

Supplementary Table S1. Results of the analysis of National Institute of Standards and Technology standard reference materials (SRM) 2670a ($n = 5$ for each level)

Metals	Levels	Reference concentration (mean $\pm$ SD, $\mu\text{g/L}$)	Measured concentration (mean $\pm$ SD, $\mu\text{g/L}$)	CV
Cadmium (Cd)	Low level	1.056 $\pm$ 0.052	1.109 $\pm$ 0.095	8.56%
Chromium (Cr)	Low level	1.08 $\pm$ 0.31	0.963 $\pm$ 0.097	10.07%
Lead (Pb)	Low level	1.234 $\pm$ 0.061	1.267 $\pm$ 0.070	5.52%
Cadmium (Cd)	High level	16.40 $\pm$ 0.25	16.297 $\pm$ 0.659	4.04%
Nickel (Ni)	High level	115.3 $\pm$ 5.2	118.413 $\pm$ 2.062	1.74%
Cobalt (Co)	High level	51.8 $\pm$ 1.7	51.885 $\pm$ 1.807	3.48%
Lead (Pb)	High level	137.9 $\pm$ 3.6	140.238 $\pm$ 10.210	7.28%
Selenium (Se)	High level	221 $\pm$ 12	221.668 $\pm$ 12.07	5.44%

Note. SD, standard deviations; CV, coefficient of variation.

Supplementary Table S2. Summary of the limit of quantification (LOQ), coefficient of variations (CVs) in qualitycontrol samples (processed along with each batch), spiked concentrations, recoveries and CVs of individual metals in matrix spiking tests

Metals	LOQ ($\mu\text{g/L}$)	CV of QC samples	Spiking concentration ($\mu\text{g/L}$)	Recovery (mean $\pm$ SD)	CV of recovery
Al	4.963	9.18%	5	82.47% $\pm$ 6.46%	7.83%
Mn	0.087	14.62%	0.5	88.55% $\pm$ 6.20%	7.00%
Ni	0.147	14.74%	0.5	122.91% $\pm$ 6.73%	5.48%
Zn	3.605	6.46%	50	70.24% $\pm$ 8.01%	11.41%
Sr	0.105	5.92%	50	88.38% $\pm$ 6.08%	6.88%
Cd	0.015	4.94%	0.5	87.97% $\pm$ 1.14%	1.30%

Note. SD, standard deviations; CV, coefficient of variation; LOQ, limit of quantification; QC, quality control.

Supplementary Table S3. Study population characteristics ($n = 1,120$)

Characteristic	Total ($n = 1,120$)
Age (mean $\pm$ SD, years)	39.64 $\pm$ 6.82
BMI (mean $\pm$ SD, kg/m^2)	25.38 $\pm$ 3.43
Work years (mean $\pm$ SD, years)	16.07 $\pm$ 6.18
Occupational dust exposure ($\text{mg/m}^3 \cdot \text{year}$, %)	
High dust exposure	380 (33.9)
medium dust exposure	368 (32.9)
Low dust exposure	372 (33.2)
Marital status (%)	
Never	39 (3.5)
Married	1,056 (94.3)
Other	25 (2.2)

Characteristic	Total (n = 1,120)
Educational level (%)	
High school and below	418 (37.3)
University and above	702 (62.7)
Hypertension	
No	1,082 (96.6)
Yes	38 (3.4)
Family income (%)	
Low	238 (21.2)
High	882 (78.8)
Smoking (%)	
No	506 (45.2)
Yes	614 (54.8)
Drinking (%)	
No	631 (56.3)
Yes	489 (43.7)
Regular exercise (%)	321 (28.7)
Meat intake frequency (%)	
5–7 times/week	700 (62.5)
1–4 times/week	323 (28.8)
<1 times/week	97 (8.7)
Lung function level (mean ± SD)	
FEV ₁ (L)	2.37 ± 0.73
FEV ₁ % (%)	72.66 ± 14.92
FVC (L)	2.57 ± 0.79
FVC% (%)	88.39 ± 17.17
FEV ₁ /FVC (%)	82.60 ± 9.76

Note. Urinary heavy metals concentrations were corrected for creatinine. Continuous variables are presented as mean ± standard deviation, categorical variables are expressed as frequency (percentage). Intergroup comparisons were performed using the χ^2 test, Student's t-test, and the Mann-Whitney U test. SD, standard deviations; FEV₁, forced expiratory volume in the first second; FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity. * $P < 0.05$.

Supplementary Table S4. Detection rate and distribution of urinary metals concentrations ($\mu\text{g/g}$ creatinine) in the study population ($n = 1,120$) and comparison with general population

Metals	Rate of detection (%)	Total (n = 1,120)	General population* Median	Multiple higher
Al	100%	37.45 (22.62, 55.61)	<37	Similar
Sr	100%	961.90 (668.73, 1,398.06)	10–300	~ 3–100 times higher
Cd	100%	2.06 (1.33, 3.44)	0.2–0.7	~ 3–10 times higher
Mn	100%	0.55 (0.13, 1.19)	0.03–0.1	~ 5–18 times higher
Zn	100%	2,199.81 (1,574.04, 3,098.60)	300–600	~ 3–7 times higher
Ni	100%	5.28 (3.00, 8.86)	0.3–1.5	~ 3–17 times higher

Note. The data were presented as medians and interquartile ranges, the distributions were derived after substituting concentrations <LOQ with the LOQ divided by 2. Li, B, and V were also measured but had detection rates below 70% and were excluded from the main analysis.

Supplementary Table S5. Posterior inclusion probabilities (PIPs) of BKMR model

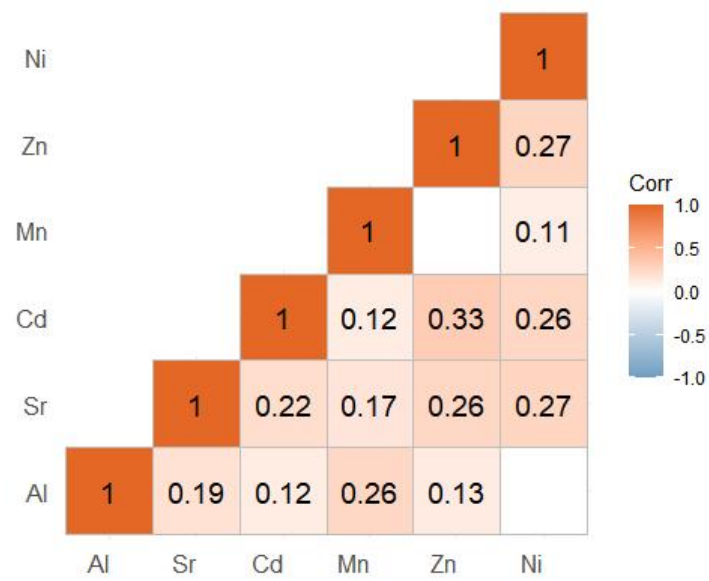
Metals	FEV ₁	FEV ₁ %	FVC	FVC%	FEV ₁ /FVC
Al	0.018	0.014	0.013	0.005	0.258
Sr	0.080	0.002	0.260	0.015	1.000
Cd	0.034	0.030	0.009	0.013	0.029
Mn	0.103	0.035	0.112	0.017	1.000
Zn	0.012	0.046	0.029	0.097	0.426
Ni	0.008	0.019	0.035	0.011	0.847

Note. BKMR, Bayesian kernel machine regression; PIPs, posterior inclusion probabilities; FEV₁, forced expiratory volume in the first second; FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity. * $P < 0.05$.

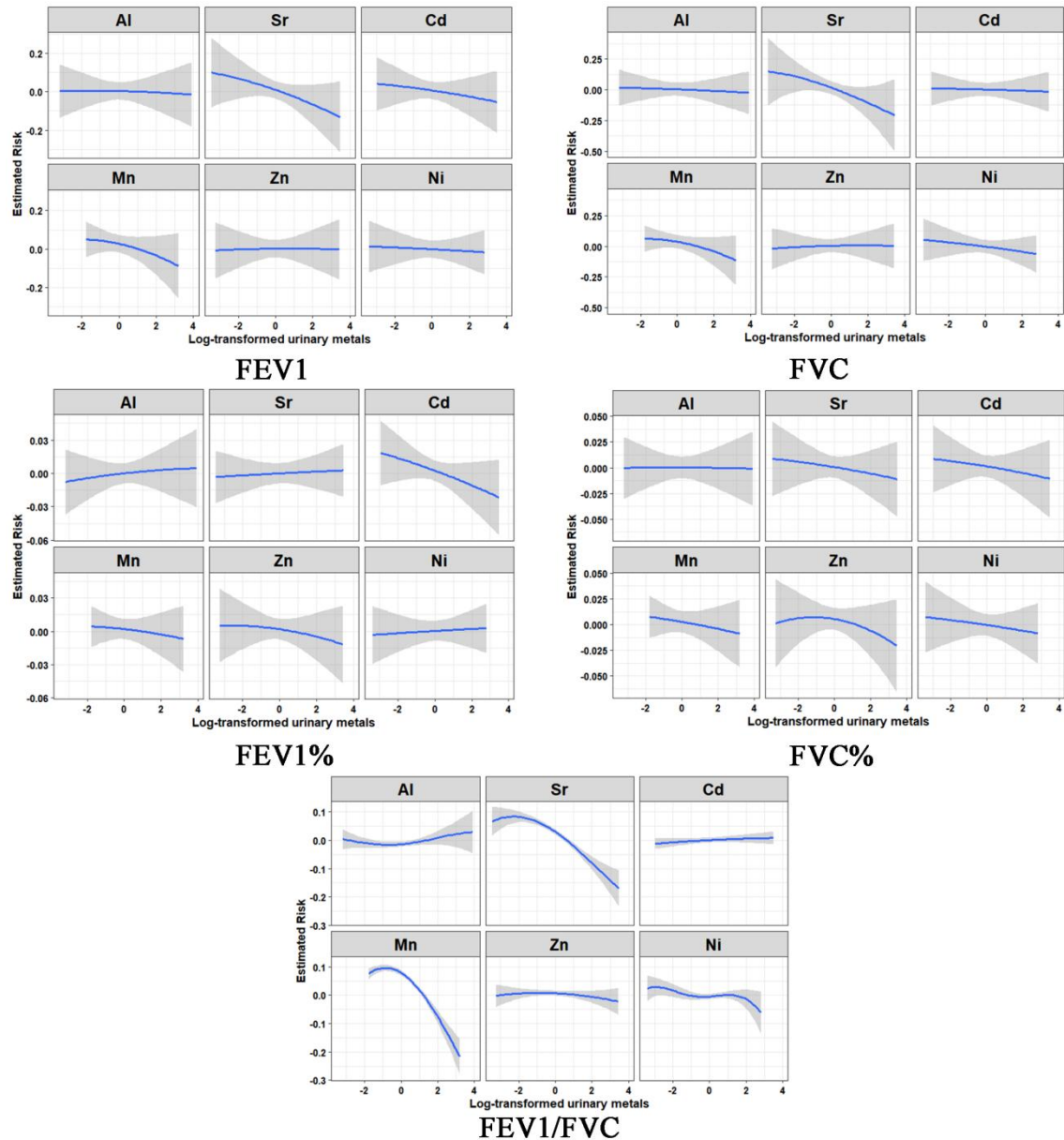
Supplementary Table S6. Quantile-based g-computation was used to estimate the association between multi-metal mixtures and lung function

Outcomes	β	95% CI	P value
FEV ₁	-0.064	(-0.133, 0.003)	0.062
FEV ₁ %	-0.004	(-0.019, 0.009)	0.521
FVC	-0.088	(-0.162, -0.015)	0.018*
FVC%	-0.013	(-0.029, 0.003)	0.120
FEV ₁ /FVC	-0.056	(-0.065, -0.047)	<0.001*

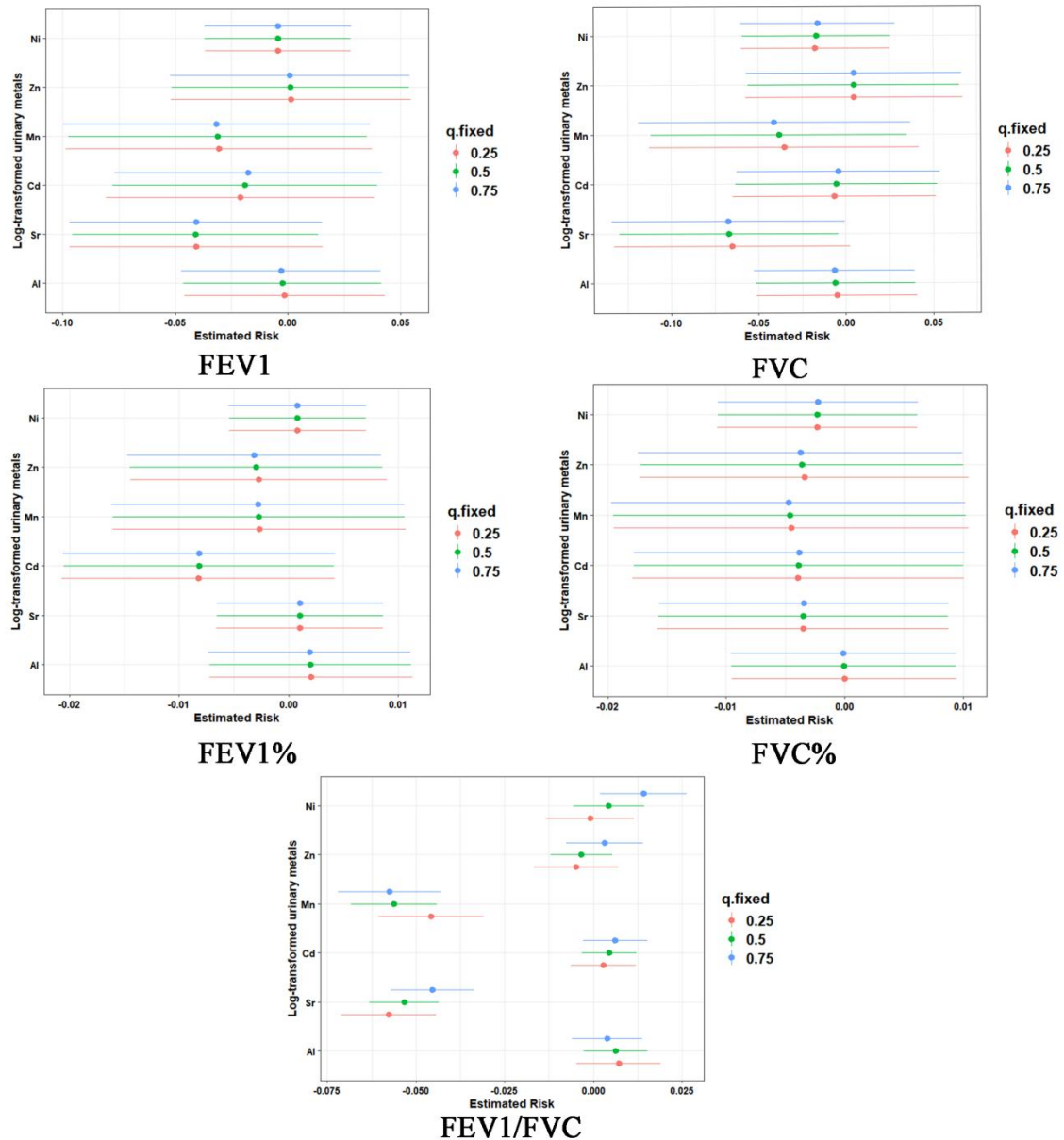
Note. β , represents the average change in the lung-function indicator per one-quartile increase in the exposure mixture. The model was adjusted for age, BMI, smoking, drinking, occupational dust, work of years, education, and exercise. FEV₁, forced expiratory volume in the first second; FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity; BMI, body mass index.



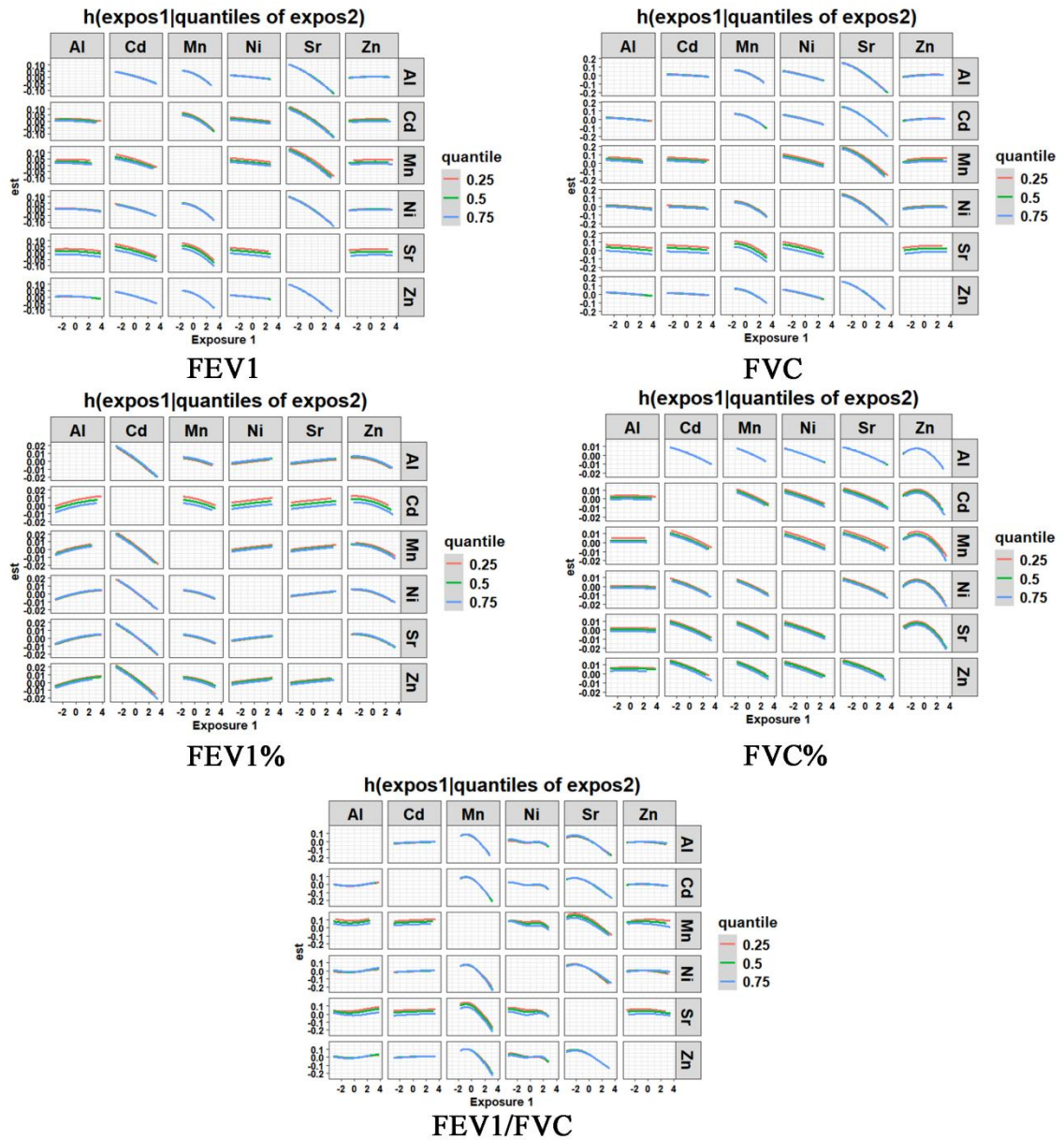
Supplementary Figure S1. Spearman correlation matrix for log-transformed urinary metals in the study population.



Supplementary Figure S2. BKMR evaluates the univariate exposure - response functions and 95 % confidence intervals (CIs) for each metal. The shaded area represents the 95 % CI, with all other metals fixed at their percentile levels. The model was adjusted for age, BMI, smoking, drinking, occupational dust, work of years, education, and exercise. FEV₁, forced expiratory volume in the first second. FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity; BMI, body mass index.



Supplementary Figure S3. BKMR evaluates the association between individual metals and lung-function indicators. This figure compares the effect estimates (with 95% CI) of a given metals on lung-function indicators when all other metals are fixed at their 25th, 50th, and 75th percentiles, respectively. The model was adjusted for age, BMI, smoking, drinking, occupational dust, work of years, education, and exercise. FEV₁, forced expiratory volume in the first second. FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity; CI, confidence index; BMI, body mass index.



Supplementary Figure S4. BKMR evaluates the interaction effects of metal pairs on lung-function indicators. BKMR, Bayesian kernel machine regression. The figure illustrates the dose response relationships between two specific metals (at their 25th, 50th, and 75th percentiles) and lung function when all other metals are fixed at their median levels. The model was adjusted for age, BMI, smoking, drinking, Occupational dust, work of years, education, and exercise. FEV₁, forced expiratory volume in the first second. FEV₁%, percentage of predicted forced expiratory volume in the first second; FVC, forced vital capacity; FVC%, percentage of predicted forced vital capacity; FEV₁/FVC, ratio of forced expiratory volume in the first second to forced vital capacity; CI, confidence index; BMI, body mass index.