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Long-term exposure to air pollution and gastrointestinal disease: findings from a nationwide cohort study in China

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Abstract

Background and aims Air pollution poses significant risks to human health, but its impact on gastrointestinal (GI) health remains underexplored. This study assesses the long-term effects of air pollution on GI diseases using data from the China Health and Retirement Longitudinal Study (CHARLS).

Methods This nationwide cohort study utilized CHARLS data from participants recruited in 2011, followed by surveys in 2013, 2015, 2018, and 2020. Long-term exposure to $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 was assessed using geocoded residential addresses linked to air quality data. Cox proportional hazards models and subgroup interaction analyses were used to evaluate associations between pollutants and GI disease incidence, adjusting for demographic and behavioral confounders.

Results The incidence of GI disease was 21.4% among participants. Long-term exposure to $PM_{2.5}$ (HR = 1.38, 95% CI: 1.33–1.44), PM_{10} (HR = 1.31, 95% CI: 1.26–1.36), SO_2 (HR = 1.74, 95% CI: 1.68–1.81), NO_2 (HR = 1.21, 95% CI: 1.17–1.25), CO (HR = 1.48, 95% CI: 1.42–1.54), and O_3 (HR = 0.56, 95% CI: 0.54–0.59) was significantly associated with GI disease. Interaction analyses showed that the effects of pollutants varied by region, residence, smoking, and alcohol use. Urban residents and those living in specific regions experienced stronger associations, likely due to higher pollution levels and different environmental factors. Smokers and alcohol users were also more susceptible to the adverse effects of pollutants.

Conclusions Long-term exposure to multiple air pollutants increases the risk of GI diseases, while ozone may potentially offer some protective effects. Public health measures to reduce air pollution, especially in urban areas, and to protect high-risk groups are urgently needed.

Keywords Air pollutions, Gastrointestinal diseases, Longitudinal study, Public health, CHARLS

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Introduction

In recent years, the impact of air pollution on human health has become a major focus of global public health research, particularly in rapidly urbanizing and industrializing nations [1, 2]. Air pollutants, especially particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone(O_3) and carbon monoxide (CO) are significant contributors to respiratory, cardiovascular, and neurological diseases [3–5]. Long-term exposure to $PM_{2.5}$ and PM_{10} has been strongly linked to the increased incidence of chronic obstructive pulmonary disease (COPD), asthma, non-alcoholic fatty liver disease (NAFLD), and cardiovascular conditions such as hypertension, myocardial infarction, and stroke, primarily through mechanisms involving inflammatory responses, oxidative stress, and immune dysregulation [6–10]. Furthermore, an increasing body of evidence suggests that air pollution also exerts detrimental effects on the nervous and metabolic systems [11–13], with prolonged exposure being associated with elevated risks of neurodegenerative disorders, such as Alzheimer's disease and Parkinson's disease, as well as type 2 diabetes [14–17].

Despite these findings, research on the association between air pollution and gastrointestinal (GI) diseases has been limited. The gastrointestinal tract serves as a critical barrier to harmful external substances, and emerging evidence suggests that air pollutants may negatively affect it through several mechanisms, including triggering systemic inflammatory responses, altering gut microbiota, and increasing intestinal permeability [18–22]. Studies have indicated that air pollution may compromise gastrointestinal health by triggering systemic inflammatory responses, altering gut microbiota, and increasing intestinal permeability. Specifically, particulate matter and gaseous pollutants such as SO_2 and NO_2 have been implicated in the development of intestinal inflammation and gastric ulcers [23, 24]. Evidence indicates that $PM_{2.5}$ may induce oxidative stress and cellular damage in intestinal epithelial cells, thereby elevating the risk of gastrointestinal diseases [25, 26]. Furthermore, air pollution may disrupt the stability of gut microbiota, weakening the intestinal barrier and promoting the onset of inflammatory bowel disease (IBD) and gastrointestinal cancers [27, 28]. Although some studies have highlighted the connection between air pollution and gastrointestinal health, most research has focused on specific pollutants or short-term exposures, and there is limited evidence on the long-term effects of different combinations of pollutants on gastrointestinal health [29]. Moreover, research in large-scale, longitudinal cohorts—particularly in China—remains scarce, despite the significant burden of gastrointestinal diseases in this population. Demographic and behavioral factors, such as age, sex, smoking, alcohol consumption, and rural vs. urban residence, may significantly modify the association between air pollution and disease risk, yet these aspects remain underexplored. Our previous cross-sectional study, using 2015 data from the China Health and Retirement Longitudinal Study (CHARLS), found that long-term exposure to air pollution is associated with an increased risk of non-neoplastic digestive system diseases in Chinese adults [30]. This finding further emphasizes the need for large-scale, longitudinal studies to better understand these long-term effects.

This study, based on the China Health and Retirement Longitudinal Study (CHARLS), aims to evaluate the long-term effects of air pollution on gastrointestinal diseases in a nationally representative cohort. CHARLS is a longitudinal study that enrolled participants in 2011, with follow-up surveys conducted in 2013, 2015, 2018, and 2020. This design allows for the assessment of the long-term effects of air pollution exposure on gastrointestinal health while accounting for temporal changes in exposure and disease incidence. By examining the potential modifiers of this relationship, such as demographic and behavioral factors, this study provides valuable evidence to inform public health policies aimed at mitigating the health burden of air pollution, especially in high-risk populations.

Methods

Study population

The sample for this study was derived from CHARLS, a nationwide cohort study designed to represent 28 provinces in China. CHARLS employed multistage probability sampling and Geographic Information System (GIS) tools to ensure representative coverage. This longitudinal survey gathered comprehensive household and individual-level data through structured face-to-face interviews, supported by a networked system to optimize data collection efficiency. The baseline survey, conducted in 2011, involved 17,708 participants from 150 counties within 28 provinces. Follow-up surveys were administered biennially or triennially from 2011 to 2020. The CHARLS protocol received ethical approval from Peking University's Ethics Review Board (IRB00001052-11015) in compliance with the Declaration of Helsinki, and all participants provided informed consent.

Since its inception in 2011, CHARLS has consistently operated on a two- to three-year survey cycle. Notably, systematic assessments of air pollution in China began around 2011 or 2013. To evaluate the potential effects of air pollution on GI diseases, this study analyzed

data from participants surveyed between the 2011 and 2020 waves.

Outcome assessment

The identification of GI disease was derived from responses to the health status and functioning questionnaire administered during the baseline and follow-up surveys. Participants were asked questions such as, "Have you ever been diagnosed by a doctor with stomach or other digestive diseases (excluding tumors or cancer)?" A respondent was classified as having a GI disease if they answered "Yes" to this question.

Air pollution exposure assessment

Between 2011 and 2020, a geocoding system was used to map the residential addresses of study participants, enabling the assessment of long-term exposure to air pollution. Air pollutant data were obtained from the ChinaHighAirPollutants (CHAP) dataset, with $PM_{2.5}$, PM_{10}, NO_2 and O_3 data available starting in 2011, and SO_2 and CO data available starting in 2013. Ground-level concentrations of these pollutants were calculated using Artificial Intelligence (AI) algorithms, which integrated surface measurements, remote sensing data, atmospheric reanalysis outputs, and model simulations. For validation, surface measurements underwent 10-fold cross-validation to calculate the coefficient of determination (R^2) and root mean square error (RMSE) for daily mean concentrations (Table S1). Annual long-term exposures to $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO were calculated, representing cumulative pollutant levels prior to the baseline 2011 CHARLS survey for primary analysis.

Covariates

This study utilized covariate data collected from the 2011 wave of CHARLS. Demographic variables included age, sex (male or female), type of residence (rural or urban), geographic region (northeast, eastern, western, or central), educational attainment (primary school or below, secondary school or above), and marital status (married/cohabiting or separated/divorced/widowed). Health behavior variables encompassed Body Mass Index (BMI), smoking status (yes or no), alcohol consumption status (yes or no), and self-reported health status categorized as good/very good, fair, or poor/very poor. For the geographic region classification, we divided China into four regions based on geographical and socio-economic factors, which may influence pollution levels and health outcomes: northeast, eastern, western, and central. These regional divisions are commonly used in epidemiological studies to reflect broad geographic and socio-economic differences.

Statistical analyses

For baseline characteristics, continuous variables were reported as mean ± standard deviation (SD), while categorical variables were presented as frequencies (percentages). The relationships between air pollutants were assessed using Pearson's correlation coefficients (Table S2). The association between air pollutant concentrations and GI disease was analyzed using Cox proportional hazards models. Initially, a base model was constructed without adjustments. Subsequently, base models were adjusted for demographic covariates, including sex, age, residence type, region, education level, and marital status. Fully adjusted models incorporated additional covariates, such as smoking, alcohol consumption, BMI, and health status. The results for GI disease risk were expressed as hazard ratios (HRs) per interquartile range (IQR) increment in pollutant concentrations, along with corresponding 95% confidence intervals (CIs).

Subgroup and interaction analyses were performed across categories of sex, residence, region, education level, marital status, smoking, drinking, and health status, based on models adjusted for all covariates. Sensitivity analyses were also conducted to confirm the robustness of the findings. First, raw pollutant measurements were used as continuous variables to reanalyze their associations with GI disease. Second, participants reporting poor or very poor health were excluded from the analysis. Additionally, propensity score matching (PSM) was applied to reduce confounding by balancing covariates between GI disease and non-GI disease groups, using a nearest-neighbor ratio of 1:1 without replacement and a caliper width of 0.05. All statistical analyses were performed using R software (version 4.2.2), with significance defined as a two-tailed P-value of less than 0.05.

Results

Characteristics of study participants

A total of 17,708 individuals participated in the 2011 survey. After excluding 3,780 individuals with pre-existing GI disease, 13,928 participants were included in this study. Based on 13,928 participants from 28 provinces in China, Fig. 1 illustrates their distribution. A summary of the basic characteristics of the study participants is provided in Table 1. The incidence of GI disease among participants was 21.4%(2,984 cases). Among these, 58.0% were female, and the mean age of participants with GI disease was slightly lower(58 ± 10 years) compared to those without GI disease(59 ± 10 years). Most participants with GI disease resided in rural areas(64.1%) and had an education level of elementary school or below(69.6%). Geographically, the majority of GI disease cases were distributed in the

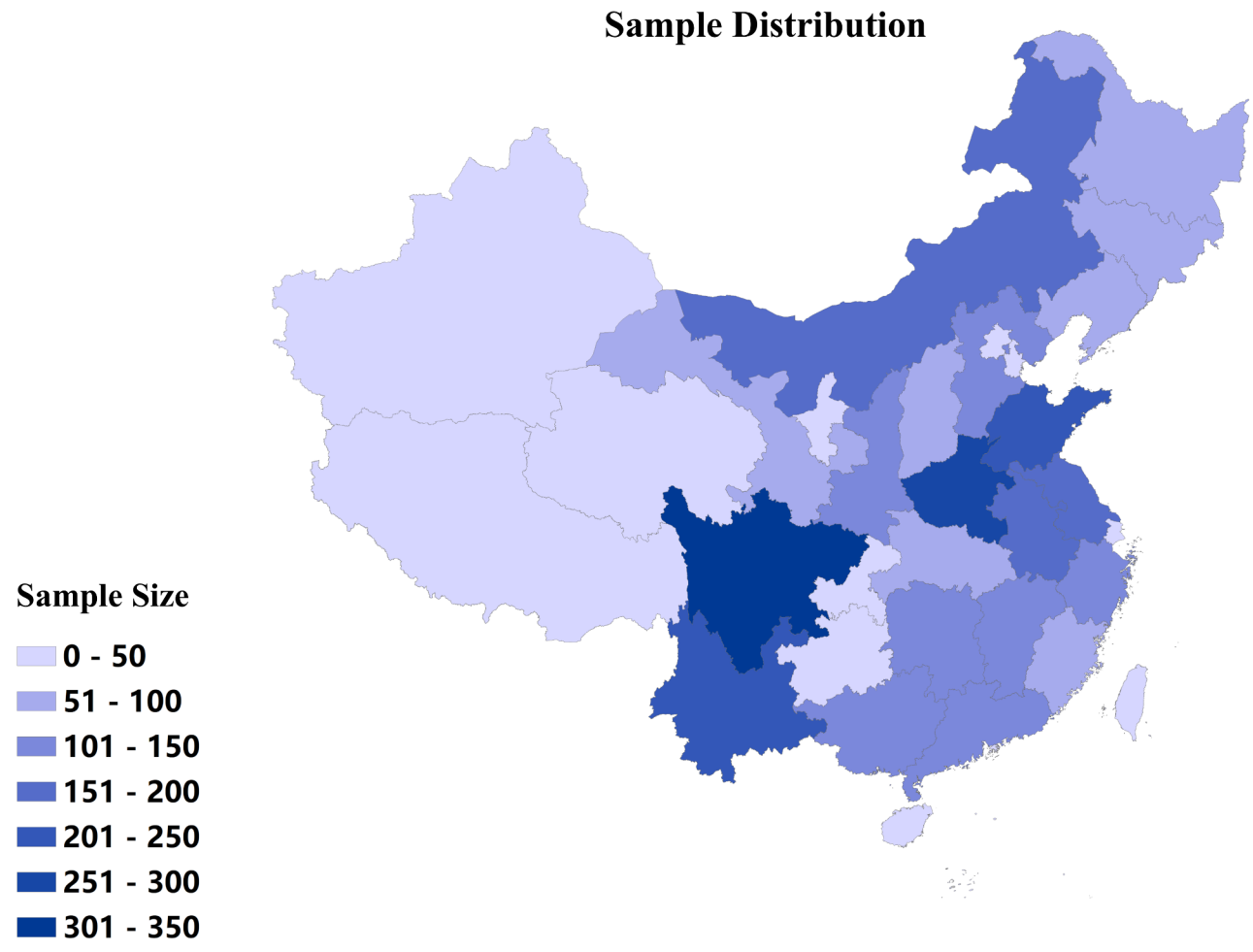

Fig. 1 The geographical distribution of 13,928 participants in 28 provinces of China

eastern(41.3%) and western(36.3%) regions, with fewer cases in the northeast(6.4%). In terms of health behaviors, a lower proportion of participants with GI disease were smokers(35.7%) or drinkers(39.3%) compared to those without GI disease. Additionally, a larger percentage of GI disease cases reported poor or very poor health status(32.2%) compared to those without GI disease(21.6%). There was no significant difference in marital status between participants with and without GI disease. Significant differences between participants with and without GI disease were observed in terms of sex, residence, region, education level, BMI, smoking, drinking, and health status.

The average ambient concentrations of six air pollutants over the study period are shown in Table 2; Fig. 2. The mean levels were 49.13 ± 16.34 μg/m³ for $PM_{2.5}$, 84.47 ± 30.52 μg/m³ for PM_{10}, 22.36 ± 9.95 μg/m³ for SO_2, 28.28 ± 9.06 μg/m³ for NO_2, 90.17 ± 7.80 μg/m³ for O_3, and 1.01 ± 0.26 mg/m³ for CO. Pearson correlation analysis (Table S2) revealed strong positive correlations among $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, with coefficients ranging from 0.71 to 0.92. In contrast, O_3 exhibited weaker correlations with the other pollutants, particularly with CO (0.43) and SO_2 (0.50). These findings highlight the interplay among specific pollutants while indicating O_3's distinct behavior in comparison to the others.

Associations between air pollutants and incidence of GI disease

The associations between long-term exposure to air pollutants and the incidence of GI disease are presented in Fig. 3 and Table S3. Across the three models, higher levels of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO were consistently associated with an increased incidence of GI disease, while O_3 showed a negative association. In the crude model (unadjusted), the HR per IQR increase in air pollutants were as follows: $PM_{2.5}$ (HR = 1.22, 95%CI: 1.18–1.26), PM_{10} (HR = 1.20, 95%CI: 1.17–1.24), SO_2 (HR = 1.50, 95%CI: 1.45–1.55), NO_2 (HR = 1.08, 95%CI: 1.05–1.12), CO (HR = 1.32, 95%CI: 1.28–1.36), and O_3 (HR = 0.62, 95%CI: 0.60–0.64), all

Table 1 Basic characteristics of participants

Characteristics	Total ($n=13928$)	Non-GI disease ($n=10944$)	GI disease ($n=2984$)	*P*
Age, (years, M ± SD)	59 ± 10	59 ± 10	58 ± 10	< 0.001
Sex, n (%)				< 0.001
Males	6,859 (49.2%)	5,607 (51.2%)	1,252 (42.0%)	
Females	7,069 (50.8%)	5,337 (48.8%)	1,732 (58.0%)	
Residence, n (%)				< 0.001
Rural	8,108 (58.2%)	6,194 (56.6%)	1,914 (64.1%)	
Urban	5,820 (41.8%)	4,750 (43.4%)	1,070 (35.9%)	
Region, n (%)				< 0.001
Northeast	1,064 (7.6%)	873 (8.0%)	191 (6.4%)	
Eastern	6,350 (45.6%)	5,118 (46.8%)	1,232 (41.3%)	
Western	4,370 (31.4%)	3,288 (30.0%)	1,082 (36.3%)	
Central	2,144 (15.4%)	1,665 (15.2%)	479 (16.1%)	
Marital status, n (%)				0.094
Married and living with a spouse	12,111 (87.0%)	9,489 (86.7%)	2,622 (87.9%)	
Single, divorced, and windowed	1,817 (13.0%)	1,455 (13.3%)	362 (12.1%)	
Education level, n (%)				< 0.001
Elementary school or below	9,069 (65.1%)	6,992 (63.9%)	2,077 (69.6%)	
Middle school or above	4,859 (34.9%)	3,952 (36.1%)	907 (30.4%)	
BMI, (kg/m^2, M ± SD)	23.7 ± 3.6	23.7 ± 3.6	23.5 ± 3.7	< 0.001
Smoking, n (%)				< 0.001
Yes	5,574 (40.0%)	4,510 (41.2%)	1,064 (35.7%)	
No	8,354 (60.0%)	6,434 (58.8%)	1,920 (64.3%)	
Drinking, n (%)				0.001
Yes	5,830 (41.9%)	4,658 (42.6%)	1,172 (39.3%)	
No	8,098 (58.1%)	6,286 (57.4%)	1,812 (60.7%)	
Health status, n (%)				< 0.001
Good/very good	3,701 (26.6%)	3,180 (29.1%)	521 (17.5%)	
Fair	6,905 (49.6%)	5,404 (49.4%)	1,501 (50.3%)	
Poor/very poor	3,322 (23.9%)	2,360 (21.6%)	962 (32.2%)	

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); GI disease, gastrointestinal disease

Table 2 Descriptive statistics average levels of air pollution

Variables	Mean	SD	P_{25}	P_{50}	P_{75}	IQR
$PM_{2.5}$($\mu g/m^3$)	49.13	16.34	35.95	46.51	61.13	25.18
PM_{10}($\mu g/m^3$)	84.47	30.52	58.09	80.06	106.90	48.81
SO_2 ($\mu g/m^3$)	22.36	9.95	15.52	18.65	28.05	12.53
NO_2 ($\mu g/m^3$)	28.28	9.06	20.47	26.93	34.64	14.17
O_3($\mu g/m^3$)	90.17	7.80	83.97	89.06	96.06	12.09
CO (mg/m^3)	1.01	0.26	0.85	0.94	1.13	0.28

Abbreviations: $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; PM_{10}, particle with aerodynamic diameter ≤ 10 μm; SO_2, sulfur dioxide; NO_2, nitrogen dioxide; O_3, ozone; CO, carbonic oxide; SD, standard deviation; P_{25}, P_{50}, P_{75}, Lower, median and upper quartiles of variables; IQR, interquartile range

with $p < 0.001$. This indicates that higher exposure to all pollutants except O_3 was associated with a higher incidence of GI disease, while O_3 exposure showed a protective association. In the base model, adjusted for age, sex, education level, marital status, region, and residence, these associations strengthened for most pollutants. The negative association for O_3 persisted and became more pronounced. In the main model, which additionally adjusted for smoking, drinking, body mass index, and health status, the results remained robust. The HRs were: $PM_{2.5}$ (HR = 1.38, 95%CI: 1.33–1.44), PM_{10} (HR = 1.31, 95%CI: 1.26–1.36), SO_2 (HR = 1.74, 95%CI: 1.68–1.81), NO_2 (HR = 1.21, 95%CI: 1.17–1.25), CO (HR = 1.48, 95%CI: 1.42–1.54), and O_3 (HR = 0.56, 95%CI: 0.54–0.59).

These results highlight that $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO long-term exposure were positively associated with GI disease incidence in all models, even after adjusting for demographic and behavioral factors. In contrast, O_3 consistently showed a significant negative

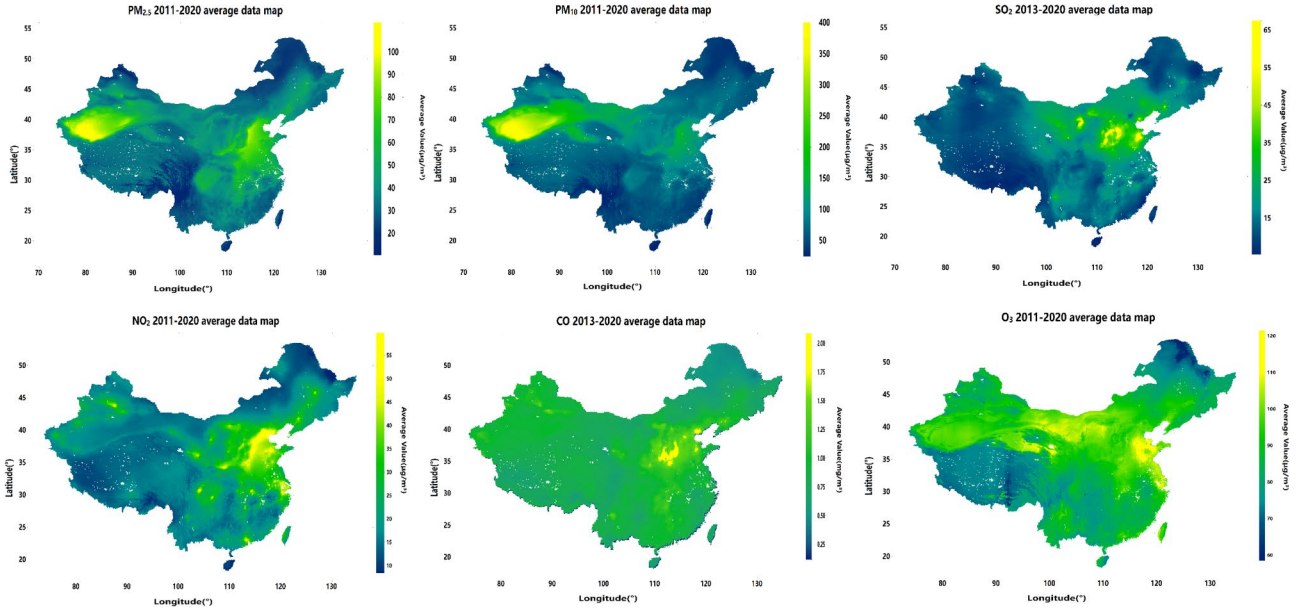

Fig. 2 Air pollution distribution over 11(or 13) to 20 years of follow-up. $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; PM_{10}, particle with aerodynamic diameter ≤ 10 μm; SO_2, sulfur dioxide; NO_2, nitrogen dioxide; CO, carbonic oxide; O_3, ozone

association with GI disease incidence across all models, suggesting a different effect mechanism compared to the other pollutants.

Subgroup and interaction analyses of air pollutants and GI disease

Subgroup and interaction analyses revealed significant modifiers in the associations between air pollution and GI disease incidence (Figs. 4 and 5). For $PM_{2.5}$, PM_{10}, and SO_2, drinking status was a notable modifier, with drinkers consistently showing stronger associations with GI disease compared to non-drinkers (P interaction = 0.004 for $PM_{2.5}$, P interaction = 0.010 for PM_{10}, and P interaction = 0.001 for SO_2). Additionally, both $PM_{2.5}$ and SO_2 showed stronger associations in urban areas compared to rural areas (P interaction = 0.008 for $PM_{2.5}$ and P interaction = 0.021 for SO_2). Participants with poor or very poor health experienced greater risks associated with $PM_{2.5}$ (P interaction = 0.023). Regional variation was also significant, with the Northeast showing the highest hazard ratio for $PM_{2.5}$ (P interaction < 0.001) and PM_{10} (P interaction < 0.001), while SO_2 showed the strongest association in the Western region (P interaction < 0.001).

For NO_2, the association was stronger in urban areas compared to rural areas (P interaction = 0.024) and among participants with poor or very poor health (P interaction = 0.043). Regional differences for NO_2 were significant, with the Western showing the strongest association (P interaction = 0.002). In contrast, O_3 exhibited a protective association with GI disease, with stronger protective effects observed in urban areas compared to rural areas (P interaction < 0.001) and among participants with no smoking people (P interaction = 0.044). Regional differences for O_3 were also notable, with the Western showing the strongest protective effect (P interaction < 0.001). For CO, the association was strongest in the Central region (P interaction < 0.001) and among participants with lower education levels compared to those with higher education (P interaction = 0.032).

These findings highlight significant subgroup and regional variations in the associations between air pollution and GI disease. While urban residents face greater risks from $PM_{2.5}$, SO_2, and NO_2, O_3 shows a stronger protective effect in urban areas. Regional differences were particularly notable, with the Northeast showing the highest risks for $PM_{2.5}$ and PM_{10}, the Western region demonstrating the strongest risks for SO_2 and NO_2, the Central region showing the strongest risks for CO, and the strongest protective effect of O_3 observed in the Western region. This underscores the need for tailored public health strategies to address air pollution's health impacts.

Sensitivity analyses

Sensitivity analyses confirmed the robustness of the main findings regarding the association between air pollution and GI disease incidence. When the analysis was conducted using continuous variables of air pollutants instead of IQR increments, the significant associations for all pollutants remained consistent (Table S4). Further sensitivity analyses were conducted by excluding participants with poor or very poor health.

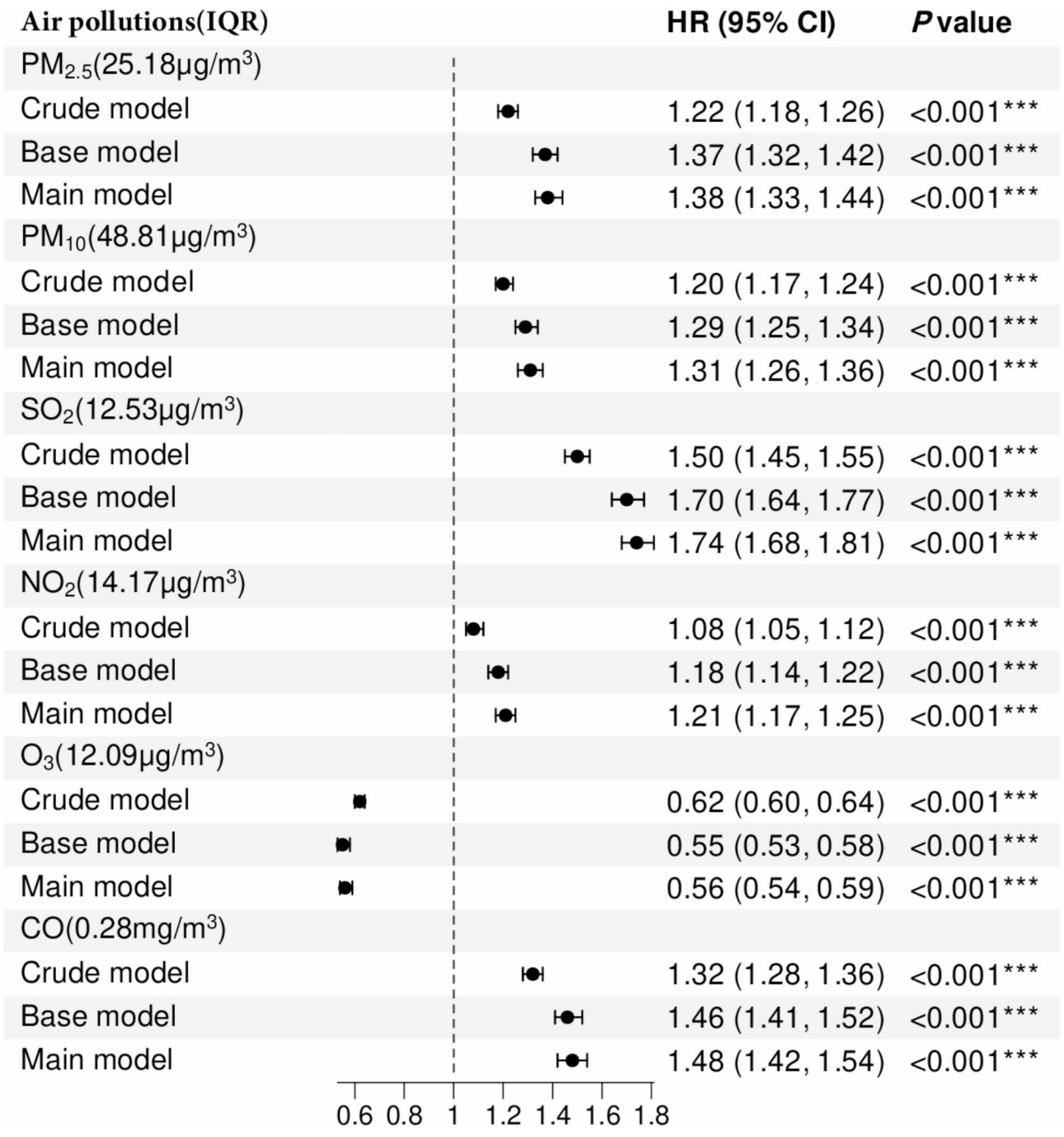

Fig. 3 Associations between air pollution and GI disease, per IQR increment in air pollutants. Crude model: no adjustment; Base model: Adjusted for age, sex, education level, marital status, region and residence; Main model: Base model + smoking, drinking, BMI and health status. $PM_{2.5}$, particle with aerodynamic diameter ≤ 2.5 μm; PM_{10}, particle with aerodynamic diameter ≤ 10 μm; SO_2, sulfur dioxide; NO_2, nitrogen dioxide; CO, carbonic oxide; O_3, ozone; GI disease, gastrointestinal disease; IQR, interquartile range; HR, Hazard Ratio; CI, confidence interval. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$

This exclusion did not alter the results substantially, with effect sizes and statistical significance remaining similar to the main results for all pollutants, including O_3 (Table S5). PSM was also performed to control for potential confounding factors. After matching 2978 participants with GI disease to an equal number without GI disease, baseline characteristics between the two groups showed no significant differences (Table S7). Post-PSM results aligned closely with pre-PSM findings, further supporting the robustness of the associations (Table S6).

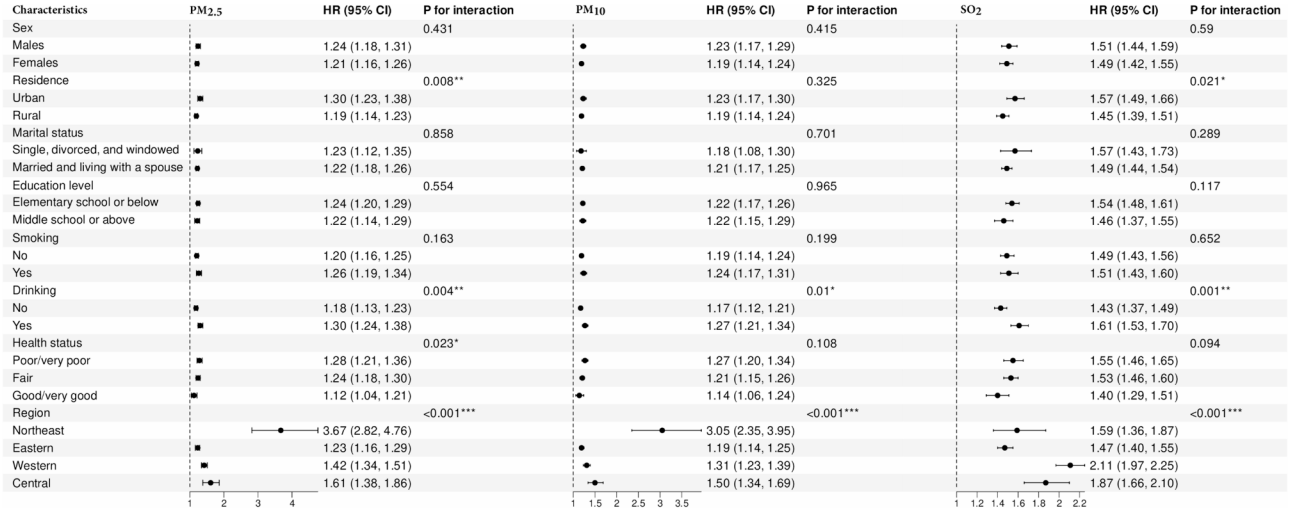

Fig. 4 Subgroup and interaction analyses of air pollutants ($PM_{2.5}$, PM_{10}, SO_2) and GI disease

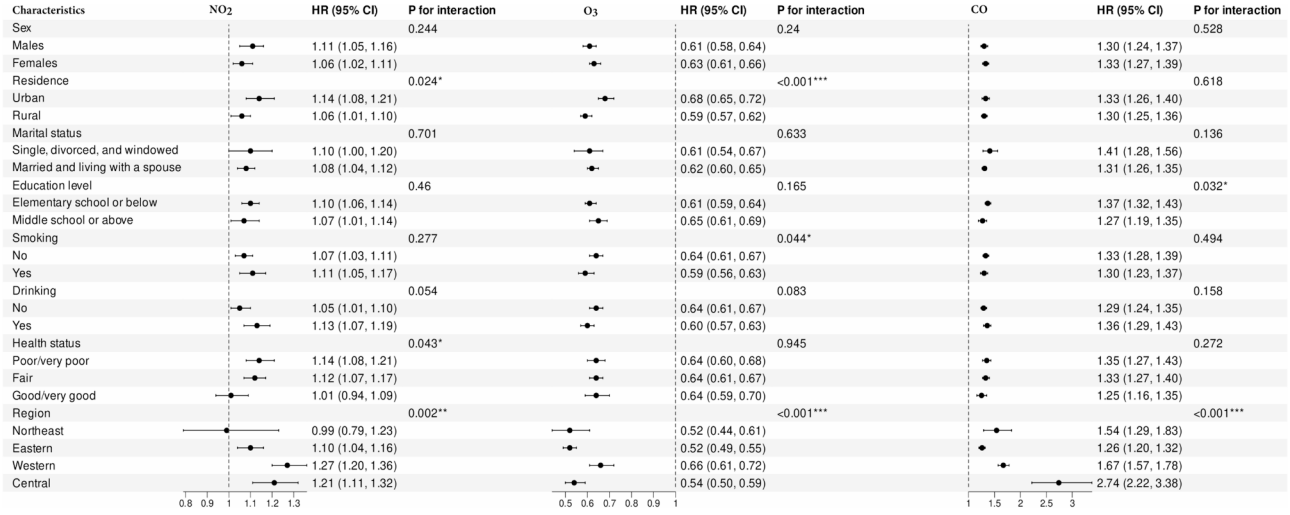

Fig. 5 Subgroup and interaction analyses of air pollutants (NO_2, O_3, CO) and GI disease

Overall, these sensitivity analyses demonstrated that the associations between air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) and GI disease incidence were robust across various analytical approaches, including the use of continuous exposure variables and adjustments for confounders.

Discussion

This study based on data from the CHARLS, systematically evaluated the long-term relationship between air pollution and GI diseases. The findings indicate that prolonged exposure to $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO is significantly associated with an increased incidence of GI diseases, while O_3 exhibits a negative correlation with GI health. These results are consistent with previous studies and contribute to a deeper understanding of the health impacts of air pollution. For instance, a study by Qiu et al. (2024) found that exposure to ambient air pollutants such as $PM_{2.5}$, PM_{10}, and O_3, which fluctuate over time, is linked to changes in the gut microbiome during early childhood, potentially influencing future GI health [31]. Additionally, a systematic review by Van Pee et al. (2023) underscored the significant effects of particulate air pollution on gut health [32]. Furthermore, a study from Taiwan demonstrated that higher levels of ambient air pollutants, particularly $PM_{2.5}$ and NO_2, are associated with an increased frequency of hospital admissions for GI diseases [33]. Together, these findings, along with our own, further highlight the critical connection between air pollution and GI health.

Firstly, our study found that long-term exposure to fine particulate matter ($PM_{2.5}$ and PM_{10}) significantly increased the risk of GI diseases, consistent with previous research. The literature suggests that airborne

particulate matter can impair gut barrier function by inducing oxidative stress and systemic inflammatory responses, leading to GI inflammation and other diseases [34–36]. Specifically, Ran et al. reported that $PM_{2.5}$ may stimulate oxidative stress in intestinal epithelial cells, exacerbating gut damage and thereby increasing the risk of GI diseases [19]. PM_{10} exposure has been linked to the disruption of gut microbiota and an increase in systemic inflammatory markers, which may ultimately impair the gut barrier function and promote the onset of GI diseases [37, 38]. Similar studies have shown that particulate matter can alter the composition of the gut microbiota, promoting the growth of harmful bacteria, which in turn triggers intestinal inflammation and dysfunction [26, 39, 40]. These findings provide further evidence of the role of particulate matter in mediating systemic inflammation and gastrointestinal health issues.

In addition, our study found that long-term exposure to SO_2 and NO_2 is significantly associated with a higher incidence of GI diseases, consistent with numerous previous studies. It has been shown that these gaseous pollutants can adversely affect GI health by increasing intestinal mucosal permeability and triggering inflammatory responses [41–43]. Specifically, SO_2 and NO_2 are believed to enter the circulatory system after inhalation, thereby inducing chronic inflammation and oxidative damage within the gastrointestinal tract [42]. Li et al. also found similar results in a study of urban populations, highlighting a significant association between NO_2 exposure and worsening gut health [23]. Our findings highlight the importance of reducing exposure to gaseous pollutants to reduce gastrointestinal health risks. This study also identifies a significant association between long-term CO exposure and increased GI disease risk, a relationship less frequently discussed in prior research. Existing studies suggest that chronic CO exposure can impair mitochondrial function, disrupt cellular respiration, and promote inflammation, which may contribute to GI tract damage [44, 45]. Furthermore, CO has been implicated in altering gut microbiota, potentially exacerbating inflammatory processes in the gut [46]. Our results highlight the need for more focused research on CO's impact on GI disease, particularly in regions with high ambient CO levels due to traffic or industrial emissions. Our findings regarding O_3 contrast with those reported in our earlier cross-sectional analysis [31], which identified a positive association between O_3 and GI disease prevalence. This discrepancy likely stems from fundamental differences in study design: whereas the prior work assessed short-term exposure (2013–2015) and prevalent cases, our longitudinal approach (2011–2020) evaluated incident disease risk, accounting for temporal variations in pollution levels and individual covariates (e.g., region). Notably, experimental studies suggest that chronic O_3 exposure may induce adaptive antioxidative responses (Erginel et al., 2023; Azmy et al., 2022), potentially explaining the protective trend observed here [47–49]. It is important to note, however, that this result may be influenced by specific exposure levels and other factors in the study population, and further research is required to validate the biological mechanisms and applicability of this finding [48].

We found that demographic and behavioral factors significantly modify the relationship between air pollution and GI diseases. Urban residents, for example, exhibited a stronger correlation between air pollution and GI diseases compared to their rural counterparts. This difference likely reflects the higher intensity and complexity of pollution in urban areas, where traffic emissions and industrial pollutants dominate. Urban populations are also exposed to a broader mix of pollutants, which may have cumulative or synergistic effects on gut health [50, 51]. Given these factors, public health strategies should prioritize pollution control in urban areas, focusing on reducing emissions from transportation and industrial sources. Health interventions, such as promoting air filtration in homes and workplaces, and raising awareness of pollution risks, should also be implemented for urban populations.

Regional differences in health risks associated with air pollution were also pronounced. These disparities underscore the importance of considering local pollution conditions and health risks when designing interventions. Variations in air pollution's impact on GI diseases across regions stem from differences in pollutant sources, environmental conditions, and socio-economic factors [52, 53]. In the Northeast, higher levels of $PM_{2.5}$ and PM_{10}, primarily from industrial emissions and winter heating, contribute to increased GI disease risk [54, 55]. Therefore, policies in this region should focus on improving air quality through stricter industrial emission regulations and promoting cleaner heating technologies. Similarly, in the Western regions, high concentrations of SO_2 and NO_2 contribute to chronic inflammation and oxidative damage in the gastrointestinal system [56]. Targeted policies in these areas should aim to reduce emissions from industrial and traffic sources, while ensuring community access to health screening and early intervention for GI diseases. The protective effect of O_3 observed in the Western region may be due to the region's unique air quality, suggesting that further research is needed to better understand O_3's role in mitigating health risks [57, 58]. In the Central region, CO exposure, primarily linked to traffic and industrial emissions, is associated with increased GI disease risk [59]. Regulatory measures to reduce CO emissions in urban and industrial areas are critical to protecting vulnerable populations.

Finally, behavioral factors such as alcohol consumption and smoking were found to modulate the relationship between air pollution and GI disease risk. These behaviors impair antioxidant and immune functions, exacerbating the harmful effects of pollution [60, 61]. Public health campaigns should focus on promoting healthier lifestyle choices, such as reducing smoking and alcohol consumption, particularly in high-pollution areas. These efforts could mitigate some of the harmful effects of air pollution and reduce GI disease incidence.

The longitudinal design of this study provided a significant advantage over traditional cross-sectional studies by allowing for dynamic observation of the long-term causal relationship between air pollution and GI health. By utilizing years of follow-up data, we were able to assess the potential long-term effects of various air pollutants on GI health. This design helps minimize the risk of reverse causality and strengthens the reliability of causal inferences. However, some limitations remain. First, although we accounted for long-term exposure to multiple pollutants, confounding factors such as dietary habits and occupational exposures could still influence the results. Second, air pollution exposure was assessed based on participants' residential addresses, which may not fully capture individual exposure, such as at workplaces or during commuting. We acknowledge this limitation and suggest that future research include more precise measures of individual exposure, such as personal air monitoring or more granular geographic data. Despite these limitations, the robustness of our findings was confirmed through multiple sensitivity analyses and propensity score matching, enhancing the study's credibility and minimizing the potential for bias due to confounding.

Conclusion

In conclusion, our study provides new evidence for understanding the relationship between air pollution and GI health and underscores the potential long-term impacts of air pollution on public health. Based on these findings, we recommend that public health policies focus on reducing the concentration of air pollutants, especially in urban areas, and adopt targeted interventions for high-risk populations to mitigate the health burden posed by air pollution.

Supplementary information

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Supplementary Material 1

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Author contributions
Y.K.: Conceptualization, Validation, Formal analysis, Data curation, Writing – original draft. S.Y.: Validation, Formal analysis, Data curation, Writing – original draft. W.D.: Validation, Formal analysis, Data curation, Writing – original draft. Z.L., K.Y., L.Z., Y.H.: Methodology, Visualization, Validation. L.Q.: Resources, Supervision, Conceptualization, Writing – review & editing. Y.Y.: Resources, Supervision, Conceptualization, Writing – review & editing.All authors reviewed and approved the final manuscript.

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Data availability
The data used above were openly available on the CHARLS public website.

Declarations

Ethical approval
Peking University's institutional review board reviewed and approved the studies that involved human participants. The research was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants.

Consent for publication
Not Applicable.

Conflict of interest
The authors declared no competing interests for this work.

Declaration of figures authenticity
All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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References

1. Xu Y, Zhou SC, Feng YX, Zou B, He C. Global air quality enhancement pathways to health benefits and environmental justice. J Hazard Mater. 2024;480:136460.
2. Marcella S, Apicella B, Secondo A, Palestra F, Opromolla G, Ciardi R, Tedeschi V, Ferrara AL, Russo C, Rosaria Galdiero M, et al. Size-based effects of anthropogenic ultrafine particles on activation of human lung macrophages. Environ Int. 2022;166:107395.
3. Weber SA, Insaf TZ, Hall ES, Talbot TO, Huff AK. Assessing the impact of fine particulate matter ($PM_{2.5}$) on respiratory-cardiovascular chronic diseases in the New York City Metropolitan area using Hierarchical Bayesian Model estimates. Environ Res. 2016;151:399–409. https://doi.org/10.1016/j.envres.2016.07.012
4. Aimuzi R, Xie Z, Qu Y, Luo K, Jiang Y. Proteomic signatures of ambient air pollution and risk of non-alcoholic fatty liver disease: a prospective cohort study in the UK Biobank. Sci Total Environ. 2024;957:177529.
5. Miller MR, Di Cesare M, Rahimzadeh S, Adeoye M, Perel P, Taylor S, Shrikhande S, Armstrong-Walenczak K, Shah ASV, Berenstein CD, et al. Clearing the Air to address Pollution's Cardiovascular Health Crisis. Glob Heart. 2024;19(1):82.
6. Lin TY, Chang PJ, Lo CY, Chuang HC, Lee CS, Chang CH, Yu CT, Hsieh MH, Liu CY, Kuo CS, et al. Correlation between mRNA expression of activated eosinophils and Air Pollutant exposure in patients with asthma. Immun Inflamm Dis. 2024;12(11):e70065.
7. Barbosa JV, Branco P, Alvim-Ferraz MCM, Martins FG, Sousa SIV. Firefighters' occupational exposure to air pollution: impact on COPD and asthma-study protocol. BMJ Open Respir Res. 2024;11(1).
8. Qin GT, Zhao Q, Fujita A, Damiani I, Easwaran M, Basu S, Gu W, Li DY, Worssam M, Palmisano B et al. Aryl-hydrocarbon receptor in smooth muscle

cells protect against dioxin induced adverse remodeling of atherosclerosis. bioRxiv. 2024.
9. Razzaghi S, Mousavi S, Jaberinezhad M, Farshbaf Khalili A, Banan Khojasteh SM. Time-Series analysis of short-term exposure to air pollutants and daily hospital admissions for stroke in Tabriz, Iran. PLoS ONE. 2024;19(11):e0309414.
10. Zhu A, Liu M, Yu J, Zhang R, Zhang Y, Chen R, Ruan Y. Association between air pollution and hypertension hospitalizations: a time series analysis in Lanzhou. BMC Public Health. 2024;24(1):3260.
11. Jaiswal C, Singh AK. Particulate matter exposure and its consequences on hippocampal neurogenesis and cognitive function in experimental models. Environ Pollut. 2024;363(Pt 2):125275.
12. Soeterboek J, Deckers K, van Boxtel MPJ, Backes WH, Eussen S, van Greevenbroek MMJ, Jansen JFA, Koster A, Schram MT, Stehouwer CDA, et al. Association of ambient air pollution with cognitive functioning and markers of structural brain damage: the Maastricht study. Environ Int. 2024;192:109048.
13. Zhou X, Guo Z, Ling Y, Teng W, Cui J, Yan Z, Hou X, Cen W, Long N, Li W, et al. Causal effect of air pollution on the risk of brain health and potential mediation by gut microbiota. Ecotoxicol Environ Saf. 2024;285:117080.
14. Williams VJ, Trane R, Sicinski K, Herd P, Engelman M, Asthana S. Midlife and late-life environmental exposures on dementia risk in the Wisconsin Longitudinal Study: The modifying effects of ApoE. Alzheimers Dement. 2024;20(12):8263–8278. https://doi.org/10.1002/alz.14216
15. Xie D, Shen Z, Yang L, Zhou D, Li C, Liu F. Global, regional, and national burden of type 2 diabetes mellitus attributable to particulate matter pollution from 1990 to 2021: an analysis of the global burden of disease study 2021. Diabetes Res Clin Pract. 2024;218:111934.
16. Xu H, Xu H, Wu J, Wang L, Guo B, Li W, Zhang J, Xiao X, Zhao X. Ambient air pollution exposure, plasma metabolomic markers, and risk of type 2 diabetes: a prospective cohort study. J Hazard Mater. 2023;463:132844.
17. Calderón-Garcidueñas L, González-Maciel A, Reynoso-Robles R, Hammond J, Kulesza R, Lachmann I, Torres-Jardón R, Mukherjee PS, Maher BA. Quadruple abnormal protein aggregates in brainstem pathology and exogenous metal-rich magnetic nanoparticles (and engineered Ti-rich nanorods). The substantia nigrae is a very early target in young urbanites and the gastrointestinal tract a key brainstem portal. Environ Res. 2020;191:110139.
18. Feng J, Cavallero S, Hsiai T, Li R. Impact of air pollution on intestinal redox lipidome and microbiome. Free Radic Biol Med. 2020;151:99–110.
19. Ran Z, Yang J, Liu L, Wu S, An Y, Hou W, Cheng T, Zhang Y, Zhang Y, Huang Y, et al. Chronic PM(2.5) exposure disrupts intestinal barrier integrity via microbial dysbiosis-triggered TLR2/5-MyD88-NLRP3 inflammasome activation. Environ Res. 2024;258:119415.
20. Liu Y, Wang T, Si B, Du H, Liu Y, Waqas A, Huang S, Zhao G, Chen S, Xu A. Intratracheally instillated diesel PM(2.5) significantly altered the structure and composition of indigenous murine gut microbiota. Ecotoxicol Environ Saf. 2021;210:111903.
21. Dujardin CE, Mars RAT, Manemann SM, Kashyap PC, Clements NS, Hassett LC, Roger VL. Impact of air quality on the gastrointestinal microbiome: a review. Environ Res. 2020;186:109485.
22. Cheng HJ, Hsu WL, Lin P, Chen YC, Lin TH, Fang SS, Tsai MH, Lin YJ, Wang SP, Chen H, et al. Involvement of autophagy and gut dysbiosis in ambient particulate matter-induced colonic inflammation. Ecotoxicol Environ Saf. 2024;286:117171.
23. Li J, He C, Ying J, Hua B, Yang Y, Chen W, Liu W, Ye D, Sun X, Mao Y, et al. Air pollutants, genetic susceptibility, and the risk of incident gastrointestinal diseases: a large prospective cohort study. Environ Res. 2024;247:118182.
24. Zhan ZQ, Li JX, Chen YX, Fang JY. The effects of air and transportation noise pollution-related altered blood gene expression, DNA methylation, and protein abundance levels on gastrointestinal diseases risk. Sci Total Environ. 2024;951:175633.
25. Chang C, Louie A, Zhou Y, Gupta R, Liang F, Xanthou G, Ereso J, Koletic C, Yang JC, Sedighian F et al. Ambient particulate matter induces in Vitro toxicity to intestinal epithelial cells without exacerbating Acute Colitis Induced by Dextran Sodium Sulfate or 2,4,6-Trinitrobenzenesulfonic acid. Int J Mol Sci. 2024;25(13).
26. Mazumder MHH, Hussain S. Air-Pollution-mediated Microbial Dysbiosis in Health and Disease: Lung-Gut Axis and Beyond. J Xenobiot. 2024;14(4):1595–612.
27. Chen J, Dan L, Sun Y, Yuan S, Liu W, Chen X, Jiang F, Fu T, Zhang H, Deng M, et al. Ambient air Pollution and Risk of Enterotomy, Gastrointestinal Cancer, and all-cause mortality among 4,708 individuals with inflammatory bowel disease: a prospective cohort study. Environ Health Perspect. 2023;131(7):77010.
28. Pritchett N, Spangler EC, Gray GM, Livinski AA, Sampson JN, Dawsey SM, Jones RR. Exposure to Outdoor Particulate Matter Air Pollution and Risk of gastrointestinal cancers in adults: a systematic review and Meta-analysis of epidemiologic evidence. Environ Health Perspect. 2022;130(3):36001.
29. Qiu T, Fang Q, Zeng X, Zhang X, Fan X, Zang T, Cao Y, Tu Y, Li Y, Bai J, et al. Short-term exposures to PM(2.5), PM(2.5) chemical components, and antenatal depression: exploring the mediating roles of gut microbiota and fecal short-chain fatty acids. Ecotoxicol Environ Saf. 2024;277:116398.
30. Kou Y, Du S, Du W, Ye W, Yang Y, Qin L. Exposure to air pollution and non-neoplastic digestive system diseases: findings from the China Health and Retirement Longitudinal Study. Front Public Health 2024;12:1372156.
31. Qiu T, Fang Q, Tian X, Cao Y, Fan X, Li Y, Tu Y, Liu L, Chen Z, Wei Y et al. Time-varying ambient air pollution exposure is associated with gut microbiome variation in the first 2 years of life. *Environmental pollution (Barking, Essex*: 1987.) 2024;360:124705.
32. Van Pee T, Nawrot TS, van Leeuwen R, Hogervorst J. Ambient particulate air pollution and the intestinal microbiome; a systematic review of epidemiological, in vivo and, in vitro studies. Sci Total Environ. 2023;878:162769.
33. Chen CC, Yang CY. Effects of ambient air pollution exposure on frequency of hospital admissions for appendicitis in Taipei, Taiwan. J Toxicol Environ Health Part A. 2018;81(17):854–60.
34. Xie S, Zhang C, Zhao J, Li D, Chen J. Exposure to concentrated ambient PM(2.5) (CAPM) induces intestinal disturbance via inflammation and alternation of gut microbiome. Environ Int. 2022;161:107138.
35. Ziegler K, Kunert AT, Reinmuth-Selzle K, Leifke AL, Widera D, Weller MG, Schuppan D, Fröhlich-Nowoisky J, Lucas K, Pöschl U. Chemical modification of pro-inflammatory proteins by peroxynitrite increases activation of TLR4 and NF-κB: implications for the health effects of air pollution and oxidative stress. Redox Biol. 2020;37:101581.
36. Celebi Sözener Z, Cevhertas L, Nadeau K, Akdis M, Akdis CA. Environmental factors in epithelial barrier dysfunction. J Allergy Clin Immunol. 2020;145(6):1517–28.
37. Raftery AL, Tsantikos E, Harris NL, Hibbs ML. Links between inflammatory bowel Disease and Chronic Obstructive Pulmonary Disease. Front Immunol. 2020;11:2144.
38. Son YS, Son N, Yu WD, Baek A, Park YJ, Lee MS, Lee SJ, Kim DS, Son MY. Particulate matter 10 exposure affects intestinal functionality in both inflamed 2D intestinal epithelial cell and 3D intestinal organoid models. Front Immunol. 2023;14:1168064.
39. Dai S, Wang Z, Yang Y, Du P, Li X. PM(2.5) induced weight loss of mice through altering the intestinal microenvironment: mucus barrier, gut microbiota, and metabolic profiling. J Hazard Mater. 2022;431:128653.
40. Bailey MJ, Naik NN, Wild LE, Patterson WB, Alderete TL. Exposure to air pollutants and the gut microbiota: a potential link between exposure, obesity, and type 2 diabetes. Gut Microbes. 2020;11(5):1188–202.
41. Cruells A, Cabrera-Rubio R, Bustamante M, Pelegrí D, Cirach M, Jimenez-Arenas P, Samarra A, Martínez-Costa C, Collado MC, Gascon M. The influence of pre- and postnatal exposure to air pollution and green spaces on infant's gut microbiota: results from the MAMI birth cohort study. Environ Res. 2024;257:119283.
42. Suarez RG, Osornio-Vargas AR, Wine E. Ambient air Pollution and Pediatric Inflammatory Bowel diseases: an updated scoping review. Dig Dis Sci. 2022;67(9):4342–54.
43. Feathers A, Lovasi GS, Grigoryan Z, Beem K, Datta SK, Faleck DM, Socci T, Maggi R, Swaminath A. Crohn's Disease Mortality and Ambient Air Pollution in New York City. Inflamm Bowel Dis. 2024;30(10):1732–9.
44. Zhang X, Yuan Z, Wu J, He Y, Lu G, Zhang D, Zhao Y, Wu R, Lv Y, Cai K, et al. An orally-administered nanotherapeutics with Carbon Monoxide supplying for inflammatory bowel Disease Therapy by scavenging oxidative stress and restoring gut Immune Homeostasis. ACS Nano. 2023;17(21):21116–33.
45. Damasceno ROS, Soares PMG, Barbosa A, Nicolau LAD, Medeiros JR, Souza M. Modulatory Role of Carbon Monoxide on the inflammatory response and oxidative stress linked to gastrointestinal disorders. Antioxid Redox Signal. 2022;37(1–3):98–114.
46. Benrahla DE, Mohan S, Trickovic M, Castelli FA, Alloul G, Sobngwi A, Abdiche R, Kieser S, Demontant V, Trawinski E, et al. An orally active carbon monoxide-releasing molecule enhances beneficial gut microbial species to combat obesity in mice. Redox Biol. 2024;72:103153.
47. Erginel B, Yanar F, Ilhan B, Yüksel S, Mikailova P, Berker N, Keskin E, Gün Soysal F. Is the increased ozone dosage key factor for its anti-inflammatory effect in an experimental model of mesenteric ischemia? Ulus Travma Acil Cerrahi Derg. 2023;29(10):1069–74.

48. Azmy AM, Abd Elbaki BT, Ali MA, Mahmoud AA. Effect of ozone versus naringin on testicular injury in experimentally induced ulcerative colitis in adult male albino rats. Ultrastruct Pathol. 2022;46(5):439–61.
49. Erel S, Küçükk A, Dikmen K, Tekin E, Yığman Z, Ceyhan M, Gökgöz S, Bostancı H, Arslan M, Kavutcu M. Evaluation of the Efficacy of Ozone Therapy on Liver Tissue in the Treatment of Sepsis in Rats with Cecal Perforation. Medicina (Kaunas, Lithuania). 2024;60(9).
50. Li N, Chen G, Liu F, Mao S, Liu Y, Liu S, Mao Z, Lu Y, Wang C, Guo Y, et al. Associations between long-term exposure to air pollution and blood pressure and effect modifications by behavioral factors. Environ Res. 2020;182:109109.
51. Huang B, Xiao T, Grekousis G, Zhao H, He J, Dong G, Liu Y. Greenness-air pollution-physical activity-hypertension association among middle-aged and older adults: evidence from urban and rural China. Environ Res. 2021;195:110836.
52. Brugha R, Grigg J. Urban air pollution and respiratory infections. Paediatr Respir Rev. 2014;15(2):194–9.
53. Liu J, Kiesewetter G, Klimont Z, Cofala J, Heyes C, Schöpp W, Zhu T, Cao G, Gomez Sanabria A, Sander R, et al. Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. Environ Int. 2019;125:236–44.
54. Wang Y, Sun Y, Zhao G, Cheng Y. Air Quality in the Harbin-Changchun Metropolitan Area in Northeast China: unique episodes and New trends. Toxics. 2021;9(12).
55. Sun L, Ai X, Yao X, An Q, Liu X, Yakovleva E, Zhang L, Sun H, Zhang K, Zang S. Relationship between atmospheric pollution and polycyclic aromatic hydrocarbons in fresh snow during heavy pollution episodes in a cold city, northeast China. Ecotoxicol Environ Saf. 2023;260:115091.
56. Shen JS, Wang Q, Shen HP. Does Industrial Air Pollution increase Health Care expenditure? Evidence from China. Front Public Health. 2021;9:695664.
57. Sahu SK, Liu S, Liu S, Ding D, Xing J. Ozone pollution in China: background and transboundary contributions to ozone concentration & related health effects across the country. Sci Total Environ. 2021;761:144131.
58. Tan Z, Lu K, Jiang M, Su R, Dong H, Zeng L, Xie S, Tan Q, Zhang Y. Exploring ozone pollution in Chengdu, southwestern China: a case study from radical chemistry to O(3)-VOC-NO(x) sensitivity. Sci Total Environ. 2018;636:775–86.
59. Wang Y, Yao C, Xu C, Zeng X, Zhou M, Lin Y, Zhang P, Yin P. Carbon monoxide and risk of outpatient visits due to cause-specific diseases: a time-series study in Yichang, China. Environ Health: Global Access Sci Source. 2019;18(1):36.
60. Hashimoto K, Maeda H, Iwasa H, Kyozuka H, Maeda R, Kume Y, Ono T, Chishiki M, Sato A, Ogata Y, et al. Tobacco exposure during pregnancy and infections in infants up to 1 year of age: the Japan Environment and Children's study. J Epidemiol. 2023;33(10):489–97.
61. Caslin B, Mohler K, Thiagarajan S, Melamed E. Alcohol as friend or foe in autoimmune diseases: a role for gut microbiome? Gut Microbes. 2021;13(1):1916278.

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