Long-term exposure to outdoor fine particulate and physical activity with mortality and cardiovascular events: an analysis of the Prospective Urban Rural Epidemiology (PURE)-China cohort study

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Summary

Background Long-term exposure to PM2.5 and low physical activity are independently associated with an increased risk of cardiovascular disease (CVD). However, there is limited research investigating the combined effects of PM2.5 exposure and physical activity on CVD risk. This study aims to explore these interactions related to CVD and mortality.

Methods We analysed data from the PURE-China cohort, including 39,970 adults aged 35–70 years, with a median follow-up of 11.9 years. PM2.5 exposure was estimated using a Bayesian hierarchical model. Physical activity was quantified using metabolic equivalent task (MET)-minutes per week. The primary outcome was a composite of all-cause mortality and major cardiovascular events. Cox frailty models and restricted cubic splines were used to assess associations. Interaction effects were evaluated using measures of multiplicative and additive interaction, including the relative excess risk due to interaction (RERI) and the proportion attributable to interaction (AP).

Findings Participants were divided into high and low PM2.5 exposure groups by the median concentration (47.70 μg/m^3). In low-exposure areas, higher total physical activity significantly reduced the risk of composite outcome (HR: 0.84, 95% CI: 0.73–0.97, p trend = 0.012) and major cardiovascular events (HR: 0.80, 0.67–0.95, p trend = 0.022). However, in high-exposure regions, physical activity showed no protective effect for the composite outcome (HR: 0.97, 0.85–1.09, p trend = 0.551) and major cardiovascular events (HR: 0.98, 0.85–1.13, p trend = 0.864). Higher non-recreational physical activity reduced the risks of composite outcome and major CVD in low-exposure areas but provided no benefit in high-exposure regions (p interaction = 0.011, 0.024, respectively). Significant antagonistic interaction was observed between high PM2.5 exposure and low non-recreational physical activity for the composite outcome (RERI: –0.215, 95% CI: –0.406 to –0.024; AP: –0.155, 95% CI: –0.294 to –0.017).

Interpretation Long-term exposure to high PM2.5 concentrations diminishes the cardiovascular benefits of physical activity, particularly non-recreational activities. These findings underscore the need for tailored physical activity guidelines and air quality interventions in heavily polluted regions to maximize public health benefits.

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Research in context

Evidence before this study

We searched the PubMed database on January 15, 2025, for studies examining the interactive effect of physical activity and PM2.5 exposure on mortality or cardiovascular disease. The search was unrestricted by language or publication date. Search terms included ("particulate matter" OR "PM2.5" OR "air pollution") AND ("physical activity") AND ("cardiovascular" OR "cerebrovascular" OR "coronary" OR "myocardial infarction" OR "stroke" OR "death" OR "mortality"). We also searched Embase and Google Scholar using a similar strategy. Previous research on the interaction between physical activity and long-term exposure to fine particulate matter (PM2.5) has primarily focused on populations with relatively low PM2.5 exposure. These studies often showed limited variation in population characteristics and geographic distribution and frequently included activities such as active commuting or farming. However, the impact of PM2.5 exposure in regions with high pollution levels and broader geographic variation on the cardiovascular benefits of both recreational and non-recreational physical activities remains unclear.

Added value of this study

To the best of our knowledge, this is the largest prospective study to date that comprehensively examines how physical activity—both recreational and non-recreational—modifies the risk of cardiovascular disease and mortality concerning long-term exposure to PM2.5 across a broad geographic area in China. Our findings reveal significant differences in the associations between total and non-recreational physical activity (including occupational, transportation, and housework activities) and major cardiovascular events, as well as a composite endpoint of cardiovascular events or death, depending on PM2.5 exposure levels. Specifically, high PM2.5 exposure combined with low non-recreational physical activity demonstrated significant antagonistic interactions for the composite outcome of all-cause death and major cardiovascular events. These results suggest that high PM2.5 exposure may reduce the protective benefits of physical activity—particularly non-recreational activities—on cardiovascular health and mortality.

Implications of all the available evidence

Long-term exposure to high levels of PM2.5 significantly diminishes the cardiovascular benefits of physical activity, particularly non-recreational activities. These results emphasize the need for region-specific physical activity guidelines and air quality interventions in areas with high pollution to improve public health outcomes. Tackling both air pollution and physical inactivity is essential for reducing the global burden of cardiovascular disease, especially in low- and middle-income countries.

Introduction

Cardiovascular diseases (CVD) remain a primary cause of mortality globally, posing significant health challenges.[1] Physical activity is widely recognized for its protective effects against CVD.[2,3] The World Health Organization (WHO) 2020 guidelines recommend that all adults should engage in regular physical activity, aiming for at least 150 min of moderate-intensity aerobic activity, 75 min of vigorous-intensity aerobic activity, or an equivalent combination of both per week.[4] However, despite these recommendations, an estimated 31.3% of the global population failed to meet sufficient physical activity levels,[5] and 7.2% and 7.6% of all-cause and CVD deaths, respectively, are attributable to physical inactivity.[6]

Particulate matter (PM) air pollution has also emerged as a critical global health concern and was the leading contributor to the global disease burden in 2021.[7] Long-term exposure to PM2.5, a critical constituent of air pollution, is associated with an elevated risk of CVD.[8,9] Of note, nearly 99% of the global population breathes air that exceeds the WHO's updated air quality limits set in 2021 and contains high concentrations of pollutants, with residents in low–and middle-income countries (LMICs) most exposed.[10] In China, the annual average concentration of PM2.5 has dropped from 72 $\mu g/m^3$ in 2013 to 30 $\mu g/m^3$ in 2023, marking a significant improvement in the ambient air quality.[11] This progress is mainly attributed to China's long-term efforts and policies to combat environmental air pollution, especially indoor air pollution.[12,13] A key example of successful intervention is Beijing's experience, where the use of coal as an energy source was banned in surrounding areas, contributing to cleaner air.[14] However, despite these improvements, the annual average concentration of PM2.5 in China remains well above the WHO's recommended air quality guideline,[10] highlighting that further efforts are needed in air pollution control. These developments underscore an important public health debate about the interplay between physical activity and air pollution: Should outdoor physical activity be encouraged in areas with relatively high levels of air pollution?[15]

Few studies have explored the interaction of physical activity and long-term exposure to PM2.5 on cardiovascular risk,[16–21] metabolic syndrome,[22] and hypertension.[23] Some evidence suggests that engaging in outdoor physical activity in areas with high levels of air pollution may reduce its protective effects on CVD or even increase CVD risk, particularly among individuals involved in active commuting and farming activity.[19–21] However, studies conducted in high-income countries with relatively lower PM2·5 concentrations indicate that higher levels of physical activity can reduce CVD risk regardless of air pollution exposure.[16–18] This inconsistency likely arises from variations in study settings, income levels, geographical coverage, and population characteristics. To our knowledge, limited research has examined whether long-term exposure to outdoor fine particulate matter weakens the protective association of physical activity with CVD in low-income countries, where outdoor air pollution levels are typically higher. This study aims to address this gap by evaluating the combined effects of PM2.5 exposure and physical activity—both recreational and non-recreational—on the incidence of CVD.

Methods

Study design and participants

The details of the PURE study have been previously described (Supplementary material, Appendix A).[24] In brief, PURE-China, a substudy of the PURE cohort, is a prospective epidemiological study that enrolled participants aged 35–70 years from 115 communities (45 urban and 70 rural) across 12 provinces in China between 2005 and 2009 (Supplementary material, Fig. S1). Using multistage sampling, PURE-China ensured an approximate 1:1 urban-to-rural ratio, selecting provinces based on regional diversity and feasibility for long-term follow-up. These provinces were categorized by socioeconomic development at the time into Western regions (Shaanxi, Sichuan, Yunnan, Inner Mongolia, Qinghai, Xinjiang), Central (Shanxi, Jiangxi), and Eastern (Beijing, Jiangsu, Liaoning, Shandong). The participant selection process is detailed in Supplementary material, Appendix A1. Previous analyses of PURE have demonstrated strong concordance between the study population and national demographic data, minimizing the likelihood of bias in exposure-disease associations.[25] The study protocol received approval from the institutional review boards of the Beijing Hypertension League Institute and Fuwai Hospital Chinese Academy of Medical Sciences (Approval NO. 2020-1313). All participants provided written informed consent for the use of their data in scientific research, including publication.

The eligible study population includes all PURE-China participants recruited between 2005 and 2009, with follow-up data collected through August 2021. Inclusion criteria are: (1) Age between 35 and 70 years; (2) At least 1 follow-up information. Participants were excluded if they had missing data for age, sex, physical activity, and PM2.5 exposure, or had a history of CVD at baseline.

Exposure

The methodology for estimating PM2.5 concentrations has been previously described in the PURE global research.[9] Outdoor PM2.5 levels for each PURE community were derived through a Bayesian hierarchical model, which integrates ground-based PM2.5 monitoring data, satellite-derived aerosol optical depth results, and chemical transport models.[26] This approach accurately predicted ground monitor values and was utilised in the Global Burden of Disease (GBD) 2017 study.[27] The PM2.5 estimations are available with an approximate spatial resolution of 1×1 km^2 in 2000, 2005, 2010, and 2011–2016. These predicted PM2.5 concentrations were assigned to the GPS coordinates of each PURE community at baseline, using data from the nearest preceding year.

Participants' sociodemographic factors, medical history, lifestyle behaviours, and risk factors were collected using standardised measures and procedures (Supplementary material, Appendix A2). Education level, occupational classification and household air pollution exposure were self-reported. Blood pressure was measured using a digital sphygmomanometer, with hypertension defined as systolic blood pressure ≥140 mmHg or diastolic blood pressure ≥90 mmHg, self-reported diagnosis, or antihypertensive treatment. Diabetes was defined by fasting glucose ≥7 mmol/L or self-reported diagnosis/treatment. Behavioural and psychological factors—including tobacco and alcohol use, sitting time, diet, and depressive symptoms—were assessed through standardized questionnaires. Use of any medication was defined as taking it at least once a week for the last month. Medication names were recorded through direct inspection of drug packages or prescriptions during face-to-face assessments.[28] All reported medications were centrally coded into standard medication classes by trained staff. Blood samples were centrally analysed for lipid profiles using validated methods. Information on physical activity was collected as minutes per day of moderate to vigorous activity (MVPA) in 10-min bouts using the long-form International Physical Activity Questionnaire (IPAQ) and converted to metabolic (MET)-minutes per week.[29] Detailed questionnaire items are provided in the Supplementary material, Appendix A3. In brief, The IPAQ collects information on physical activity performed in the past seven days across four domains: occupational, transportation, household, and leisure-time activity. Participants were asked to report the frequency (days per week) and duration (hours and minutes per day) of physical activity within each domain, if the activity lasted at least 10 min at a time. In addition, sitting time was recorded

separately for weekdays and weekends. Physical activity was categorised as low (<600 MET × minutes per week), moderate (600–3000 MET × minutes per week), and high (>3000 MET × minutes per week) physical activity, corresponding to less than 150 min per week, 150–750 min per week, and more than 750 min per week of MVPA.[2] Meeting physical activity guidelines was defined as ≥600 MET × min per week and ≥150 min per week of moderate intensity physical activity. Physical activity was further classified into recreational physical activity and non-recreational physical activity (occupational, transportation, and housework). Full definitions and measurement details are provided in Supplementary material, Table S1.

Outcomes

Participants were followed through face-to-face interviews or telephone calls annually for the first three years, and then every three years thereafter to gather information on clinical outcomes from participants or their family members. The primary outcome is the composite of all-cause mortality and major cardiovascular events, defined as death from cardiovascular causes and non-fatal myocardial infarction (MI), stroke, and heart failure. Events were documented using information from household interviews, medical records, death certificates, and other relevant sources. The causes of mortality were categorized based on the International Classification of Diseases, Tenth Revision (ICD-10) codes, or study-specific codes when ICD-10 codes were unavailable. All outcomes were adjudicated by professional physicians following standardized procedures and definitions (Supplementary material, Appendix A4).[30,31] This analysis included all follow-up data recorded through August 2021.

Statistical analysis

To ensure adequate statistical power, we classified PM2.5 concentrations into low and high levels based on the median of 3-year average PM2.5 concentration at baseline (47.70 μg/m^3, IQR: 31.77–75.10), similar to previous studies in China.[18,20,21,23] Baseline characteristics were described and stratified according to the median PM2.5 concentration. Age- and sex-standardised incidence rates (per 1000 person-years) for all outcomes were calculated using Poisson regression across different categories of total physical activity. We employed the Cox frailty model with a random intercept for the community to estimate the hazard ratios (HRs) and 95% confidence intervals (CIs) for the association between physical activity and outcomes. Proportional hazard assumptions were tested using Schoenfeld residuals, with no violation detected. Potential confounders were selected based on the existing literature.[2,9,20] Model 1 included age, sex, urban/rural location, and a community random intercept. Model 2 was additionally adjusted for education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, history of hypertension and diabetes. A random intercept for the community was included in the models to account for the within-community clustering of individuals and the fact that PM2.5 was obtained at the community level. We examined the additive interactions between PM2.5 and physical activity with outcomes using relative excess risk due to interaction (RERI), and attributable proportion due to interaction (AP).[32,33] Details of the calculation for these measures were provided in Supplementary material, Appendix A5. To comply with the additive interaction method, physical activity was categorized into two levels: low, and moderate/high. Restricted cubic splines (RCS) with four knots at the 5th, 35th, 65th, and 95th percentiles were used to graphically estimate the associations of physical activity with study outcomes. Since 46% of participants had no recreational physical activity, we chose 40th, 67.5th, and 95th percentile as the knots. We also selected the three knots at the 10th, 50th, and 90th percentiles and used the median 3-year average PM2.5 concentration as the reference to graphically assess the dose-response relationships.

To strengthen the robustness of our findings, we conducted several sensitivity analyses. To minimize potential reverse causation, where individuals with illness may be less active, we excluded participants who experienced the composite outcome within the first five years of follow-up. Second, we also performed sensitivity analyses using 5-year average PM2.5 concentrations to examine the consistency of results over a longer exposure window. Third, to assess the potential influence of medication use, we repeated the analysis with additional adjustments for antihypertensive and statin use. Finally, we used multiple imputation to handle incomplete covariate information to evaluate the impact of missing data. Specifically, we used the Multiple Imputation by Chained Equations (MICE) approach implemented via the Proc MI procedure in SAS to generate five imputed datasets.[34] Continuous variables were imputed using regression methods, binary or ordinal variables with logistic regression, and nominal variables with the discriminant function method.[35] We also conducted subgroup analyses stratified by sex, age, education level, occupational class, and hypertension status within low and high PM2.5 exposure groups to explore potential effect modification. All analyses were performed using SAS 9.4 (SAS Institute Inc., US) or R version 4.4.1 (R Foundation for Statistical Computing). A two-sided $p < 0.05$ was considered statistically significant.

Role of the funding source

The funders played no role in data collection, analysis, interpretation of findings, manuscript composition, or the decision to submit for publication.

Results

The PURE-China study recruited 47,931 participants, of whom 47,345 are eligible for this analysis based on complete data for age, sex, and at least one follow-up. After excluding individuals with prior CVD, and missing physical activity or PM2.5 data, 39,970 participants (83.4%) were included in the final analysis (Supplementary material, Fig. S2).

Baseline characteristics

The mean (SD) age was 50.51 (9.52) years, comprising 58.5% women, and 45.9% urban residents. Participants were categorized into low and high PM2.5 exposure groups based on the median 3-year average concentration at baseline (47.70 μg/m^3, IQR: 31.77–75.10). The median PM2.5 concentration was 32.13 μg/m^3 (IQR: 30.20–42.93) in the low-exposure group, and 76.73 μg/m^3 (IQR: 54.13–88.90) in the high-exposure group (Table 1). The baseline 3-year mean PM2.5, baseline 5-year mean PM2.5, and study period (2001–2015) mean PM2.5, and PM2.5 concentrations for 2000, 2005, 2010, and 2015 were highly correlated, with correlation coefficients ≥ 0.930 (Supplementary material, Table S2). The details of PM2.5 concentrations for PURE-China communities by province were provided in Supplementary material, Table S3.

Total physical activity was lower in the high-exposure group (2352 MET × min/week vs. 2367 MET × min/week), with minimal recreational physical activity. In areas with high PM2.5 exposure, the prevalence of abdominal obesity (43.7% vs. 39.6%), and hypertension (43.3% vs. 39.0%) were higher. Current tobacco use was more frequent in low-exposure areas, whereas current alcohol use was more frequent in high-exposure areas. Participants in high-exposure regions also had lower PURE diet scores (2.91 vs. 3.08) and higher depression prevalence (2.5% vs. 2.3%). Notably, household air pollution exposure was more common in low-exposure regions (45.0% vs. 34.7%). Participants in low-exposure areas had a higher proportion of urban residents with increased physical activity, whereas similar trend was not observed in high-exposure regions. Regardless of PM2.5 levels, participants with higher physical activity had lower prevalences of hypertension and abdominal obesity, although both conditions were more prevalent in high-exposure areas (Supplementary material, Table S4).

Incidence of cardiovascular disease

During a median follow-up period of 11.9 years (IQR: 9.6–12.7), 1316 major cardiovascular events and 1084 all-cause deaths occurred in the low-exposure group, compared to 1859 major cardiovascular events and 1048 all-cause deaths in the high-exposure group (Table 2). In low-exposure regions, higher total physical activity significantly reduced the composite outcome rate from 10.00 (95% CI: 9.00–11.11) to 6.42 (5.94–6.95) per 1000 person-years (p for trend < 0.001, Table 2). Similar trends were observed for major cardiovascular events, with rates declining from 6.79 (5.98–7.73) to 4.30 (3.91–4.74, p for trend < 0.001). All-cause and cardiovascular mortality rates also decreased significantly with increased total physical activity in these low-exposure areas. Conversely, in high-exposure regions, total physical activity did not significantly reduce event rates across activity levels. Similar findings were observed across different categories of both non-recreational and recreational physical activity (Supplementary material, Tables S5 and S6).

Association of PM2.5 concentrations and physical activity with cardiovascular disease and death

In the entire study population, the RCS curve for PM2.5 concentrations and outcomes revealed a significantly positive association between long-term PM2.5 exposure and composite outcome and major CVD (both p for overall < 0.001, p for nonlinearity> 0.05, Supplementary material, Fig. S3). Increased total, recreational, or non-recreational physical activity was not significantly associated with lower risks of composite outcome, major cardiovascular events, and all-cause mortality (Supplementary material, Fig. S4).

Among participants exposed to average annual PM2.5 levels below 47.70 μg/m^3, those with higher total physical activity had reduced risk of composite outcome (highest vs. lowest: HR 0.84, 95% CI: 0.73–0.97, p for trend = 0.012, Table 3). Increased total physical activity was associated with a lower risk of major cardiovascular events (highest vs. lowest: HR 0.80, 0.67–0.95, p for trend = 0.022). In contrast, in high-exposure regions, total physical activity did not significantly affect these outcomes, and the slopes flattened out with increases in activity (Fig. 1). Multiplicative interactions were observed between total physical activity and composite outcome (p = 0.062) and major CVD (p = 0.038) (Table 4). An antagonistic interaction between high PM2.5 exposure and low total physical activity was noted for the composite outcome (RERI: –0.162, 95% CI: –0.369 to 0.044) and major cardiovascular events (RERI: –0.259, 95% CI: –0.534 to 0.015), although the findings approached but did not reach statistical significance.

The non-recreational physical activity showed a similar pattern in low-exposure regions, reducing risks of composite outcome, major cardiovascular events, and all-cause mortality (Table 3). In high-exposure regions, non-recreational physical activity did not significantly affect composite or cardiovascular outcomes, and the curve fluctuates steadily near HR = 1 (Fig. 2). The associations for the composite outcome and major cardiovascular events differed significantly between low- and high-exposure groups (p interaction = 0.011 and 0.024, respectively; Table 4). Significant antagonistic interactions were seen between high PM2.5 and low

Variables	Total (N = 39,970)	PM2.5 < 47.70 μg/m^3 (N = 20,793)	PM2.5 ≥ 47.70 μg/m^3 (N = 19,177)
PM2.5 concentration, μg/m^3	47.70 (31.77–75.10)	32.13 (30.20–42.93)	76.73 (54.13–88.90)
Location			
Urban	18,348 (45.9)	9030 (43.4)	9318 (48.6)
Rural	21,622 (54.1)	11,763 (56.6)	9859 (51.4)
Age, years	50.51 ± 9.52	50.71 ± 9.46	50.29 ± 9.58
Sex			
Female	23,394 (58.5)	12,276 (59.0)	11,118 (58.0)
Male	16,576 (41.5)	8517 (41.0)	8059 (42.0)
Education			
Primary or less	13,636 (34.2)	6534 (31.5)	7102 (37.2)
Secondary	20,798 (52.2)	11,316 (54.5)	9482 (49.6)
Trade/college/university	5423 (13.6)	2897 (14.0)	2526 (13.2)
BMI, kg/m^2	24.51 ± 3.65	24.19 ± 3.54	24.86 ± 3.73
Waist-to-hip ratio	0.86 ± 0.07	0.85 ± 0.07	0.86 ± 0.07
Abdominal obesity	16,292 (41.6)	8190 (39.6)	8102 (43.7)
Hypertension	16,413 (41.1)	8104 (39.0)	8309 (43.3)
Diabetes	2865 (7.2)	1517 (7.3)	1348 (7.0)
Tobacco use			
Former	1621 (4.1)	816 (4.0)	805 (4.2)
Current	9337 (23.6)	5200 (25.4)	4137 (21.7)
Never	28,526 (72.2)	14,439 (70.6)	14,087 (74.0)
Alcohol use			
Former	1123 (2.8)	566 (2.7)	557 (2.9)
Current	8786 (22.1)	4404 (21.4)	4382 (22.9)
Never	29,804 (75.0)	15,627 (75.9)	14,177 (74.2)
Total physical activity, MET × min per week	2361.0 (951.0–5290.5)	2367.0 (1035.0–4878.0)	2352.0 (858.0–5766.0)
Non-recreational physical activity, MET × min per week	1761.0 (693.0–4248.0)	1746.0 (743.0–3791.0)	1795.5 (630.0–4968.0)
Recreational physical activity, MET × min per week	118.8 (0.0–693.0)	198.0 (0.0–693.0)	0.0 (0.0–495.0)
Total physical activity			
Low	6680 (16.7)	3042 (14.6)	3638 (19.0)
Moderate	16,370 (41.0)	9075 (43.6)	7295 (38.0)
High	16,920 (42.3)	8676 (41.7)	8244 (43.0)
Meeting physical activity guidelines	33,290 (83.3)	17,751 (85.4)	15,539 (81.0)
Non-recreational physical activity			
Low	8495 (21.3)	4016 (19.3)	4479 (23.4)
Moderate	17,789 (44.6)	10,208 (49.2)	7581 (39.6)
High	13,642 (34.2)	6536 (31.5)	7106 (37.1)
Recreational physical activity			
Low	29,370 (73.5)	14,592 (70.3)	14,778 (77.1)
Moderate	9401 (23.5)	5439 (26.2)	3962 (20.7)
High	1176 (2.9)	739 (3.6)	437 (2.3)
Daily sitting time, hour/day	3.00 (1.64–4.49)	3.00 (1.71–4.57)	2.93 (1.50–4.29)
PURE diet score	3.00 ± 1.73	3.08 ± 1.71	2.91 ± 1.74
Depression	947 (2.4)	475 (2.3)	472 (2.5)
Household wealth index			
Tertile 1	13,027 (33.1)	6899 (33.7)	6128 (32.5)
Tertile 2	12,338 (31.4)	5618 (27.5)	6720 (35.6)
Tertile 3	13,960 (35.5)	7943 (38.8)	6017 (31.9)
Occupational class			
Professional/managers	4598 (11.5)	2669 (12.9)	1929 (10.1)
Skilled workers	13,739 (34.5)	7511 (36.2)	6228 (32.6)
Unskilled workers	14,412 (36.2)	6641 (32.0)	7771 (40.7)
Homemaker	7116 (17.9)	3941 (19.0)	3175 (16.6)
Household air pollution	15,602 (40.1)	9133 (45.0)	6469 (34.7)
Grip strength, kg	32.09 ± 10.30	32.01 ± 10.00	32.17 ± 10.62

(Table 1 continues on next page)

Variables	Total (N = 39,970)	PM2.5 < 47.70 μg/m³ (N = 20,793)	PM2.5 ≥ 47.70 μg/m³ (N = 19,177)
(Continued from previous page)			
Lipid measures, mmol/L			
Total cholesterol	4.58 ± 0.93	4.56 ± 0.94	4.61 ± 0.92
Non-HDL cholesterol	3.40 ± 0.81	3.37 ± 0.80	3.44 ± 0.83
Triglycerides	1.48 ± 1.17	1.51 ± 1.14	1.45 ± 1.21
LDL cholesterol	2.74 ± 0.77	2.68 ± 0.74	2.81 ± 0.79

Values are mean ± SD, median (IQR) or n (%). MET = metabolic equivalent task; PM = Particulate matter.

Table 1: **Baseline characteristics by the median of average PM2.5 concentration.**

non-recreational physical activity for the composite outcome (RERI: –0.215, 95% CI: –0.406 to –0.024; AP: –0.155, 95% CI: –0.294 to –0.017). Recreational physical activity was not significantly associated with the composite outcome, cardiovascular events, or all-cause mortality across activity levels (Fig. 3; Table 3), and showed no significant multiplicative or additive interactions with exposure to PM2.5.

For the components of major cardiovascular events, in low-exposure regions, higher total physical activity was associated with a reduced risk of cardiovascular mortality (highest vs. lowest: HR 0.71, 95% CI: 0.50–0.98, p for trend = 0.041) and stroke (highest vs. lowest: HR 0.81, 95% CI: 0.66–0.99, p for trend = 0.044) (Supplementary material, Table S7). However, no such association was observed in high-exposure regions. Increased total, recreational, or non-recreational physical activity was not significantly associated with lower risks of myocardial infarction or heart failure regardless of PM2.5 levels (Supplementary material, Tables S7 and S8).

For non-recreational physical activity, we observed that multiplicative interaction between occupational activity and PM2.5 exposure was statistically significant for the composite outcome, major cardiovascular events, and all-cause mortality (p for interaction = 0.002, 0.007, and 0.041, respectively). No significant interactions were found for transportation- or housework-related physical activity (Supplementary material, Table S9). Among participants in the low-exposure group, higher levels of

	PM2.5 < 47.70 μg/m³ (N = 20,793)				PM2.5 ≥ 47.70 μg/m³ (N = 19,177)			
	Low physical activity (N = 3042)	Moderate physical activity (N = 9075)	High physical activity (N = 8676)	p for trend	Low physical activity (N = 3638)	Moderate physical activity (N = 7295)	High physical activity (N = 8244)	p for trend
Composite outcome								
Events	375	920	745		482	943	1068	
Rate	10.00 (9.00–11.11)	7.94 (7.38–8.53)	6.42 (5.94–6.95)	<0.001	10.13 (9.23–11.11)	10.05 (9.38–10.76)	10.63 (9.98–11.32)	0.413
Major cardiovascular events								
Events	250	574	492		359	709	791	
Rate	6.79 (5.98–7.73)	5.01 (4.57–5.49)	4.30 (3.91–4.74)	<0.001	7.76 (6.97–8.64)	7.73 (7.15–8.37)	8.02 (7.46–8.63)	0.750
All-cause mortality								
Events	207	506	371		216	385	447	
Rate	4.93 (4.27–5.70)	3.94 (3.56–4.36)	2.87 (2.56–3.22)	<0.001	3.83 (3.32–4.42)	3.49 (3.12–3.91)	3.88 (3.50–4.30)	0.284
Cardiovascular mortality								
Events	73	141	112		87	138	155	
Rate	1.52 (1.18–1.96)	0.94 (0.77–1.15)	0.74 (0.60–0.93)	<0.001	1.40 (1.11–1.77)	1.14 (0.94–1.38)	1.24 (1.04–1.49)	0.323
Stroke								
Events	176	436	360		258	499	540	
Rate	4.75 (4.07–5.53)	3.75 (3.38–4.17)	3.11 (2.78–3.49)	<0.001	5.59 (4.93–6.34)	5.45 (4.96–5.99)	5.47 (5.01–5.97)	0.943
Myocardial infarction								
Events	62	137	121		96	191	238	
Rate	1.67 (1.29–2.16)	1.23 (1.02–1.48)	1.08 (0.89–1.31)	0.027	2.06 (1.67–2.53)	2.04 (1.76–2.37)	2.37 (2.08–2.71)	0.240
Heart failure								
Events	19	31	35		29	50	48	
Rate	0.42 (0.26–0.69)	0.21 (0.14–0.32)	0.24 (0.16–0.36)	0.078	0.46 (0.30–0.69)	0.39 (0.28–0.55)	0.37 (0.27–0.52)	0.694

Event rates are standardised for age and sex. Data are n, or n per 1000 person-years (95% CI). PM = Particulate matter.

Table 2: **Age-sex-standardised incidence rates across categories of total physical activity stratified by the median of average PM2.5 concentration.**

Physical activity (MET × minutes per week)	Hazard ratio (95% CI)			
	PM2.5 < 47.70 μg/m^3		PM2.5 ≥ 47.70 μg/m^3	
	Model 1	Model 2	Model 1	Model 2
Total physical activity				
Composite outcome				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.88 (0.77–0.99)	0.93 (0.82–1.07)	0.97 (0.87–1.09)	0.99 (0.88–1.12)
High (>3000)	0.79 (0.69–0.90)	0.84 (0.73–0.97)	0.96 (0.85–1.07)	0.97 (0.85–1.09)
p for trend	<0.001	0.012	0.457	0.551
Major cardiovascular events				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.78 (0.67–0.91)	0.83 (0.71–0.98)	0.97 (0.85–1.10)	0.97 (0.84–1.11)
High (>3000)	0.75 (0.64–0.89)	0.80 (0.67–0.95)	0.98 (0.86–1.12)	0.98 (0.85–1.13)
p for trend	0.003	0.022	0.885	0.864
All-cause mortality				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.93 (0.79–1.10)	1.02 (0.85–1.22)	0.93 (0.79–1.11)	1.00 (0.84–1.21)
High (>3000)	0.75 (0.62–0.89)	0.82 (0.68–1.00)	0.85 (0.72–1.02)	0.89 (0.73–1.07)
p for trend	<0.001	0.014	0.065	0.142
Non-recreational physical activity				
Composite outcome				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.87 (0.78–0.98)	0.91 (0.81–1.02)	1.00 (0.90–1.11)	1.00 (0.90–1.12)
High (>3000)	0.77 (0.67–0.87)	0.81 (0.71–0.93)	0.98 (0.87–1.09)	0.96 (0.86–1.09)
p for trend	<0.001	0.002	0.669	0.520
Major cardiovascular events				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.83 (0.73–0.96)	0.87 (0.75–1.00)	0.98 (0.87–1.10)	0.98 (0.87–1.12)
High (>3000)	0.75 (0.64–0.88)	0.79 (0.67–0.94)	0.98 (0.86–1.12)	0.96 (0.84–1.10)
p for trend	<0.001	0.007	0.794	0.538
All-cause mortality				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.87 (0.75–1.01)	0.92 (0.79–1.08)	0.97 (0.83–1.14)	1.00 (0.84–1.19)
High (>3000)	0.73 (0.62–0.87)	0.78 (0.65–0.94)	0.90 (0.76–1.06)	0.91 (0.76–1.09)
p for trend	<0.001	0.008	0.189	0.282
Recreational physical activity				
Composite outcome				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.91 (0.81–1.02)	0.91 (0.81–1.03)	1.00 (0.90–1.10)	1.04 (0.93–1.16)
High (>3000)	1.00 (0.78–1.28)	1.08 (0.84–1.39)	0.94 (0.72–1.21)	0.95 (0.72–1.26)
p for trend	0.271	0.529	0.738	0.717
Major cardiovascular events				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.88 (0.76–1.02)	0.89 (0.77–1.04)	0.98 (0.87–1.11)	1.03 (0.90–1.16)
High (>3000)	1.03 (0.77–1.38)	1.14 (0.84–1.54)	0.91 (0.67–1.24)	0.97 (0.71–1.34)
p for trend	0.319	0.623	0.602	0.841
All-cause mortality				
Low (<600)	Reference	Reference	Reference	Reference
Moderate (600–3000)	0.95 (0.81–1.11)	0.97 (0.82–1.15)	0.98 (0.84–1.14)	1.03 (0.87–1.21)
High (>3000)	0.79 (0.54–1.16)	0.84 (0.57–1.26)	0.92 (0.62–1.36)	0.79 (0.51–1.23)
p for trend	0.242	0.459	0.649	0.722

Model 1 was adjusted for age, sex, urban and rural location, and a random intercept for clustering of communities. Model 2 was additionally adjusted for education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, history of hypertension and diabetes. MET = metabolic equivalents; PM = Particulate matter.

Table 3: **Associations of total physical activity categories with outcomes stratified by the median of PM2.5 concentration.**

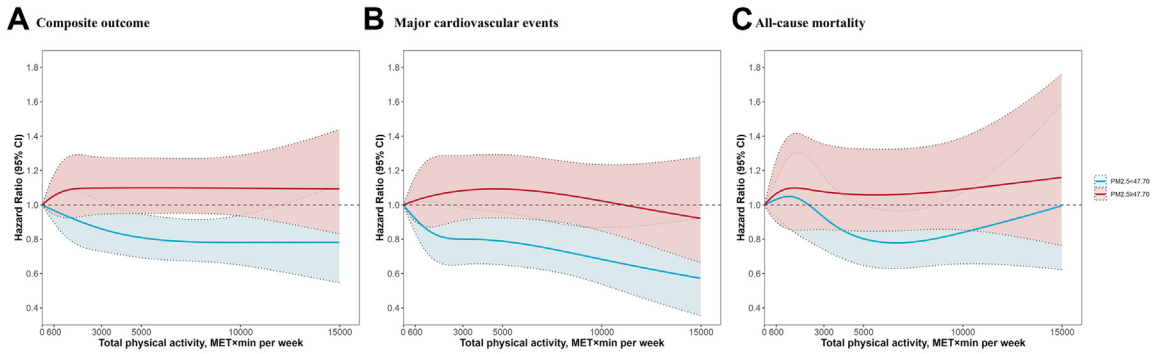

Fig. 1: **Associations of total physical activity with outcomes stratified by the median of average PM2.5 concentration.** Notes: (A) Composite outcome. (B) Major cardiovascular events. (C) All-cause mortality. Solid lines represent HRs, and the shaded areas represent 95% CIs. The models were adjusted for age, sex, urban and rural location, education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, and history of hypertension and diabetes. Physical activity data were truncated due to sparse observations beyond the respective thresholds. The composite outcome includes all-cause mortality and major cardiovascular events, defined as CVD mortality, incident myocardial infarction, stroke, and heart failure. Abbreviation: HR = hazard ratio; MET = metabolic equivalent task; PM = Particulate matter.

occupational physical activity were significantly associated with lower risks of composite outcomes and all-cause mortality (Model 2 HR for highest vs. lowest: 0.81 [0.68–0.96] and 0.73 [0.58–0.91], respectively; p-trend both < 0.05). In contrast, no protective associations were observed in the high-exposure group.

Sensitivity and subgroup analyses

We conducted several sensitivity analyses to examine the robustness of our findings. For our primary analysis, 36,086 (90.28%) participants had complete covariate data (Supplementary material, Table S10). After performing multiple imputation for incomplete covariate variables, the analysis yielded similar findings (Supplementary material, Table S11). Among participants exposed to average annual PM2.5 levels below 47.70 μg/m^3, higher total physical activity was associated with a reduced risk of the composite outcome (highest vs. lowest: HR 0.83, 95% CI: 0.72–0.95; p for trend = 0.005). Similarly, increased total physical activity was linked to a lower risk of major cardiovascular events (HR 0.80, 95% CI: 0.68–0.95; p for trend = 0.024). In contrast, no significant associations were observed in high-exposure regions. To address concerns about reverse causality, we excluded individuals with known cardiovascular disease and performed an analysis that further excluded those who experienced events during the first five years of follow-up. The results of this analysis were consistent with our primary findings (Supplementary material, Table S12). Furthermore, we performed sensitivity analyses using 5-year average PM2.5 concentrations, which also produced consistent results (Supplementary material, Table S13). To further assess the potential effect of medication use, we conducted a sensitivity analysis with additional adjustment for antihypertensive and statin use. The results remained materially unchanged, supporting the robustness of our findings (Supplementary material, Table S14).

In subgroup analyses, the protective associations of higher total and non-recreational physical activity with the composite outcome, major cardiovascular events, and all-cause mortality were more consistently observed among older adults, females, individuals with lower education or occupational class, and those without

	p for multiplicative interaction	RERI (95% CI)	AP (95% CI)
Low physical activity			
Composite outcome	0.062	−0.162 (−0.369, 0.044)	−0.118 (−0.269, 0.032)
Major cardiovascular events	0.038	−0.259 (−0.534, 0.015)	−0.165 (−0.340, 0.010)
All-cause mortality	0.539	−0.038 (−0.296, 0.220)	−0.034 (−0.263, 0.196)
Low non-recreational physical activity			
Composite outcome	0.011	−0.215 (−0.406, −0.024)	−0.155 (−0.294, −0.017)
Major cardiovascular events	0.024	−0.242 (−0.490, 0.005)	−0.154 (−0.310, 0.003)
All-cause mortality	0.321	−0.138 (−0.382, 0.106)	−0.122 (−0.337, 0.093)
Low recreational physical activity			
Composite outcome	0.264	−0.077 (−0.268, 0.113)	−0.056 (−0.193, 0.082)
Major cardiovascular events	0.329	−0.071 (−0.314, 0.171)	−0.045 (−0.200, 0.109)
All-cause mortality	0.861	−0.036 (−0.277, 0.206)	−0.032 (−0.250, 0.186)

Multiplicative interaction was assessed across three levels of physical activity and two levels of PM2.5 concentrations. For the additive interaction metrics, physical activity was categorized into two levels: low and moderate/high. Models were adjusted for age, sex, urban and rural location, education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, history of hypertension and diabetes, and a random intercept for clustering of communities. PM = Particulate matter; RERI = Relative excess risk due to interaction; AP = The proportion of disease attributable to interaction.

Table 4: **Interactive effects of PM2.5 concentration and physical activity on outcomes.**

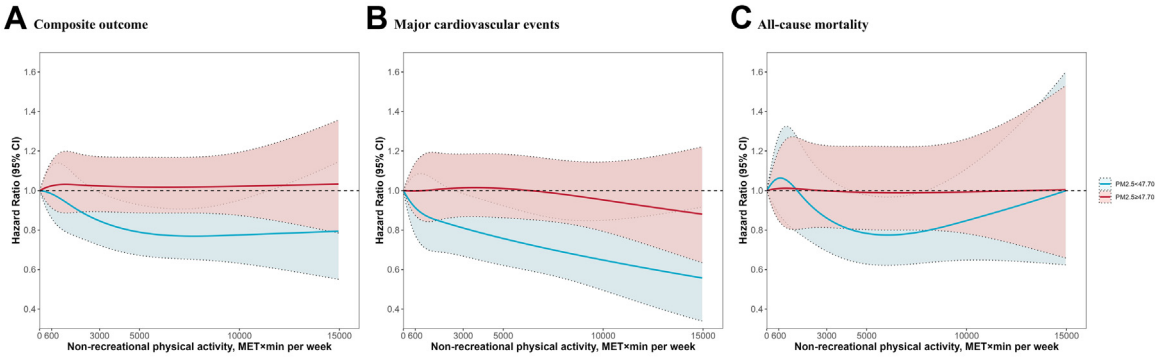

***Fig. 2:* Associations of non-recreational physical activity with outcomes stratified by the median of average PM2.5 concentration**. Notes: (A) Composite outcome. (B) Major cardiovascular events. (C) All-cause mortality. Solid lines represent HRs, and the shaded areas represent 95% CIs. The models were adjusted for age, sex, urban and rural location, education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, and history of hypertension and diabetes. Physical activity data were truncated due to sparse observations beyond the respective thresholds. The composite outcome includes all-cause mortality and major cardiovascular events, defined as CVD mortality, incident myocardial infarction, stroke, and heart failure. Abbreviation: HR = hazard ratio; MET = metabolic equivalent task; PM = Particulate matter.

hypertension—particularly in regions with lower PM2.5 exposure. These associations were not observed in high-exposure areas. Among all subgroups, notably, the interactions between total and non-recreational physical activity and sex in the low-exposure group were statistically significant for the composite outcome and all-cause mortality (p for interaction < 0.1). Detailed results are provided in Supplementary material, Tables S15–S19.

Discussion

In this study of 39,970 participants from 12 provinces across western, central, and eastern China, we investigated how outdoor fine particulate matter (PM2.5) interacts with physical activity to affect mortality and CVD. We observed significant differences in the associations of total and non-recreational physical activity with major cardiovascular events and a composite endpoint of major CVD events or death, depending on PM2.5 exposure. In particular, high PM2.5 exposure combined with low non-recreational physical activity showed significant antagonistic interactions for the composite outcome. These results suggest that high PM2.5 exposure may diminish the protective benefits of physical activity—particularly non-recreational activity—on mortality and cardiovascular events.

In regions with low PM2.5 levels (<47.70 μg/m^3), we observed a clear inverse dose-response relationship, whereby higher levels of physical activity were

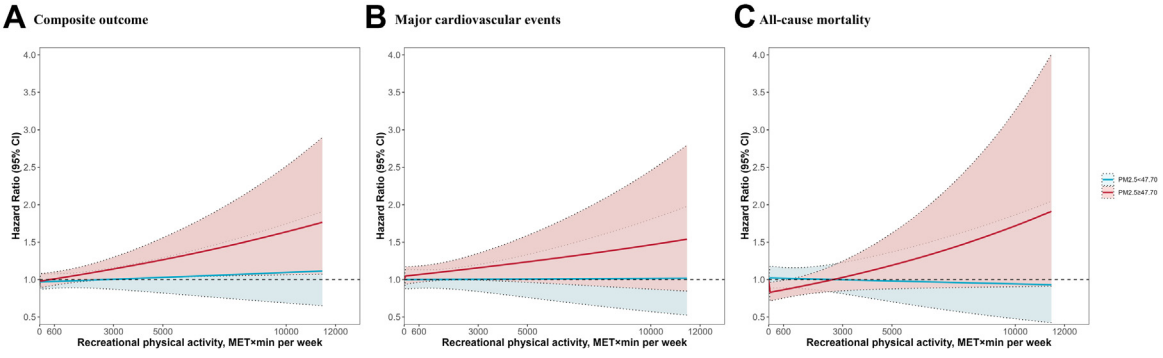

***Fig. 3:* Associations of recreational physical activity with outcomes stratified by the median of average PM2.5 concentration**. Notes: (A) Composite outcome. (B) Major cardiovascular events. (C) All-cause mortality. Solid lines represent HRs, and the shaded areas represent 95% CIs. The models were adjusted for age, sex, urban and rural location, education level, occupational class, household wealth index, use of solid fuels for cooking, smoking status, alcohol use, depression, PURE diet score, waist-to-hip ratio, BMI, daily sitting time, and history of hypertension and diabetes. Physical activity data were truncated due to sparse observations beyond the respective thresholds. The composite outcome includes all-cause mortality and major cardiovascular events, defined as CVD mortality, incident myocardial infarction, stroke, and heart failure. Abbreviation: HR = hazard ratio; MET = metabolic equivalent task; PM = Particulate matter.

associated with progressively lower hazard ratios—particularly for the composite outcome and major cardiovascular events. In contrast, among participants living in areas with high PM2.5 exposure (≥47.70 μg/m^3), the protective effect of physical activity appeared attenuated and largely plateaued with increasing activity levels. Several biological mechanisms may underlie these findings. In highly polluted environments, increased physical activity may lead to deeper and more frequent inhalation of pollutants, potentially counteracting its cardiovascular benefits.[36] PM2.5 has also been associated with systemic inflammation and heightened oxidative stress, both established risk factors for CVD.[37,38] Exposure to PM2.5 also leads to endothelial dysfunction, which is a critical factor in the progression of atherosclerosis and CVD.[39,40] This mechanism could explain why participants in areas with high PM2.5 do not experience the same protective effects of exercise seen in lower-exposure settings. Our findings align with a large South Korean study of 1,469,972 young adults.[19] In that study, participants who increased their physical activity from 0 to ≥1000 MET-min/week experienced a reduction in CVD risk when exposed to low-to-moderate levels of PM2.5 (HR: 0.73, 95% CI 0.52 to 1.03; p for trend 0.04). However, this protective effect was not evident under conditions of high pollution (HR: 1.33, 95% CI 0.96 to 1.84). Conversely, another research involving a three-year cohort of 59,115 adults in South Korea reported that engaging in moderate-to-vigorous physical activity more frequently was associated with a lower CVD risk irrespective of PM2.5 exposure levels.[17] The relatively lower concentrations and less variability of PM2.5 in this study (cutoff < 27.86 μg/m^3) may explain no observed effect modification. Our results also revealed that higher total physical activity was associated with a lower risk of cardiovascular mortality in low PM2.5 exposure regions; however, no such association was observed in high-exposure regions. The interaction between total physical activity and PM2.5 exposure on cardiovascular mortality was not statistically significant. This may partly reflect the lack of differentiation between types of physical activity. This finding mirrors results from a 10-year cohort study of 58,643 older adults in Hong Kong, which similarly found no difference in the relationship between physical activity and cardiovascular mortality when comparing high with low PM2.5 concentrations.[18]

Non-recreational physical activity (occupational, transportation, and housework) proved particularly crucial. A similar dose-response pattern was observed for non-recreational physical activity. In regions with low PM2.5 levels, higher engagement in non-recreational activities lowered the risks of composite outcome, major cardiovascular events, and all-cause mortality, but this protective effect was absent in high-exposure areas. This was supported by significant multiplicative and antagonistic interactions, indicating that individuals exposed to both high pollution and low activity levels face compound health risks.

Among the three non-recreational domains, occupational physical activity showed the strongest interaction with PM2.5 exposure. In low-exposure regions, higher occupational activity was consistently associated with reduced risks of cardiovascular events and mortality. However, in high-exposure areas, this benefit was not observed. This significant interaction suggested that long-term exposure to PM2.5 may substantially attenuate the cardiovascular benefits of occupational activity—an issue especially relevant in LMICs, where occupational activity is often more prevalent and unavoidable, and typically occurs in outdoor environments with higher pollution levels.[10,41] In contrast, transportation-related physical activity showed no significant associations and no significant interaction with PM2.5 levels, differing from findings in previous studies. For example, the China-PAR study observed a greater reduction in CVD risk from active commuting in areas with lower PM2.5 exposure, though no significant interaction was detected.[21] The China Kadoorie Biobank study reported that high PM2.5 exposure negated the protective effects of active commuting and farming activities.[20] One possible explanation for this discrepancy is that physical activity levels in our study were categorized based on total activity, which includes both recreational and non-recreational components. The same cut-offs were then applied to each non-recreational domain—including occupational, transportation, and housework—which are subcomponents of non-recreational activity. This classification approach may not accurately reflect the true intensity, frequency, or distribution of activity within each domain, and thus the domain-specific findings should be interpreted with caution. Overall, high pollution appears to offset the typical advantages of daily non-recreational activities, especially occupational activity. We also noted a plateau effect in regions with higher PM2.5 concentration, suggesting non-recreational activity may not yield additional health benefits under these conditions.

In contrast, recreational physical activity did not significantly reduce the risks of composite outcomes, cardiovascular events, or all-cause mortality across any PM2.5 level. The limited precision of this relationship might be because only 54% of participants reported engaging in recreational physical activity. No significant differences emerged between high and low PM2.5 groups, echoing the Nurses' Health Study, which found no disparity in cardiovascular outcomes associated with leisure-time exercise across different PM2.5 concentration levels.[16]

Physical activity remains a cornerstone of cardiovascular disease prevention. However, our findings suggest that high levels of air pollution may attenuate its protective effects. This highlights the need for integrated interventions that not only encourage physical

activity but also reduce exposure to PM2.5, particularly in regions with high ambient air pollution. Potential strategies include promoting cleaner energy sources, enforcing stricter emissions standards, and adopting urban planning approaches that minimize population-level exposure. These considerations are especially pertinent for LMICs, where air pollution levels are often higher and non-recreational physical activity—such as work-related or transport-related activity—is more prevalent.[10,41] In such settings, individuals are often exposed to harmful pollutants during routine physical activity, which may reduce or negate its cardiovascular benefits. Our findings suggest that while non-recreational physical activity is associated with cardiovascular benefits in low-pollution settings, these benefits may be diminished or absent in more polluted environments.

Accordingly, current physical activity guidelines may require adaptation for populations living in areas with poor air quality. Future recommendations could encourage safer forms of physical activity—such as indoor exercise, use of protective masks, or adjusting activity timing based on pollution levels— alongside broader environmental improvements, including workplace air filtration and accessible, low-emission public transportation. Tailoring these strategies to the specific challenges faced by LMICs will be essential to ensure that populations in these regions can safely and fully benefit from physical activity.

While our exposure assessment was based on ambient PM2.5 concentrations at the community level, individual exposure to fine particulate matter comprises both outdoor and indoor sources. Outdoor emissions from traffic, industry, and combustion processes infiltrate indoor spaces through mechanical ventilation, natural ventilation, and infiltration.[42] In addition, factors such as season, and the type of cooking or heating fuel used are strong predictors of indoor PM2.5 levels.[43] In this study, we adjusted for household solid fuel use as a proxy for indoor air pollution to reduce potential confounding. Given the observed attenuation of the cardiovascular benefits of physical activity by long-term outdoor PM2.5 exposure, future studies could aim to more precisely assess total personal exposure by incorporating direct measurements of both indoor and outdoor PM2.5, as well as detailed physical activity types and duration and ventilation characteristics. These efforts would enable a more accurate evaluation of how air pollution may modify the health effects of different domains of physical activity and help refine public health recommendations in polluted environments.

To our knowledge, this is the largest prospective study to comprehensively examine how both recreational and non-recreational physical activity modify cardiovascular disease and mortality risks in relation to long-term exposure to PM2.5 across a broad geographic area in China. However, our study has several limitations. First, physical activity was assessed using the self-reported IPAQ, which may slightly overestimate activity levels. Despite this, the IPAQ is a reliable and moderately valid tool compared to accelerometer-based measurements. Higher IPAQ scores generally correlate well with higher physical activity levels as measured by accelerometers, ensuring good internal validity.[29,44,45] Moreover, follow-up IPAQ data were not available, limiting our ability to assess changes in physical activity over time—an important factor when evaluating interactions between physical activity and air pollution on clinical outcomes.[19] We recommend that future analyses incorporate longitudinal assessments of physical activity. Second, we were unable to account for daily or seasonal variations in PM2.5 exposure, and we lacked annual estimates before 2010. Nevertheless, PM2.5 concentrations across PURE communities showed a high correlation ($r \geq 0.93$) over different periods.[9] Third, PM2.5 exposure was assigned based on the study community level (e.g., urban neighbourhoods and rural villages). While outdoor PM2.5 concentrations within these areas likely do not vary significantly, some exposure misclassification may still occur. Finally, our study focused solely on PM2.5 mass and did not consider the varying composition of PM2.5, which may differ substantially across PURE communities. In addition, our dataset lacked information on co-occurring air pollutants such as ozone, which may have influenced the observed associations.[46] The absence of these exposure data may have introduced unmeasured confounding or effect modification in the relationship between long-term PM2.5 exposure, physical activity, and outcomes. Moreover, we lacked the temporal resolution necessary to assess the impact of short-term pollution peaks. While short-term studies can capture acute physiological responses, they are often limited by small sample sizes, short follow-up durations, and a focus on subclinical endpoints.[47] In contrast, our long-term cohort design enables the assessment of cumulative exposure effects on major clinical outcomes. We recommend that future research incorporate more detailed information on pollutant composition, co-pollutants, and short-term exposure variability to better understand the complex interactions between air pollution, physical activity, and cardiovascular risk.

Contributors

S.Y. and W.Li designed this analysis and obtained funding. J.H. and Z.L. have contributed equally to this work. J.H. and Z.L. verified the data, had access to raw data and took responsibility for the accuracy of the data analysis. J.H. and Z.L. drafted the manuscript and participated in data acquisition and interpretation. S.R. coordinated the Prospective Urban Rural Epidemiology (PURE) study and B.H. coordinated the PURE-China study. D.W., Y.W. and C.W. provided technical and material support. L.A.T., W. Liu, S.L., M.Y. and Q.C. provided critical comments and revisions of the manuscript. All authors approved the final manuscript and had final responsibility for the decision to submit for publication.

Data sharing statement

The Population Health Research Institute (PHRI), as the funder of this analysis, underscores the critical importance of disseminating research findings and emphasizes the significance of data sharing. PHRI prioritizes granting data access to researchers who have been long-term participants in the Prospective Urban Rural Epidemiology (PURE) study, made substantial contributions to PURE, and participated in securing research funding. Data access is granted upon approval of a data usage proposal by the PURE Review Committee. PHRI permits collaboration with external research teams on specific joint analysis projects, provided there is reciprocal data exchange and the proposal enhances PURE study findings. The foundational data for this analysis includes participants' personal information and health information, which are protected under Canadian privacy laws, the U.S. Health Insurance Portability and Accountability Act (HIPAA) of 1996, the European Union's General Data Protection Regulation (GDPR), and other international privacy regulations. Since consent for public disclosure has not been obtained, public sharing could compromise data confidentiality and violate privacy laws. Therefore, individual-level data are generally accessible only to PURE researchers. PHRI does not oppose data sharing under strict confidentiality and adherence to appropriate data protection and privacy measures, which can be discussed on a case-by-case basis. PHRI adheres to this policy and will not publicly share or link clinical research data, particularly those involving personal health information. Requests for data access should be directed to the PURE Publication Committee and the PHRI Research Project Office (phri.contracts@phri.ca).

Editor note

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Declaration of interests

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lanwpc.2025.101584.

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