4×10^{7}-1.5×10^{8})	4.5×10^{9}(1.7×10^{9},1.3×10^{8}-1.4×10^{10})	3.0×10^{8}(2.0×10^{8},1.0×10^{8}-6.8×10^{8})	/
SCu	7.5×10^{7}(7.6×10^{7},1.3×10^{7}-1.3×10^{8})	3.0×10^{8}(4.0×10^{8},1.3×10^{8}-4.8×10^{10})	6.4×10^{8}(5.3×10^{8},4.0×10^{7}-1.7×10^{9})	3.5×10^{8}(4.3×10^{8},1.3×10^{8}-2.0×10^{9})
SAl	1.2×10^{8}(8.1×10^{7},1.4×10^{7}-2.9×10^{8})	7.7×10^{8}(7.2×10^{8},4.4×10^{8}-1.6×10^{10})	2.9×10^{9}(3.5×10^{9},1.4×10^{9}-3.4×10^{10})	2.2×10^{7}(2.2×10^{7},1.4×10^{7}-2.9×10^{7})
SPb	8.0×10^{8}(8.0×10^{8},1.5×10^{8}-1.5×10^{9})	7.6×10^{8}(9.8×10^{8},3.1×10^{8}-2.0×10^{10})	6.2×10^{8}(1.5×10^{8},4.2×10^{7}-5.5×10^{10})	/
SZn	2.3×10^{8}(2.1×10^{8},1.4×10^{7}-4.6×10^{8})	5.2×10^{8}(5.4×10^{8},1.4×10^{8}-2.4×10^{9})	1.6×10^{9}(1.9×10^{9},2.8×10^{7}-3.0×10^{9})	/
WI	2.0×10^{9}(2.0×10^{9},9.8×10^{8}-3.0×10^{9})	3.1×10^{9}(3.2×10^{9},5.4×10^{8}-6.0×10^{9})	3.4×10^{9}(4.2×10^{9},1.1×10^{9}-9.9×10^{9})	/
HWI	1.1×10^{9}(1.1×10^{9},1.0×10^{9}-1.1×10^{9})	8.3×10^{9}(4.1×10^{9},1.1×10^{8}-7.7×10^{10})	6.5×10^{10}(2.4×10^{10},1.8×10^{9}-2.3×10^{11})	1.7×10^{9}(1.7×10^{9},1.0×10^{9}-2.4×10^{9})
BFI	2.8×10^{9}(2.1×10^{9},7.0×10^{8}-6.8×10^{9})	3.7×10^{9}(4.8×10^{9},3.0×10^{8}-7.6×10^{11})	1.9×10^{10}(1.7×10^{10},1.0×10^{9}-1.8×10^{11})	8.0×10^{8}(5.9×10^{8},1.0×10^{8}-1.9×10^{9})
IOS	2.3×10^{8}(2.3×10^{8},1.1×10^{8}-3.4×10^{8})	1.7×10^{8}(2.1×10^{8},9.7×10^{7}-8.3×10^{8})	8.0×10^{8}(9.0×10^{8},1.9×10^{8}-4.1×10^{9})	1.0×10^{8}(1.0×10^{8},9.3×10^{7}-1.1×10^{8})
Industry	**Ni (NPs/g)**	**Cu (NPs/g)**	**Zn (NPs/g)**	**As (NPs/g)**
EAF	/	1.6×10^{10}(1.5×10^{10},6.8×10^{8}-1.3×10^{11})	1.2×10^{11}(1.7×10^{11},1.8×10^{9}-1.5×10^{12})	1.0×10^{9}(1.4×10^{9},1.4×10^{8}-4.2×10^{9})
COP	1.5×10^{8}(1.3×10^{8},5.6×10^{7}-2.6×10^{8})	4.1×10^{8}(4.2×10^{8},2.7×10^{7}-1.7×10^{9})	1.2×10^{9}(1.3×10^{9},2.4×10^{8}-2.7×10^{9})	8.3×10^{7}(8.3×10^{7},2.6×10^{7}-1.4×10^{8})
CK	1.1×10^{8}(8.6×10^{7},2.8×10^{7}-2.6×10^{8})	1.1×10^{9}(1.1×10^{9},1.2×10^{8}-7.0×10^{9})	1.9×10^{9}(2.5×10^{9},8.1×10^{7}-4.2×10^{10})	1.5×10^{8}(1.4×10^{8},2.8×10^{7}-1.2×10^{9})
CFPP	5.4×10^{8}(4.2×10^{8},1.3×10^{8}-3.4×10^{9})	1.3×10^{9}(4.3×10^{8},1.3×10^{8}-4.2×10^{10})	2.6×10^{9}(1.8×10^{9},4.1×10^{8}-8.4×10^{9})	2.3×10^{8}(2.1×10^{8},1.3×10^{8}-4.2×10^{8})
PCu	8.9×10^{7}(8.9×10^{7},4.3×10^{7}-1.3×10^{8})	5.1×10^{10}(5.5×10^{10},1.1×10^{9}-1.1×10^{11})	8.7×10^{8}(6.8×10^{8},7.2×10^{7}-9.6×10^{9})	8.9×10^{9}(1.1×10^{10},1.3×10^{8}-1.4×10^{10})
SCu	1.0×10^{9}(1.4×10^{8},2.9×10^{7}-2.7×10^{10})	7.1×10^{10}(1.5×10^{10},7.1×10^{8}-6.2×10^{11})	1.6×10^{10}(1.5×10^{10},1.4×10^{8}-2.5×10^{11})	7.1×10^{8}(4.2×10^{8},1.2×10^{8}-1.0×10^{11})
SAl	7.2×10^{7}(5.7×10^{7},1.4×10^{7}-1.4×10^{8})	4.3×10^{9}(3.5×10^{9},2.9×10^{8}-3.4×10^{10})	4.6×10^{9}(4.8×10^{9},1.5×10^{9}-3.3×10^{10})	2.9×10^{7}(2.9×10^{7},1.4×10^{7}-4.3×10^{7})
SPb	2.0×10^{7}(2.0×10^{7},1.4×10^{7}-2.6×10^{7})	9.8×10^{8}(7.1×10^{8},5.6×10^{7}-2.6×10^{10})	7.1×10^{9}(1.8×10^{9},5.7×10^{7}-4.1×10^{10})	2.6×10^{8}(1.4×10^{8},2.6×10^{7}-6.0×10^{8})
SZn	5.7×10^{7}(1.5×10^{7},1.4×10^{7}-1.4×10^{8})	6.0×10^{8}(5.9×10^{8},1.4×10^{8}-3.1×10^{9})	4.0×10^{9}(6.0×10^{9},1.2×10^{8}-1.6×10^{10})	9.9×10^{7}(9.9×10^{7},5.5×10^{7}-1.4×10^{8})
WI	1.0×10^{9}(1.1×10^{9},9.8×10^{8}-2.2×10^{9})	1.9×10^{9}(1.7×10^{9},8.2×10^{8}-3.5×10^{9})	4.9×10^{9}(2.3×10^{9},9.8×10^{8}-3.3×10^{10})	/
HWI	2.9×10^{9}(3.2×10^{9},1.1×10^{9}-1.5×10^{10})	1.9×10^{10}(1.8×10^{10},1.6×10^{9}-1.7×10^{11})	1.2×10^{11}(8.4×10^{10},3.3×10^{9}-7.2×10^{11})	/

BFI	6.0×10^{8}(6.0×10^{8},2.3×10^{8}-9.7×10^{8})	2.3×10^{9}(2.4×10^{9},9.5×10^{8}-1.1×10^{10})	1.7×10^{10}(8.6×10^{9},6.8×10^{8}-6.8×10^{11})	/
IOS	1.1×10^{8}(1.1×10^{8},1.0×10^{8}-1.1×10^{8})	4.8×10^{8}(3.1×10^{8},1.0×10^{8}-3.4×10^{9})	2.8×10^{8}(2.2×10^{8},9.2×10^{7}-4.9×10^{8})	/
Industry	**Cd (NPs/g)**	**Sn (NPs/g)**		
EAF	2.2×10^{9}(2.8×10^{9},1.4×10^{8}-8.5×10^{9})	1.5×10^{11}(1.9×10^{11},4.5×10^{9}-3.2×10^{11})		
COP	1.8×10^{8}(2.0×10^{8},2.6×10^{7}-5.7×10^{8})	6.2×10^{9}(6.4×10^{9},1.3×10^{8}-2.8×10^{10})		
CK	1.9×10^{8}(1.4×10^{8},2.8×10^{7}-3.9×10^{8})	1.7×10^{10}(1.9×10^{10},2.5×10^{8}-3.4×10^{10})		
CFPP	0.0×10^{0}(0.0×10^{0},0.0×10^{0}-0.0×10^{0})	1.8×10^{9}(1.8×10^{9},4.1×10^{8}-9.5×10^{9})		
PCu	4.1×10^{10}(1.8×10^{10},1.3×10^{8}-1.3×10^{11})	2.2×10^{10}(1.9×10^{10},1.1×10^{8}-5.6×10^{10})		
SCu	1.4×10^{8}(1.4×10^{8},1.3×10^{7}-5.2×10^{10})	3.6×10^{11}(2.3×10^{11},9.5×10^{9}-1.1×10^{12})		
SAl	8.3×10^{7}(8.6×10^{7},1.4×10^{7}-1.5×10^{8})	1.2×10^{10}(1.2×10^{10},5.5×10^{9}-1.7×10^{10})		
SPb	9.9×10^{8}(1.4×10^{9},1.3×10^{8}-4.1×10^{10})	5.5×10^{10}(4.2×10^{10},2.3×10^{9}-8.6×10^{11})		
SZn	1.6×10^{8}(1.8×10^{8},2.7×10^{7}-3.6×10^{9})	2.9×10^{9}(2.8×10^{9},4.5×10^{7}-3.8×10^{10})		
WI	/	5.2×10^{9}(4.8×10^{9},4.1×10^{8}-1.5×10^{10})		
HWI	/	6.6×10^{11}(6.6×10^{11},2.6×10^{10}-1.5×10^{12})		
BFI	/	2.7×10^{9}(3.1×10^{9},4.5×10^{8}-9.1×10^{9})		
IOS	/	1.6×10^{8}(1.1×10^{8},9.2×10^{7}-3.3×10^{8})		

Table S9 Toxicity Contribution value (TCV) of 11 HM-containing NPs emitted by 132 actual industrial process from thirteen industrial sectors

Industry	V	Cr	Mn	Co
EAF	$1.8\times10^{9}(2.7\times10^{9},2.7\times10^{8}\text{-}2.8\times10^{9})$	$6.2\times10^{10}(4.9\times10^{10},1.9\times10^{9}\text{-}1.7\times10^{12})$	$2.4\times10^{11}(3.0\times10^{11},2.6\times10^{9}\text{-}2.9\times10^{12})$	/
COP	$5.8\times10^{8}(2.8\times10^{8},5.2\times10^{7}\text{-}1.7\times10^{9})$	$5.6\times10^{8}(6.7\times10^{8},5.4\times10^{7}\text{-}3.2\times10^{9})$	$1.9\times10^{9}(2.3\times10^{9},3.6\times10^{8}\text{-}5.0\times10^{9})$	$6.9\times10^{8}(6.8\times10^{8},1.3\times10^{8}\text{-}7.0\times10^{8})$
CK	$1.2\times10^{9}(7.3\times10^{8},5.4\times10^{7}\text{-}3.3\times10^{9})$	$7.1\times10^{8}(5.6\times10^{8},5.4\times10^{7}\text{-}1.5\times10^{9})$	$3.7\times10^{9}(3.8\times10^{9},1.1\times10^{9}\text{-}6.3\times10^{9})$	$6.8\times10^{8}(6.6\times10^{8},1.4\times10^{8}\text{-}6.4\times10^{9})$
CFPP	$3.2\times10^{9}(2.1\times10^{9},8.4\times10^{8}\text{-}3.1\times10^{10})$	$3.1\times10^{9}(2.4\times10^{9},2.7\times10^{8}\text{-}3.4\times10^{10})$	$2.9\times10^{10}(1.9\times10^{10},3.4\times10^{9}\text{-}9.1\times10^{10})$	$1.6\times10^{10}(8.2\times10^{9},6.4\times10^{8}\text{-}8.4\times10^{10})$
PCu	$1.6\times10^{8}(1.6\times10^{8},2.9\times10^{7}\text{-}2.9\times10^{8})$	$9.0\times10^{9}(3.4\times10^{9},2.6\times10^{8}\text{-}2.9\times10^{10})$	$3.0\times10^{8}(2.0\times10^{8},1.0\times10^{8}\text{-}6.8\times10^{8})$	/
SCu	$1.5\times10^{8}(1.5\times10^{8},2.7\times10^{7}\text{-}2.6\times10^{8})$	$6.0\times10^{8}(8.0\times10^{8},2.7\times10^{8}\text{-}9.7\times10^{10})$	$6.4\times10^{8}(5.3\times10^{8},4.0\times10^{7}\text{-}1.7\times10^{9})$	$1.7\times10^{9}(2.2\times10^{9},6.6\times10^{8}\text{-}1.0\times10^{10})$
SAl	$2.3\times10^{8}(1.6\times10^{8},2.9\times10^{7}\text{-}5.7\times10^{8})$	$1.5\times10^{9}(1.4\times10^{9},8.8\times10^{8}\text{-}3.2\times10^{10})$	$2.9\times10^{9}(3.5\times10^{9},1.4\times10^{9}\text{-}3.4\times10^{10})$	$1.1\times10^{8}(1.1\times10^{8},7.2\times10^{7}\text{-}1.4\times10^{8})$
SPb	$1.6\times10^{9}(1.6\times10^{9},3.0\times10^{8}\text{-}2.9\times10^{9})$	$1.5\times10^{9}(2.0\times10^{9},6.2\times10^{8}\text{-}4.1\times10^{10})$	$6.2\times10^{8}(1.5\times10^{8},4.2\times10^{7}\text{-}5.5\times10^{10})$	/
SZn	$4.5\times10^{8}(4.3\times10^{8},2.8\times10^{7}\text{-}9.2\times10^{8})$	$1.0\times10^{9}(1.1\times10^{9},2.9\times10^{8}\text{-}4.8\times10^{9})$	$1.6\times10^{9}(1.9\times10^{9},2.8\times10^{7}\text{-}3.0\times10^{9})$	/
WI	$4.0\times10^{9}(4.0\times10^{9},2.0\times10^{9}\text{-}5.9\times10^{9})$	$6.2\times10^{9}(6.3\times10^{9},1.1\times10^{9}\text{-}1.2\times10^{10})$	$3.4\times10^{9}(4.2\times10^{9},1.1\times10^{9}\text{-}9.9\times10^{9})$	/
HWI	$2.1\times10^{9}(2.1\times10^{9},2.0\times10^{9}\text{-}2.2\times10^{9})$	$1.7\times10^{10}(8.2\times10^{9},2.3\times10^{8}\text{-}1.5\times10^{11})$	$6.5\times10^{10}(2.4\times10^{10},1.8\times10^{9}\text{-}2.3\times10^{11})$	$8.4\times10^{9}(8.3\times10^{9},5.0\times10^{9}\text{-}1.2\times10^{10})$
BFI	$5.6\times10^{9}(4.2\times10^{9},1.4\times10^{9}\text{-}1.4\times10^{10})$	$7.5\times10^{9}(9.5\times10^{9},6.0\times10^{8}\text{-}1.5\times10^{12})$	$1.9\times10^{10}(1.7\times10^{10},1.0\times10^{9}\text{-}1.8\times10^{11})$	$4.0\times10^{9}(2.9\times10^{9},5.0\times10^{8}\text{-}9.7\times10^{9})$
IOS	$4.5\times10^{8}(4.6\times10^{8},2.2\times10^{8}\text{-}6.7\times10^{8})$	$3.5\times10^{8}(4.2\times10^{8},1.9\times10^{8}\text{-}1.7\times10^{9})$	$8.0\times10^{8}(9.0\times10^{8},1.9\times10^{8}\text{-}4.1\times10^{9})$	$5.1\times10^{8}(5.1\times10^{8},4.7\times10^{8}\text{-}5.6\times10^{8})$
Industry	**Ni**	**Cu**	**Zn**	**As**
EAF	/	$7.9\times10^{10}(7.4\times10^{10},3.4\times10^{9}\text{-}6.6\times10^{11})$	$1.2\times10^{11}(1.7\times10^{11},1.8\times10^{9}\text{-}1.5\times10^{12})$	$1.0\times10^{10}(1.4\times10^{10},1.4\times10^{9}\text{-}4.2\times10^{10})$
COP	$7.5\times10^{8}(6.5\times10^{8},2.8\times10^{8}\text{-}1.3\times10^{9})$	$2.0\times10^{9}(2.1\times10^{9},1.3\times10^{8}\text{-}8.5\times10^{9})$	$1.2\times10^{9}(1.3\times10^{9},2.4\times10^{8}\text{-}2.7\times10^{9})$	$8.3\times10^{8}(8.3\times10^{8},2.6\times10^{8}\text{-}1.4\times10^{9})$
CK	$5.7\times10^{8}(4.3\times10^{8},1.4\times10^{8}\text{-}1.3\times10^{9})$	$5.3\times10^{9}(5.7\times10^{9},6.1\times10^{8}\text{-}3.5\times10^{10})$	$1.9\times10^{9}(2.5\times10^{9},8.1\times10^{7}\text{-}4.2\times10^{10})$	$1.5\times10^{9}(1.4\times10^{9},2.8\times10^{8}\text{-}1.2\times10^{10})$
CFPP	$2.7\times10^{9}(2.1\times10^{9},6.4\times10^{8}\text{-}1.7\times10^{10})$	$6.4\times10^{9}(2.1\times10^{9},6.5\times10^{8}\text{-}2.1\times10^{11})$	$2.6\times10^{9}(1.8\times10^{9},4.1\times10^{8}\text{-}8.4\times10^{9})$	$2.3\times10^{9}(2.1\times10^{9},1.3\times10^{9}\text{-}4.2\times10^{9})$
PCu	$4.5\times10^{8}(4.5\times10^{8},2.2\times10^{8}\text{-}6.7\times10^{8})$	$2.6\times10^{11}(2.7\times10^{11},5.4\times10^{9}\text{-}5.3\times10^{11})$	$8.7\times10^{8}(6.8\times10^{8},7.2\times10^{7}\text{-}9.6\times10^{9})$	$8.9\times10^{10}(1.1\times10^{11},1.3\times10^{9}\text{-}1.4\times10^{11})$
SCu	$5.2\times10^{9}(7.2\times10^{8},1.4\times10^{8}\text{-}1.3\times10^{11})$	$3.6\times10^{11}(7.7\times10^{10},3.6\times10^{9}\text{-}3.1\times10^{12})$	$1.6\times10^{10}(1.5\times10^{10},1.4\times10^{8}\text{-}2.5\times10^{11})$	$7.1\times10^{9}(4.2\times10^{9},1.2\times10^{9}\text{-}1.0\times10^{12})$
SAl	$3.6\times10^{8}(2.9\times10^{8},7.2\times10^{7}\text{-}7.2\times10^{8})$	$2.1\times10^{10}(1.7\times10^{10},1.4\times10^{9}\text{-}1.7\times10^{11})$	$4.6\times10^{9}(4.8\times10^{9},1.5\times10^{9}\text{-}3.3\times10^{10})$	$2.9\times10^{8}(2.9\times10^{8},1.4\times10^{8}\text{-}4.3\times10^{8})$
SPb	$1.0\times10^{8}(1.0\times10^{8},7.1\times10^{7}\text{-}1.3\times10^{8})$	$4.9\times10^{9}(3.6\times10^{9},2.8\times10^{8}\text{-}1.3\times10^{11})$	$7.1\times10^{9}(1.8\times10^{9},5.7\times10^{7}\text{-}4.1\times10^{10})$	$2.6\times10^{9}(1.4\times10^{9},2.6\times10^{8}\text{-}6.0\times10^{9})$
SZn	$2.9\times10^{8}(7.4\times10^{7},6.9\times10^{7}\text{-}7.1\times10^{8})$	$3.0\times10^{9}(3.0\times10^{9},7.1\times10^{8}\text{-}1.6\times10^{10})$	$4.0\times10^{9}(6.0\times10^{9},1.2\times10^{8}\text{-}1.6\times10^{10})$	$9.9\times10^{8}(9.9\times10^{8},5.5\times10^{8}\text{-}1.4\times10^{9})$
WI	$5.2\times10^{9}(5.3\times10^{9},4.9\times10^{9}\text{-}1.1\times10^{10})$	$9.7\times10^{9}(8.7\times10^{9},4.1\times10^{9}\text{-}1.7\times10^{10})$	$4.9\times10^{9}(2.3\times10^{9},9.8\times10^{8}\text{-}3.3\times10^{10})$	/

HWI	$1.5\times10^{10}(1.6\times10^{10},5.3\times10^{9}\text{-}7.6\times10^{10})$	$9.6\times10^{10}(8.9\times10^{10},7.9\times10^{9}\text{-}8.5\times10^{11})$	$1.2\times10^{11}(8.4\times10^{10},3.3\times10^{9}\text{-}7.2\times10^{11})$	/
BFI	$3.0\times10^{9}(3.0\times10^{9},1.1\times10^{9}\text{-}4.8\times10^{9})$	$1.2\times10^{10}(1.2\times10^{10},4.8\times10^{9}\text{-}5.4\times10^{10})$	$1.7\times10^{10}(8.6\times10^{9},6.8\times10^{8}\text{-}6.8\times10^{11})$	/
IOS	$5.4\times10^{8}(5.5\times10^{8},5.0\times10^{8}\text{-}5.6\times10^{8})$	$2.4\times10^{9}(1.5\times10^{9},5.0\times10^{8}\text{-}1.7\times10^{10})$	$2.8\times10^{8}(2.2\times10^{8},9.2\times10^{7}\text{-}4.9\times10^{8})$	/
Industry	**Cd**	**Sn**		
EAF	$6.5\times10^{10}(8.5\times10^{10},4.1\times10^{9}\text{-}2.5\times10^{11})$	$1.5\times10^{11}(1.9\times10^{11},4.5\times10^{9}\text{-}3.2\times10^{11})$		
COP	$5.3\times10^{9}(6.1\times10^{9},7.8\times10^{8}\text{-}1.7\times10^{10})$	$6.2\times10^{9}(6.4\times10^{9},1.3\times10^{8}\text{-}2.8\times10^{10})$		
CK	$5.6\times10^{9}(4.1\times10^{9},8.5\times10^{8}\text{-}1.2\times10^{10})$	$1.7\times10^{10}(1.9\times10^{10},2.5\times10^{8}\text{-}3.4\times10^{10})$		
CFPP	/	$1.8\times10^{9}(1.8\times10^{9},4.1\times10^{8}\text{-}9.5\times10^{9})$		
PCu	$1.2\times10^{12}(5.4\times10^{11},4.0\times10^{9}\text{-}3.8\times10^{12})$	$2.2\times10^{10}(1.9\times10^{10},1.1\times10^{8}\text{-}5.6\times10^{10})$		
SCu	$4.1\times10^{9}(4.1\times10^{9},4.0\times10^{8}\text{-}1.6\times10^{12})$	$3.6\times10^{11}(2.3\times10^{11},9.5\times10^{9}\text{-}1.1\times10^{12})$		
SAl	$2.5\times10^{9}(2.6\times10^{9},4.3\times10^{8}\text{-}4.4\times10^{9})$	$1.2\times10^{10}(1.2\times10^{10},5.5\times10^{9}\text{-}1.7\times10^{10})$		
SPb	$3.0\times10^{10}(4.3\times10^{10},4.0\times10^{9}\text{-}1.2\times10^{12})$	$5.5\times10^{10}(4.2\times10^{10},2.3\times10^{9}\text{-}8.6\times10^{11})$		
SZn	$4.7\times10^{9}(5.4\times10^{9},8.1\times10^{8}\text{-}1.1\times10^{11})$	$2.9\times10^{9}(2.8\times10^{9},4.5\times10^{7}\text{-}3.8\times10^{10})$		
WI	/	$5.2\times10^{9}(4.8\times10^{9},4.1\times10^{8}\text{-}1.5\times10^{10})$		
HWI	/	$6.6\times10^{11}(6.6\times10^{11},2.6\times10^{10}\text{-}1.5\times10^{12})$		
BFI	/	$2.7\times10^{9}(3.1\times10^{9},4.5\times10^{8}\text{-}9.1\times10^{9})$		
IOS	/	$1.6\times10^{8}(1.1\times10^{8},9.2\times10^{7}\text{-}3.3\times10^{8})$		

Table S10 Emission factors (particles/t) of HM-containing NPs for thirteen industrial sectors

Industry	V	Cr	Mn	Co	Ni	Cu	Zn	As	Cd	Sn
BFI	1.3×10^{11}	1.7×10^{11}	8.5×10^{11}	3.6×10^{10}	2.7×10^{10}	1.0×10^{11}	7.5×10^{11}	/	/	1.2×10^{11}
CFPP	1.6×10^{15}	1.5×10^{15}	2.8×10^{16}	3.1×10^{15}	5.3×10^{14}	1.3×10^{15}	2.5×10^{15}	2.3×10^{14}	/	1.7×10^{15}
CK	5.3×10^{11}	3.2×10^{11}	3.3×10^{12}	1.2×10^{11}	1.0×10^{11}	9.5×10^{11}	1.7×10^{12}	1.3×10^{11}	1.7×10^{11}	1.5×10^{13}
COP	1.3×10^{11}	1.2×10^{11}	8.6×10^{11}	6.1×10^{10}	6.6×10^{10}	1.8×10^{11}	5.1×10^{11}	3.7×10^{10}	7.7×10^{10}	2.7×10^{12}
EAF	9.3×10^{10}	3.3×10^{12}	2.5×10^{13}	/	/	1.6×10^{12}	1.3×10^{13}	1.0×10^{11}	2.3×10^{11}	1.6×10^{13}
HWI	1.0×10^{10}	8.2×10^{10}	6.3×10^{11}	1.6×10^{10}	2.9×10^{10}	1.9×10^{11}	1.2×10^{12}	/	/	6.5×10^{12}
IOS	1.5×10^{10}	1.1×10^{10}	5.2×10^{10}	6.7×10^{9}	7.0×10^{9}	3.1×10^{10}	1.8×10^{10}	/	/	1.0×10^{10}
PCu	2.2×10^{10}	1.2×10^{12}	8.2×10^{10}	/	2.5×10^{10}	1.4×10^{13}	2.4×10^{11}	2.4×10^{12}	1.1×10^{13}	6.0×10^{12}
SAl	5.5×10^{10}	3.7×10^{11}	1.4×10^{12}	1.0×10^{10}	3.4×10^{10}	2.0×10^{12}	2.2×10^{12}	1.4×10^{10}	4.0×10^{10}	5.6×10^{12}
SCu	3.6×10^{10}	1.4×10^{11}	3.1×10^{11}	1.7×10^{11}	4.9×10^{11}	3.4×10^{13}	7.8×10^{12}	3.4×10^{11}	6.6×10^{10}	1.7×10^{14}
SPb	5.5×10^{11}	5.1×10^{11}	4.2×10^{11}	/	1.4×10^{10}	6.7×10^{11}	4.8×10^{12}	1.8×10^{11}	6.8×10^{11}	3.7×10^{13}
SZn	1.1×10^{11}	2.6×10^{11}	8.0×10^{11}	/	2.9×10^{10}	3.0×10^{11}	2.0×10^{12}	5.0×10^{10}	7.9×10^{10}	1.4×10^{12}
WI	1.9×10^{10}	3.0×10^{10}	3.4×10^{10}	/	1.0×10^{10}	1.9×10^{10}	4.8×10^{10}	/	/	5.1×10^{10}

Note: The emission factor is the number of HM-containing NPs emitted to the atmosphere by producing one ton (steel, copper, aluminum, lead and zinc) or disposing one ton of garbage or coal-fired power generation 1Twh.

Table S11 Atmosphere emissions (particles) of 11 HM-containing NPs from different industrial sources in China mainland

Industry Source	V	Cr	Mn	Co	Ni	Cu	Zn	As	Cd	Sn
COP	6.0×10^{19}	5.8×10^{19}	4.0×10^{20}	2.9×10^{19}	3.1×10^{19}	8.5×10^{19}	2.4×10^{20}	1.7×10^{19}	3.6×10^{19}	1.3×10^{21}
CFPP	8.4×10^{21}	8.0×10^{21}	1.5×10^{23}	1.7×10^{22}	2.8×10^{21}	6.7×10^{21}	1.4×10^{22}	1.2×10^{21}	0.0×10^{0}	9.2×10^{21}
CK	1.1×10^{21}	6.8×10^{20}	7.0×10^{21}	2.6×10^{20}	2.2×10^{20}	2.0×10^{21}	3.7×10^{21}	2.8×10^{20}	3.6×10^{20}	3.3×10^{22}
EAF	8.7×10^{18}	3.0×10^{20}	2.3×10^{21}	/	/	1.5×10^{20}	1.2×10^{21}	9.7×10^{18}	2.1×10^{19}	1.5×10^{21}
IOS	1.6×10^{19}	1.2×10^{19}	5.7×10^{19}	7.4×10^{18}	7.7×10^{18}	3.4×10^{19}	2.0×10^{19}	/	/	1.1×10^{19}
WI	2.0×10^{18}	3.1×10^{18}	3.4×10^{18}	/	1.0×10^{18}	1.9×10^{18}	4.9×10^{18}	/	/	5.2×10^{18}
BFI	1.1×10^{20}	1.5×10^{20}	7.4×10^{20}	3.1×10^{19}	2.3×10^{19}	9.0×10^{19}	6.5×10^{20}	/	/	1.1×10^{20}
PCu	1.5×10^{17}	8.2×10^{18}	5.4×10^{17}	/	1.6×10^{17}	9.4×10^{19}	1.6×10^{18}	1.6×10^{19}	7.5×10^{19}	4.0×10^{19}
SCu	8.2×10^{16}	3.3×10^{17}	7.1×10^{17}	3.8×10^{17}	1.1×10^{18}	7.9×10^{19}	1.8×10^{19}	7.8×10^{17}	1.5×10^{17}	4.0×10^{20}
SZn	7.5×10^{16}	1.7×10^{17}	5.2×10^{17}	/	1.9×10^{16}	2.0×10^{17}	1.3×10^{18}	3.3×10^{16}	5.2×10^{16}	9.5×10^{17}
SPb	1.2×10^{18}	1.1×10^{18}	9.0×10^{17}	/	3.0×10^{16}	1.4×10^{18}	1.0×10^{19}	3.9×10^{17}	1.4×10^{18}	8.0×10^{19}
SAl	3.0×10^{17}	2.0×10^{18}	7.6×10^{18}	5.7×10^{16}	1.9×10^{17}	1.1×10^{19}	1.2×10^{19}	7.6×10^{16}	2.2×10^{17}	3.1×10^{19}
HWI	8.7×10^{17}	6.9×10^{18}	5.4×10^{19}	1.4×10^{18}	2.4×10^{18}	1.6×10^{19}	9.7×10^{19}	/	/	5.5×10^{20}
Total	9.8×10^{21}	9.3×10^{21}	1.6×10^{23}	1.7×10^{22}	3.1×10^{21}	9.3×10^{21}	2.0×10^{22}	1.5×10^{21}	4.9×10^{20}	4.6×10^{22}

Table S12 The Lifetime Average Daily Dose (LADD) of HM-containing NPs for Adults and Children Through Inhalation and Dermal Exposure from 13 Industrial Sources

Province	Adult			Child		
	Cu-LADD	Cd-LADD	Sn-LADD	Cu-LADD	Cd-LADD	Sn-LADD
Beijing	1.3×10^{4}	7.9×10^{1}	2.5×10^{4}	2.8×10^{4}	1.7×10^{2}	5.2×10^{4}
Tianjin	3.7×10^{4}	5.2×10^{2}	8.9×10^{4}	7.7×10^{4}	1.1×10^{3}	1.9×10^{5}
Hebei	1.1×10^{4}	5.5×10^{2}	5.5×10^{4}	2.4×10^{4}	1.2×10^{3}	1.1×10^{5}
Shanxi	1.2×10^{4}	4.9×10^{2}	4.2×10^{4}	2.4×10^{4}	1.0×10^{3}	8.7×10^{4}
Inner Mongolia	2.1×10^{3}	4.3×10^{1}	5.1×10^{3}	4.5×10^{3}	9.1×10^{1}	1.1×10^{4}
Liaoning	6.2×10^{3}	2.7×10^{2}	2.6×10^{4}	1.3×10^{4}	5.8×10^{2}	5.5×10^{4}
Jilin	2.2×10^{3}	9.2×10^{1}	8.4×10^{3}	4.7×10^{3}	2.0×10^{2}	1.8×10^{4}
Heilongjiang	1.1×10^{3}	3.3×10^{1}	4.0×10^{3}	2.3×10^{3}	7.0×10^{1}	8.4×10^{3}
Shanghai	6.0×10^{4}	9.1×10^{2}	1.3×10^{5}	1.3×10^{5}	2.0×10^{3}	2.8×10^{5}
Jiangsu	2.4×10^{4}	9.8×10^{2}	1.0×10^{5}	5.1×10^{4}	2.1×10^{3}	2.2×10^{5}
Zhejiang	1.4×10^{4}	7.7×10^{2}	7.6×10^{4}	3.0×10^{4}	1.7×10^{3}	1.7×10^{5}
Anhui	1.1×10^{4}	7.7×10^{2}	6.1×10^{4}	2.3×10^{4}	1.7×10^{3}	1.3×10^{5}
Fujian	8.1×10^{3}	5.5×10^{2}	4.8×10^{4}	1.7×10^{4}	1.2×10^{3}	1.0×10^{5}
Jiangxi	4.9×10^{3}	4.4×10^{2}	3.2×10^{4}	1.1×10^{4}	9.7×10^{2}	6.9×10^{4}
Shandong	2.1×10^{4}	1.0×10^{3}	8.4×10^{4}	4.4×10^{4}	2.1×10^{3}	1.7×10^{5}
Henan	9.9×10^{3}	5.6×10^{2}	5.2×10^{4}	2.1×10^{4}	1.2×10^{3}	1.1×10^{5}
Hubei	4.9×10^{3}	4.1×10^{2}	3.5×10^{4}	1.0×10^{4}	8.9×10^{2}	7.6×10^{4}
Hunan	2.9×10^{3}	2.5×10^{2}	2.4×10^{4}	6.5×10^{3}	5.4×10^{2}	5.4×10^{4}
Guangdong	1.0×10^{4}	4.5×10^{2}	5.2×10^{4}	2.3×10^{4}	9.9×10^{2}	1.1×10^{5}
Guangxi	3.0×10^{3}	2.9×10^{2}	2.2×10^{4}	6.6×10^{3}	6.4×10^{2}	5.0×10^{4}
Hainan	3.8×10^{3}	2.5×10^{2}	2.6×10^{4}	8.3×10^{3}	5.4×10^{2}	5.7×10^{4}
Chongqing	4.6×10^{3}	3.5×10^{2}	3.5×10^{4}	1.0×10^{4}	7.7×10^{2}	7.6×10^{4}
Sichuan	1.2×10^{3}	1.5×10^{2}	1.4×10^{4}	2.7×10^{3}	3.2×10^{2}	3.0×10^{4}
Guizhou	3.6×10^{3}	1.7×10^{2}	1.9×10^{4}	8.0×10^{3}	3.9×10^{2}	4.3×10^{4}
Yunnan	1.3×10^{3}	1.9×10^{2}	1.4×10^{4}	2.9×10^{3}	4.2×10^{2}	2.9×10^{4}
Tibet	2.5×10^{1}	4.3×10^{0}	3.7×10^{2}	5.2×10^{1}	9.1×10^{0}	7.8×10^{2}
Shaanxi	5.8×10^{3}	2.6×10^{2}	2.7×10^{4}	1.2×10^{4}	5.6×10^{2}	5.6×10^{4}
Gansu	1.4×10^{3}	1.0×10^{2}	7.1×10^{3}	2.9×10^{3}	2.1×10^{2}	1.5×10^{4}
Qinghai	1.2×10^{2}	1.0×10^{1}	9.1×10^{2}	2.5×10^{2}	2.2×10^{1}	1.9×10^{3}
Ningxia	1.5×10^{4}	2.6×10^{2}	4.1×10^{4}	3.1×10^{4}	5.3×10^{2}	8.3×10^{4}
Xinjiang	9.8×10^{2}	2.1×10^{1}	2.7×10^{3}	2.1×10^{3}	4.5×10^{1}	5.8×10^{3}

Supplementary Method 1 Analysis Method for Particle Number Concentration (PNC) of HM-Containing Nanoparticles by ICP-TOF-MS

ICP-TOF-MS (TOFWERK icpTOF 2R/CETAC Iridia-Bio, Switzerland) was employed for analysis of PNC of HM-containing NPs. Element-specific instrument sensitivities were measured using a multi-element solution blend derived from a certified multi-element standard solution multi-element standard solution (0, 0.05, 0.1, 0.2, 0.5, 1 μg/L for multi-element standard [QC21, NIST SRM, SPEX, USA] diluted in 1% HNO3 from Beijing Institute of Chemical Reagents, China). Element-specific instrument sensitivities were measured using a multi-element solution blend derived from a certified multi-element standard solution (GSB 04-1789-2004, National Nonferrous Metals and Electronic Materials Analysis and Testing Centre, China). The linear correlation coefficients (R) for the 10 HM ions exceed 0.996, except for the Au ion, which has an R value of 0.997 (**Fig. S2**). Prior to analysis, the ICP-TOF-MS mass spectra were calibrated using TofDaq Viewer (Version, TOFWERK) with a standard tuning solution of $^{23}Na^{+}$, $^{80}Ar^{2+}$, and $^{208}Pb^{+}$ target isotopes. To reduce multi-atomic interference, we utilized the kinetic energy discrimination (KED) mode, using a collision cell gas composed of 4.5% hydrogen gas in helium.

According to **Equation (S1),** the PNC of HM-containing NPs was determined.

$$PNC \ \ (particles/g) = \frac{N \times DF \times V_{ext}}{t \times Q \times \eta \times m_i} \qquad \text{(S1)}$$

Where N is the number of detected nanoparticles, DF is the dilution factor, V_{ext} is the extraction volume, t is the acquisition time, Q is the liquid flow, η is the transport efficiency, m_i is the mass of industrial PM.

The data obtained from the single-particle experiments were analyzed using the time-of-flight single-particle investigator (TOF-SPI), an in-house LabVIEW program (LabVIEW 2018, National Instruments, TX, USA). TOF-SPI, an open-source software developed by Alexander Gundlach-Graham (https://github.com/TOFMS-GG-Group), is designed for processing SP-ICP-TOF-MS data combined with liquid calibrations. In this study's data processing, element-specific backgrounds, critical values, absolute sensitivities, particle intensities, and elemental masses (in grams) per particle were determined using TOF-SPI.

Supplementary Method 2 Quality Assurance and Quality Control

In this study, calibration curves for all 10 heavy metal ions exhibited excellent linearity, with correlation coefficients (R) exceeding 0.996, while the calibration curve for the Au ion showed an R value of 0.997 (Fig. S2). Procedural blanks consisting of ultrapure water were analyzed prior to each batch of sample measurements, and no HM-containing nanoparticles were detected in any blank samples.

A particle detection threshold based on a compound Poisson distribution was applied during data processing to ensure that the instrument response reflected true HM-containing nanoparticle signals. This threshold criterion, which separates genuine single-particle events from background noise, was embedded in the TOF-SPI software. The detection threshold was calculated as:

$$threshold = mean + (3.29\sigma + 2.71)$$

Where mean and σ correspond to the average intensity and standard deviation of the background signal determined within a 100-point analysis window. Based on this particle discrimination criterion, the minimum particle mass that could be reliably classified as a single-particle event ranged from 1.19×10^{-17} to 8.58×10^{-15} g. For HM-containing nanoparticles, approximately 85% of the analyzed samples exhibited mass detection limits on the order of 10^{-17} g (Fig. S3a).

Here, using Sn as an illustrative example, and assuming that Sn-containing nanoparticles were predominantly present as the chemically stable oxide SnO_2, the mass-based detection limits were converted to equivalent spherical diameter detection thresholds ranging from 14.9 to 133.1 nm. Notably, the inferred size detection limits for SnO_2 nanoparticles were below 30 nm in more than 82.5% of samples, below 40 nm in over 92.8% of samples, below 60 nm in more than 98.0% of samples, below 80 nm in more than 99.3% of samples, and below 100 nm in more than 99.8% of samples. All inferred size detection limits were below 140 nm (Fig. S3b).

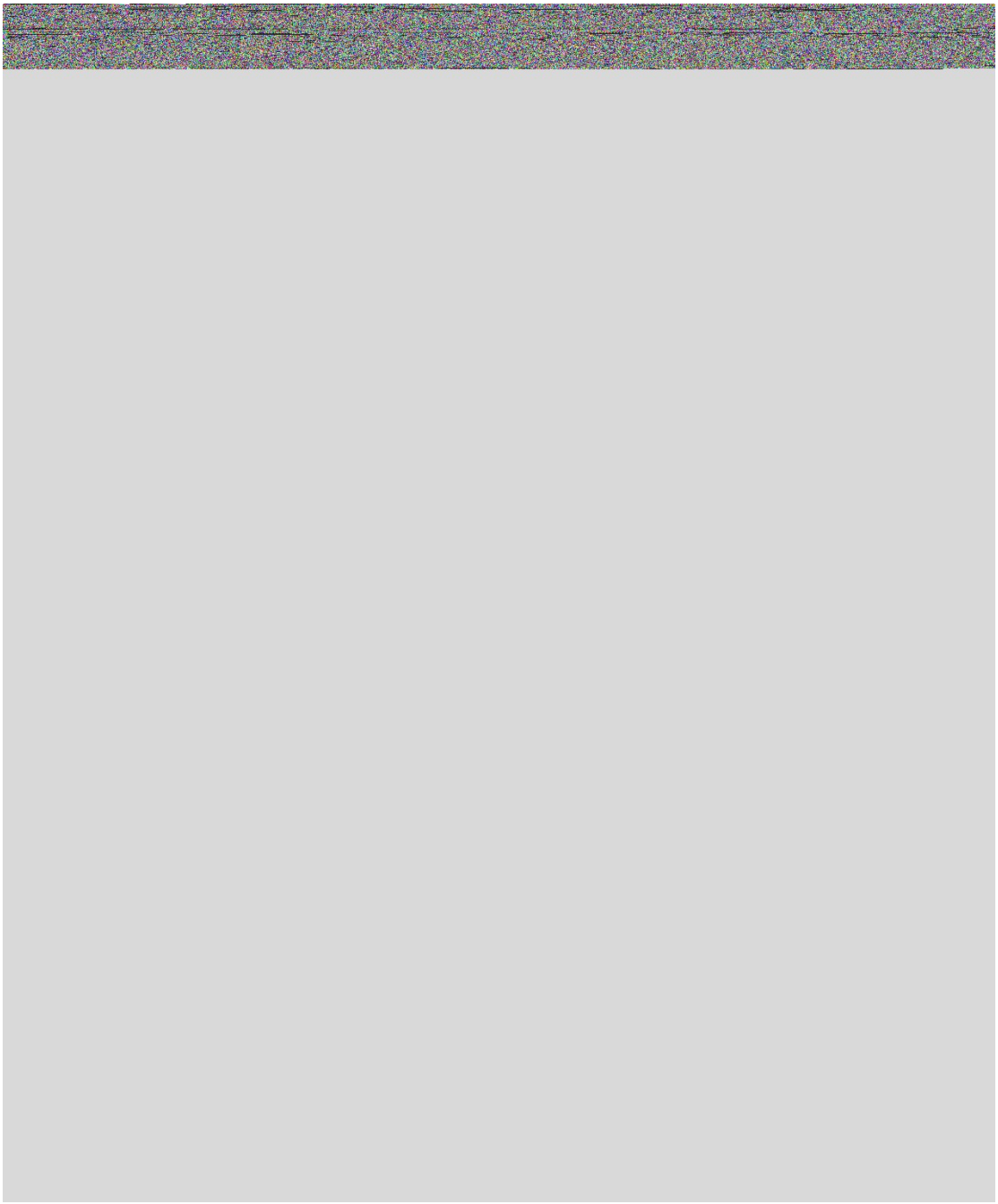

Fig. S3 (a) Mass detection limit and (b) size detection limit of HM-containing NPs for each sample

Uncertainty in analysis of HM-containing NPs

Several sources of uncertainty are inherent in the application of SP-ICP-TOF-MS for quantifying the particle number concentrations of HM-containing NPs. These include: (1) **Underestimation of transport efficiency**, whereby the fraction of nanoparticles effectively introduced into the plasma (η) may be underestimated; (2) **Size detection limits**, as particles with masses below the established

detection threshold are not recognized as valid single-particle events and are therefore excluded from the particle count; (3) **Elevated background noise**, where the complex matrix of industrial particulate matter increases background signal variability, thereby raising the spike detection threshold and potentially causing weak particle signals to be missed; (4) **Unrecognized particle aggregates**, which may be misclassified as background if aggregated particles fail to generate sufficiently distinct signal spikes; and (5) **False-positive events arising from baseline noise**, in which inappropriate threshold settings could result in random background fluctuations being incorrectly identified as nanoparticle events.

In this study, all analytical procedures were conducted in accordance with standardized protocols to minimize these uncertainties. Ultrasonication and vortex agitation were applied to promote effective nanoparticle dispersion, and repeated instrument calibrations were performed to reduce uncertainties associated with transport efficiency, particle loss, and signal stability.

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