

Supplementary Method 1: Group-based trajectory modeling (GBTM)

Group-based trajectory modeling (GBTM) was employed to characterize distinct exposure patterns of PM_{2.5} and PM₁₀ over the five years preceding renal biopsy, identifying subgroups of participants with similar exposure trajectories. GBTM estimates both the level and trend of air pollution concentration over time, making it suitable for assessing long-term exposure dynamics.

The optimal number of trajectory groups was identified through an iterative model selection process, considering both the number of groups and the polynomial order of trajectories. Model selection criteria included the Bayesian Information Criterion (BIC) (lower values indicating better fit), average posterior probability (AvePP ≥ 0.70) for classification accuracy, and practical interpretability (each trajectory group containing $\geq 5\%$ of participants). For both PM_{2.5} and PM₁₀, models with two to five groups were tested, with cubic polynomials initially specified for all groups to capture non-linear exposure trends. The final trajectory model was selected based on the best balance between model fit and interpretability. The data of PM_{2.5} are as follows:

Group	Avepp(%)	OCC	P _j (%)	π_j (%)	BIC ^{#2}	Δ BIC ^{#2}	E _k
1Group	100.00		100.00	100.00	-44068.00		0.000
2Group	98.62-98.98	122.3-56.5	36.71-63.29	36.85-63.15	-40045.82	4022.18	0.960
3Group	95.78-96.73-98.71	110.5-67.9-68.8	17.25-29.92-52.83	17.02-30.35-52.62	-38505.95	1539.87	0.948
4Group	99.46-98.11-95.97-99.05	4789.1-172.1-68.0-115.8	3.62-23.02-26.19-47.17	3.69-23.13-25.92-47.25	-37409.03	1096.92	0.962
5Group	98.86-97.41-92.15-96.99-94.63	2377.4-158.4-44.5-56.1-70.8	3.51-19.17-20.81-36.43-20.08	3.52-19.21-20.86-36.49-19.92	-36921.36	487.67	0.931

Note: Good model fit indicated by (1)Avepp(Average posterior probability)greater than 0.7 for each group,(2)P_j(Posterior probability of group membership) greater than 5%,(3)Close correspondenceP_j and π_j (Probability of group membership),(4) BIC(Bayesian information criterion) close to 0,(5)The large Δ BIC(BIC difference between complex and simple models) the more complex models are accepted,(6)OCC(Odds of Correct Classification)greater than 5,(7)E_k(Relative entropy) greater than 0.8.

The data of PM₁₀ are as follows:

Group	Avepp(%)	OCC	$P_j(\%)$	$\pi_j(\%)$	BIC ^{#2}	$\Delta BIC^{\#2}$	E_k
1Group	100.00		100.00	100.00	-48749.12		0.000
2Group	98.70-99.01	125.5-60.1	37.50-62.50	37.63-62.37	-44741.87	4007.25	0.962
3Group	97.38-96.12-98.84	175.4-57.3-77.5	17.31-30.26-52.43	17.50-30.15-52.35	-43307.35	1434.52	0.949
4Group	97.74-96.17-95.17-98.13	838.6-86.0-58.2-58.7	4.86-22.85-24.89-47.40	4.91-22.60-25.29-47.20	-42551.22	756.12	0.945
5Group	95.71-96.64-96.21-94.88-91.71	476.6-120.1-48.8-75.1-38.7	4.58-19.17-34.05-19.85-22.34	4.47-19.32-34.21-19.79-22.20	-42075.10	476.13	0.923

Note: Good model fit indicated by (1)Avepp(Average posterior probability)greater than 0.7 for each group,(2) P_j (Posterior probability of group membership) greater than 5%,(3)Close correspondence P_j and π_j (Probability of group membership),(4) BIC(Bayesian information criterion) close to 0,(5)The large ΔBIC (BIC difference between complex and simple models) the more complex models are accepted,(6)OCC(Odds of Correct Classification)greater than 5,(7) E_k (Relative entropy) greater than 0.8.

Based on BIC, and AvePP, we selected the three groups for trajectory of PM_{2.5} and PM₁₀. Meanwhile, over 5% of participants were assigned to each trajectory grouping (the above table).

Distribution of 5-Year Pre-Baseline PM2.5/PM10 Levels Across Trajectory Groups

Group of PM2.5	N	Mean ($\mu\text{g}/\text{m}^3$)	Min	Max	SD
Group1	305	43.4	14.3	52.4	8.9
Group2	529	62.2	52	72.3	5.5
Group2	934	76.6	62	83.4	4.1
Group of PM10					
Group1	306	71.4	27.2	85.7	12.2
Group2	535	100	84.5	117	8.6
Group2	927	122	102	133	6.5

Supplementary Table 1 Comparison of baseline characteristics between included and excluded study populations

Characteristic	Excluded,N=735	Included,N=1768	p-value
Age,yr	35 (26, 42)	33 (27, 43)	0.724
Male	389 (52.9)	1012 (57.2)	0.053
SBP,mmHg	124(115, 137)	126(116, 139)	0.096
DBP,mmHg	81(74, 90)	83(75, 92)	0.012
Hb,g/L	131(117, 145)	133(120, 146)	0.022
UA,μmol/L	364(305, 439)	367(302, 441)	0.793
TG,mmol/L	1.54(1.08, 2.33)	1.49(1.05, 2.18)	0.172
CHOL,mmol/L	4.78(4.10, 5.72)	4.80 (4.09, 5.64)	0.995
UP,g/24 h	1.34(0.70, 2.83)	1.41(0.73, 2.72)	0.630
eGFR,ml/min per 1.73 m ²	86.02 (57.51, 112.62)	89.01 (60.68, 113.51)	0.252
Oxford classification			
M1	479 (77.8)	1204 (68.1)	<0.001
E1	28 (4.5)	69 (3.9)	0.564
S1	374 (60.7)	1204 (68.1)	0.001
T1	94 (15.3)	250 (14.1)	0.638
T2	23 (3.7)	57 (3.2)	
C1	92 (15.7)	288 (16.3)	0.639
C2	18 (3.1)	68 (3.8)	
Steroid treatment	245 (33.3)	980 (55.4)	<0.001
RASB treatment	173 (23.5)	662 (37.4)	<0.001
Hypertension	169 (28.0)	568 (32.1)	0.064
Smoking	110 (20.3)	289 (16.3)	0.039

DBP, diastolic blood pressure;E, endocapillary proliferation; eGFR, estimated glomerular filtration rate; ESRD, end-stage renal disease; M, mesangial hypercellularity;

RASB, renin-angiotensin system blocker; S, segmental glomerulosclerosis; SBP, systolic blood pressure; T, tubular atrophy and interstitial fibrosis; UA, uric acid; UP, 24-hour urine protein excretion.

Data presented as median (IQR) or n (%).

Supplementary Table 2 Association between annual concentrations of PM_{2.5}/PM₁₀ and progression to ESRD in the 5 years prior to baseline

PM _{2.5}	Model ^a		PM ₁₀	Model ^a	
	HR(95%CI)	p-value		HR(95%CI)	p-value
Previous 1 year	1.09(0.99,1.19)	0.089	Previous 1 year	1.05(0.99,1.12)	0.102
Previous 2 year	1.10(0.99,1.23)	0.066	Previous 2 year	1.07(1.00,1.15)	0.057
Previous 3 year	1.10(0.98,1.23)	0.108	Previous 3 year	1.06(0.98,1.14)	0.130
Previous 4 year	1.15(1.01,1.30)	0.033	Previous 4 year	1.09(1.01,1.18)	0.038
Previous 5 year	1.12(0.98,1.27)	0.089	Previous 5 year	1.07(0.99,1.16)	0.086

CI, confidential interval; eGFR, estimated glomerular filtration rate; ESRD, end-stage renal disease; HR, hazard ratio; MAP, mean arterial pressure; PM_{2.5}, particulate matter that measure less than 2.5 µm in diameter; PM₁₀, particulate matter that measure less than 10 µm in diameter; RASB, renin-angiotensin system blocker; UA, uric acid; UP, 24-hour urine protein excretion.

^aModel was adjusted for baseline age, sex, eGFR, UP, UA, MAP, Oxford-MESTC, use of steroid and RASB, smoking, total cholesterol, serum triglycerides and hypertension;

Supplementary Table 3 Association of exposure to PM_{2.5} or PM₁₀ after enrollment with the risk of ESRD,after excluding participants with ESRD events within six months of baseline

	Categorical analysis				P for trend	Continuous analysis, per 10 μ g/m ³ greater
	Q1	Q2	Q3	Q4		
Cumulative average PM2.5						
PM2.5 range, μ g/m ³	<=39.45	>39.45-<=45.91	>45.91-58.17	>58.17		
Person-years	1498	1778	2670	1435		
No. of cases	24	27	60	86		
Cases/PYs(/1000)	16.0	15.2	22.5	59.9		
HR (95% CI):Model 1	ref	0.89(0.52,1.55)	1.10(0.68,1.80)	3.56(2.25,5.63)	<0.001	1.75(1.55,1.97)
HR (95% CI):Model 2	ref	0.90(0.51,1.58)	1.02(0.61,1.72)	3.47(2.10,5.73)	<0.001	1.58(1.39,1.79)
HR (95% CI):Model 3	ref	0.85(0.48,1.51)	1.05(0.62,1.77)	3.70(2.23,6.13)	<0.001	1.63(1.43,1.85)
Cumulative average PM10						
PM10 range, μ g/m ³	<=61.76	>61.76-<=74.22	>74.22-<=94.94	>94.94		
Person-years	1458	1852	2659	1412		
No. of cases	24	26	57	90		
Incidence rate	16.5	14.0	21.4	63.7		
HR (95% CI):Model 1	ref	0.77(0.44,1.34)	0.99(0.61,1.62)	3.63(2.30,5.74)	<0.001	1.43(1.33,1.54)
HR (95% CI):Model 2	ref	0.82(0.46,1.46)	0.94(0.56,1.58)	3.60(2.18,5.93)	<0.001	1.34(1.24,1.45)
HR (95% CI):Model 3	ref	0.78(0.44,1.38)	0.95(0.56,1.61)	3.75(2.27,6.18)	<0.001	1.37(1.26,1.48)

CI, confidential interval; eGFR, estimated glomerular filtration rate; ESRD, end-stage renal disease; HR, hazard ratio;MAP, mean arterial pressure; PM2.5, particulate matter that measure less than 2.5 μ m in diameter; PM10, particulate matter that measure less than 10 μ m in diameter;RASB, renin-angiotensin system blocker; UA, uric acid; UP, 24-hour urine protein excretion.

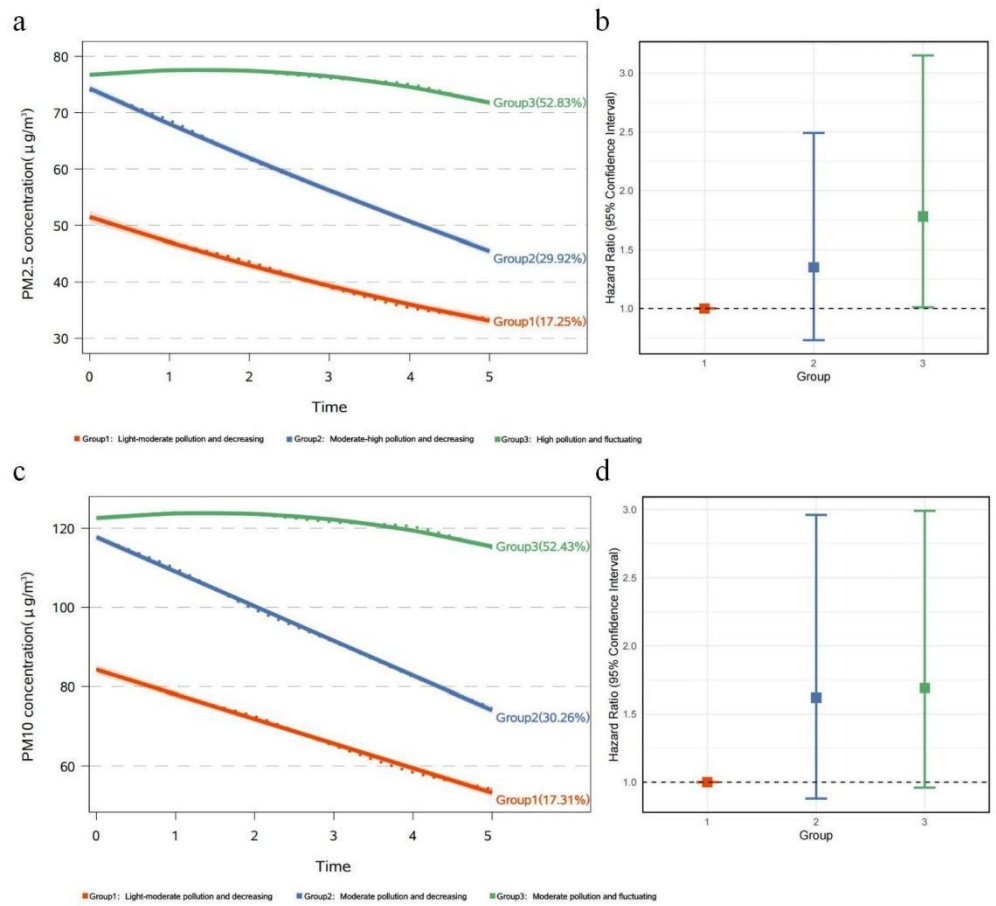
Model 1: adjusted for baseline age and sex;

Model 2: further adjusted for eGFR, UP, UA, MAP, Oxford-MESTC, use of steroid and RASB after diagnosis;

Model 3: further adjusted for smoking, total cholesterol, serum triglycerides and hypertension.

Supplementary Method 2: Quantile g-Computation for Mixture Analysis

To assess the combined effect of PM_{2.5} and PM₁₀ exposure on ESRD risk, we employed the quantile g-computation (QGComp) method(1), a flexible statistical approach that estimates the effect of increasing all components of a mixture simultaneously. This method is particularly suitable when the exposures are correlated, as in the case of ambient air pollutants. We implemented the `qgcomp.cox.noboot` function using the `qgcomp` R package (version 2.18.4). Both PM_{2.5} and PM₁₀ were included as exposure variables and were categorized into quartiles. The QGComp model was fitted using Cox proportional hazards regression, with adjustment for potential confounders, including: Demographics: age, sex; Clinical and laboratory data: baseline eGFR, UP, UA, MAP, hemoglobin, total cholesterol, triglycerides, hypertension, smoking; Histopathology and treatment: Oxford-MESTC classification, use of corticosteroids and renin-angiotensin system blockers (RASB) after diagnosis. The final model estimated that each one-quartile joint increase in PM_{2.5} and PM₁₀ was associated with a 75% higher risk of ESRD (HR = 1.75, 95% CI: 1.48–2.08, $p < 0.001$). These findings suggest a substantial and statistically significant joint effect of particulate matter exposure on renal disease progression, and further support the robustness of our main results.



Supplementary Figure 1 The trajectories of PM2.5 and PM10 concentrations over the 5 years prior to baseline were calculated using group-based trajectory

modeling (GBTM), which measures the combined effects of air pollution exposure levels and their changes. The dotted line represents the fitted value of the annual average PM_{2.5}/PM₁₀, while the point is the actual average in each group. a. Based on GBTM, the trajectory of air pollution is divided into the following states according to the average concentration and changes of PM_{2.5}: light-moderate pollution and decreasing, moderate-high pollution and decreasing, and high pollution and fluctuating. b. The hazard ratios for PM_{2.5} were adjusted for age and sex, smoking status, eGFR, UP, UA, hemoglobin, MAP, Oxford-MEST, treatment of steroid and RASB after diagnosis, total cholesterol, serum triglycerides and hypertension. c. Based on GBTM, the trajectory of air pollution is divided into the following states according to the average concentration and changes of PM₁₀: light-moderate pollution and decreasing, moderate pollution and decreasing, and moderate pollution and fluctuating. d. The hazard ratios for PM₁₀ were adjusted for age and sex, smoking status, eGFR, UP, UA, hemoglobin, MAP, Oxford-MEST, treatment of steroid and RASB after diagnosis, total cholesterol, serum triglycerides and hypertension.

Reference

1. Keil AP, Buckley JP, O'Brien KM, Ferguson KK, Zhao S, White AJ. A Quantile-Based g-Computation Approach to Addressing the Effects of Exposure Mixtures. *Environ Health Perspect* (2020) 128:047004. doi: 10.1289/EHP5838