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Long-term exposure to ambient particulate matter is associated with prognosis in people living with HIV/AIDS: Evidence from a longitudinal study

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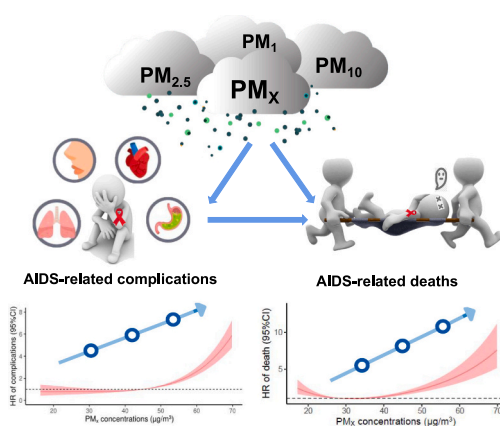[e] School of Resource and Environmental Science, Wuhan University, 115# Donghu Road, Wuhan 430071, China
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HIGHLIGHTS

- Study examined particulate matter impacts on prognosis in people with HIV/AIDS.
- Particulate matter exposure raises the risk of AIDS-related deaths and complications.
- AIDS-related complications have mediating effects in PM-induced AIDS-related deaths.

GRAPHICAL ABSTRACT

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ABSTRACT

Background: Evidence on the association between particulate matter (PM) exposure and prognosis in people living with HIV/AIDS (PWHA) is scarce. We aim to investigate the associations of long-term exposure to PM with AIDS-related deaths and complications.
Methods: We collected follow-up information on 7444 PWHAs from 2000 to 2021 from the HIV/AIDS Comprehensive Response Information Management System of the Wuhan Center for Disease Control and

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Prognosis
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Prevention. The AIDS-related deaths and complications were assessed by physicians every 3 to 6 months, and the monthly average PM concentrations for each PWHA were extracted from the China High Air Pollutants dataset. We employed time-varying Cox regression models to evaluate the associations of the average cumulative PM exposure concentrations with AIDS-related deaths and complications, as well as the mediating effects of AIDS-related complications in PM-induced AIDS-related deaths.

Results: For each 1 $\mu g/m^3$ increase in PM_1, $PM_{2.5}$, and PM_{10}, the adjusted hazard ratios (HRs) for AIDS-related deaths were 1.021 (1.009, 1.033), 1.012 (1.005, 1.020), and 1.010 (1.005, 1.015), respectively; and the HRs for AIDS-related complications were 1.049 (1.034, 1.064), 1.029 (1.020, 1.038), and 1.031 (1.024, 1.037), respectively. AIDS-related complications mediated 18.38 % and 18.68 % of the association of exposure to PM_1 and $PM_{2.5}$ with AIDS-related deaths, respectively. The association of PM exposure with AIDS-related deaths was more significant in older PWHA. Meanwhile, the association between PM exposure and AIDS-related complications was stronger in PWHA with a BMI $\geq$ 24 kg/m^2.

Conclusion: Long-term exposure to PM is positively associated with AIDS-related deaths and complications, and AIDS-related complications have mediating effects in PM-induced AIDS-related deaths. Our evidence emphasizes that enhanced protection against PM exposure for PWHAs is an additional mitigation strategy to reduce AIDS-related deaths and complications.

1. Introduction

Acquired immunodeficiency syndrome (AIDS) is a significant global public health problem (Govender et al., 2021). Despite the global expenditure of over $500 billion on AIDS prevention, care, and treatment between 2000 and 2015 (Global Burden of Disease Health Financing Collaborator Network, 2018), there were still 1.7 million people reported to be newly infected with HIV globally in 2019 (Hemelaar et al., 2020). AIDS remains the underlying cause of nearly 1 million deaths year (GBD 2017 Causes of Death Collaborators, 2018; Hemelaar et al., 2020). According to the latest data from the World Health Organization (WHO), the global number of people living with HIV/AIDS (PWHA) was approximately 37.7 million in 2020 (Cherie et al., 2022). Furthermore, the global disability-adjusted life year (DALY) for HIV had shifted from 33rd in 1990 to 11th in 2019, with a 58.5 % increase in the age-standardized DALY rate (GBD 2019 Diseases and Injuries Collaborators, 2020). Considering the incurable nature of AIDS and its substantial disease burden, it is crucial to investigate potentially modifiable risk factors to prevent AIDS-related deaths and complications.

Ambient particulate matter (PM) already carries a significant burden on public health (Ho et al., 2023b). A recent study reported that 4.58 million deaths and 142.52 million DALYs worldwide in 2017 attribute to fine particulate matter ($PM_{2.5}$) exposure (Bu et al., 2021). Accumulating evidence suggested that PM exposure was closely related to premature mortality from a wide range of illnesses such as cardiovascular disease, cancer, respiratory disease (Bo et al., 2022; Hayes et al., 2020; Khomenko et al., 2021; Pun et al., 2017). Furthermore, PM exposure was also associated with adverse perinatal outcomes, immunologic abnormality, pulmonary hypertension, and abnormal kidney function (Chen et al., 2019; Ghosh et al., 2021; Glencross et al., 2020; Ho et al., 2023a; Rasking et al., 2022; Zhang et al., 2022c). However, studies examining the association between PM exposure and prognosis in PWHAs are scarce.

A study conducted in Uganda showed that daily $PM_{2.5}$ exposure was positively related to carotid intima-media thickness in HIV-infected adolescents (β: 0.005, 95%CI: 0.001, 0.009) (Toe et al., 2022). Meanwhile, air pollution was also found to be related to cognitive decline and respiratory symptoms of PWHAs (North et al., 2019; Suter et al., 2018). Pneumocystis pneumonia (PCP) is a prevalent complication in PWHAs. The serological assessment of responses to Pneumocystis jirovecii relies on the major surface glycoprotein (Msg). A cohort study revealed that each 10 $\mu g/m^3$ increase in PM_{10}, the IgM response to the Pneumocystis jirovecii Msg reduced by a range of 25 % to 35.0 % (Blount et al., 2013). This reduction in IgM response was strongly associated with adverse clinical prognosis. Furthermore, a case-crossover study demonstrated that each 1 $\mu g/m^3$ increase in the 4-day moving average levels of PM_1, $PM_{2.5}$, and PM_{10}, the risk of AIDS-related deaths increased by 2.51 %, 1.25 %, and 0.65 %, respectively (Zhang et al., 2022a). Notably, the

above-described studies were all cross-sectional, with a small sample size, and only explored the association of air pollution with a single AIDS-related adverse outcome, which may not comprehensively reflect the association of PM exposure with prognosis in PWHAs.

Accordingly, we hypothesize that long-term exposure to PM may contribute to the development of AIDS-related complications and act as mediators for AIDS-related deaths, so PM exposure may indirectly increase the mortality of PWHAs. In the present study, the information of PWHAs who lived in Wuhan, China, from 2000 and 2021 was collected, and the PM exposure concentrations for each participant were assessed. We aim to explore the associations of long-term exposure to PM with AIDS-related deaths and complications and open a new perspective for studying prognostic factors in PWHAs.

2. Methods

2.1. Study population

In this study, data on the subjects were obtained from the HIV/AIDS Comprehensive Response Information Management System (CRIMS) of the Wuhan Center for Disease Control and Prevention (Wuhan CDC). When people with HIV/AIDS were detected, staff from the Wuhan CDC will conduct epidemiological investigations for them and enroll all subjects into CRIMS for management. Simultaneously, subjects' age, sex, education level, and other basic personal information will be recorded in the system. According to the Chinese government's guidelines, it was mandatory for all patients to undergo follow-up assessments every 3 to 6 months. The follow-up regimen included regular blood tests to evaluate liver and kidney function, the monitoring of CD4 + T cell counts, tracking for AIDS-related complications and adverse drug reactions, as well as assessing the patient's survival status.

This study was an open cohort with 7444 PWHAs enrolled, and the baseline time was defined as the moment when persons were diagnosed with HIV infection. The inclusion process of PWHAs is illustrated in Fig. 1. Firstly, we derived 8501 PWHAs from the CRIMS and collected their basic personal information, follow-up visits, and treatment plans from January 1, 2000, to December 31, 2021. Secondly, we excluded 51 individuals with information missing, 52 individuals who were diagnosed before the age of 18, 13 individuals not permanently residing in Wuhan, 4 individuals who were diagnosed before 2000, 916 individuals who did not receive antiviral medications treatment, and 21 individuals who died from non-HIV-related diseases. Ultimately, a total of 7444 PWHAs, who were permanent residents of Wuhan, were admitted to this study at baseline. This study was approved by the ethics committee of the Wuhan CDC (WHCDCIRB-K-2022027).
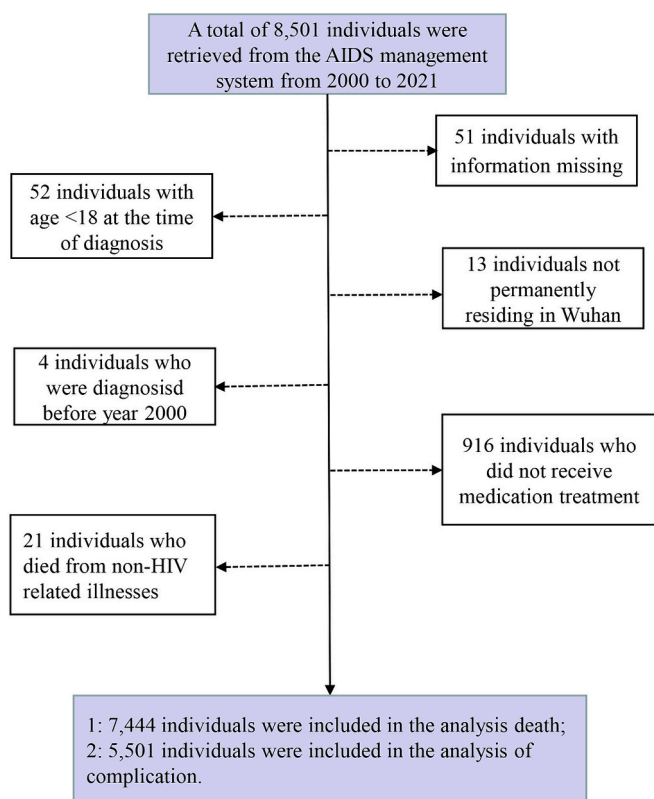
Fig. 1. Flowchart for inclusion of study subjects.

2.2. Outcome definition

The information on AIDS-related complications and deaths was registered in CRIMS. Our study focused on two outcomes, including AIDS-related complications and deaths which were coded by the International Classification of Disease 10th revision (ICD-10). AIDS-related complications were diagnosed by physicians and defined as suffering from one or more diseases, including infectious and parasitic diseases caused by HIV (B20.0-B20.9), malignant tumors caused by HIV (B21.0-B21.2, B21.3, B21.7-B21.9), and other specific diseases caused by HIV (B22.0, B22.1, B22.7). AIDS-related deaths were also diagnosed by physicians and classified as AIDS opportunistic infections (A1.1-A1.5), AIDS-related tumors (A2.1-A2.7), and AIDS-related specific syndromes (A3.1-A3.4). During each follow-up visit, physicians evaluated PWHAs for any AIDS-related complications and continued monitoring their condition until death, even if they had experienced complications. For the analysis of AIDS-related complications, we excluded those with pre-existing complications at baseline and included individuals who developed complications during follow-up.

2.3. Exposure assessment

We obtained the monthly average concentrations of PM_1, $PM_{2.5}$, PM_{10}, ozone (O_3), and nitrogen dioxide (NO_2) from the China High Air Pollutants dataset (https://weijing-rs.github.io/product.html), which was a publicly available, validated, and widely used database. The methodology for the prediction of air pollutants in this database has been published and can be found elsewhere (Wei et al., 2019; Wei et al., 2021a; Wei et al., 2020; Wei et al., 2022; Wei et al., 2021b; Wei et al., 2023). In short, we integrated satellite remote sensing products, ground-based measurements, land-use coverage, surface elevation, population density, and pollutant emissions in the space-time extremely randomized trees (STET) models. Then, we can estimate the PM levels at a spatial resolution of 1 km × 1 km, along with the O_3 and NO_2 levels at a

spatial resolution of 10 km × 10 km from the models. The cross-validated R^2 values for the daily average prediction of PM_1, $PM_{2.5}$, PM_{10}, O_3, and NO_2 were 0.83, 0.92, 0.90, 0.87, and 0.84, respectively; with root-mean-square errors of 6.17 μg/m^3, 6.32 μg/m^3, 11.22 μg/m^3, 17.10 μg/m^3, and 7.99 μg/m^3, respectively.

Each individual's residential address was geocoded for latitude and longitude via Google Maps, which was implemented by the data administrators at the Wuhan CDC. After obtaining the geocoded information, we matched the encoded data with the pollutants. The concentrations of air pollutants were extracted from the nearest grid cell to the residential address and assigned to the corresponding individual. Our study assessed the exposure levels by calculating the monthly average cumulative concentrations of air pollutants to which each PWHA was exposed during the follow-up period. This average concentration was calculated from the time of HIV diagnosis until the appearance of outcome indicators or until the follow-up cutoff date.

2.4. Covariates

The covariates were obtained from the CRIMS, medical records systems of the designated AIDS treatment hospitals, questionnaires, and telephone follow-up visits. We collected demographic information on individuals including age, sex, body mass index (BMI), education level (junior middle school, senior middle school, and college or above), marital status (unmarried, married, and divorced), and occupation (outdoor worker, indoor worker, and unknown). Habits and health status included infection status (HIV and AIDS), smoking status (never, former, and current), drinking status (never, former, and current), hypertension (no and yes), diabetes (no and yes), and coronary heart disease (no and yes). HIV treatment medications in Wuhan can be divided into four types, including reverse transcriptase inhibitors, non-nucleoside reverse transcriptase inhibitors, protease inhibitors, and integrase inhibitors. Therefore, we divided the treatment programs into two groups: highly active antiretroviral therapy (HAART), which involved a combination of three antiviral medications; and non-HAART, which involved using only one or two antiviral medications. Considering the potential influence of CD4 + T cells on prognosis, we obtained the record of CD4 + T cell counts at baseline as a covariate. Furthermore, the average cumulative ambient temperature and relative humidity during the follow-up periods were also used as covariates. The monthly average temperature at a spatial resolution of 1 km × 1 km was obtained from the National Tibetan Plateau Data Center (https://doi.org/10.11888/Meteoro.tpdc.270961) and extracted using the same method as for extracting air pollutants data. The monthly average relative humidity was collected from the National Meteorological Science Data Centre (http://data.cma.cn/) and matched with the closest meteorological detection station to the residential address.

2.5. Statistical analyses

We performed time-varying Cox proportional hazards models with follow-up time as the timescale to estimate the association of the average cumulative PM concentrations with the incidence of AIDS-related deaths and complications. We conducted a test for the proportional hazards (PH) assumption on the model. In instances where a specific variable did not meet the PH assumption, we addressed this issue by introducing time-dependent covariates. Each PWHA was followed up from the diagnosis to death or loss of follow-up, and Hazard ratios (HRs) and their 95 % confidence intervals (CIs) were reported to estimate the associations of PM (per 1 μg/m^3 increase) with AIDS-related deaths and complications. Three regression models were performed in our analyses. Model 1 was a crude model without adjusting for any covariates. Model 2 was adjusted for age, sex, BMI, education level, marital status, occupation, smoking status, drinking status, temperature, and relative humidity. Model 3 was the main model, and we further adjusted for infection status, treatment programs, CD4 + T cell counts, hypertension,

diabetes, and coronary heart disease based on model 2 according to the covariate selection suggested by the directed acyclic graph (Fig. S1).

Exposure-response association between the PM concentrations and each outcome was modeled using restricted cubic spline (RCS) regressions with 3 knots (5th, 50th, and 95th). We also performed mediation analysis using generalized linear models to explore whether AIDS-related complications, assessed at the final follow-up, mediated the association of PM exposure with the incidence of AIDS-related deaths. The proportion of mediation was determined by dividing the indirect effect by the total effect. Furthermore, we conducted subgroup analyses stratified by sex (male and female), the age criteria for the elderly in China (<60 and ≥ 60) (Li et al., 2022), and the Chinese criteria for overweight (<24 kg/m^2 and ≥ 24 kg/m^2) (Sun et al., 2010) to explore potential effect modifiers. Meanwhile, interaction variables were included to assess potential covariate effects.

Several sensitive analyses were performed to test the robustness of our primary results. 1) We employed Fine-Gray models to recalculate the correlation between PM exposure and AIDS-related deaths and complications; 2) To determine the effects of various treatment programs on outcomes, we excluded individuals who did not receive HAART treatment to ensure all PWHAs were treated with the same program, thereby reducing bias from different antiviral medication; 3) We excluded individuals whose residential address changed during the follow-up periods to eliminate possible bias in our study due to geographic changes; 4) Individuals with follow-up durations of <6 months were excluded from the model to decrease bias due to the short follow-up periods; 5) We further adjusted O$_3$ and NO$_2$ separately based on the main model to test whether gaseous pollutants influenced our findings. It should be noted that we excluded patients with HIV/AIDS diagnosed before 1 January 2013 from the sensitivity analyses because data for NO$_2$ and O$_3$ in China were available from 2013. All statistical analyses were performed using R software 4.1.4 with a two-sided significance level of 0.05.

3. Results

3.1. Description of the study sample and exposure

The characteristics of the 7444 participants included in this study are shown in Table 1. The cohort was followed up for a total of 33,926.6 person-years, with a median follow-up duration of 4.05 years. Our study revealed that the average age was 37.7 ± 15.0 years old and the average BMI was 21.6 ± 3.06 kg/m^2 for participants. The majority of participants were male (90.3 %), indoor workers (53.3 %), unmarried (55.3 %), and had a college education or above (47.5 %). Additionally, 67 % of participants were diagnosed with HIV infection but not yet progressed to AIDS, and 93.8 % of participants received HAART. Furthermore, it was observed that 73.3 % of participants never smoke, 73.7 % of participants never drink, while 10.2 %, 5.8 %, and 2.6 % of participants were diagnosed with hypertension, diabetes, and coronary heart disease, respectively.

The PM concentrations in Wuhan showed increasing annual trends from 2000 (31.9 μg/m^3 for PM$_1$, 52.9 μg/m^3 for PM$_{2.5}$, 88.7 μg/m^3 for PM$_{10}$) to 2013 (50.0 μg/m^3 for PM$_1$, 83.7 μg/m^3 for PM$_{2.5}$, 129.7 μg/m^3 for PM$_{10}$) but steady decreasing trends after 2013. The particulates with larger diameters had higher concentrations throughout. Meanwhile, AIDS mortality showed a significant upward trend before 2006, peaked in 2006, and showed a similar downward trend since 2006 (Fig. 2).

In the mortality risk analysis, a total of 390 deaths were observed, corresponding to an incidence rate of 11.5 per 1000 person-years. Moreover, among 7444 PWHAs included at baseline time, there were 1943 PWHAs had developed AIDS-related complications when they were diagnosed with HIV infection. During the follow-up periods, a total of 488 new cases with AIDS-related complications were observed among individuals without any pre-existing complications at baseline, yielding an incidence rate of 24.1 per 1000 person-years. Fig. S2 displays the

Table 1

Descriptive characteristics of study subjects at baseline.

Variables	Total ($N = 7444$)
Total person-year	33,930.7
Follow-up time, years (Median $\pm$ IQR)	4.05 ± 4.95
Age, years, (Mean $\pm$ SD)	37.7 ± 15.0
BMI, kg/m^2 (Mean $\pm$ SD)	21.6 ± 3.06
Sex, n (%)	
Male	6720 (90.3)
Female	724 (9.7)
Infection status, n (%)	
HIV	4596 (61.7)
AIDS	2848 (38.3)
Treatment program, n (%)	
Non-HAART	464 (6.2)
HAART	6980 (93.8)
Education, n (%)	
Junior	1962 (26.4)
Senior	1945 (26.1)
College or above	3537 (47.5)
Occupation, n (%)	
Outdoor worker	2962 (39.8)
Indoor worker	3966 (53.3)
Unknown	516 (6.9)
Marriage, n (%)	
Unmarried	4114 (55.3)
Married	1650 (22.2)
Divorced	1680 (22.6)
Smoking status, n (%)	
Never	5454 (73.3)
Former	661 (8.9)
Current	1329 (17.9)
Drinking status, n (%)	
Never	5489 (73.7)
Former	545 (7.3)
Current	1410 (19.0)
Hypertension, n (%)	757 (10.2)
Diabetes, n (%)	434 (5.8)
Coronary heart disease, n (%)	192 (2.6)
CD4 + T, cells/ul (Mean $\pm$ SD)	330.5 ± 208.3

Abbreviation: SD, standard deviation; IQR, interquartile range; BMI, body mass index; HIV, human immunodeficiency virus; AIDS, acquired immunodeficiency syndrome; HAART, highly active antiretroviral therapy.

distribution of AIDS-related deaths and new cases with AIDS-related complications per year during the follow-up periods.

The distribution and Spearman correlation between meteorological factors and the PM concentrations can be found in Table S1. The mean PM exposure levels of 7444 participants during the follow-up periods were 29.6 ± 8.01 μg/m^3 for PM$_1$, 47.9 ± 12.8 μg/m^3 for PM$_{2.5}$, and 79.0 ± 18.7 μg/m^3 for PM$_{10}$. These three PM levels showed strong correlations with each other, and they also moderately correlated with temperature and relative humidity.

3.2. Associations of PM exposure with AIDS-related deaths and complications

Long-term exposure to PM$_1$, PM$_{2.5}$, and PM$_{10}$ was positively associated with the incidence of AIDS-related deaths and complications (Table 2). For each 1 μg/m^3 increase in PM$_1$, PM$_{2.5}$, and PM$_{10}$, the fully
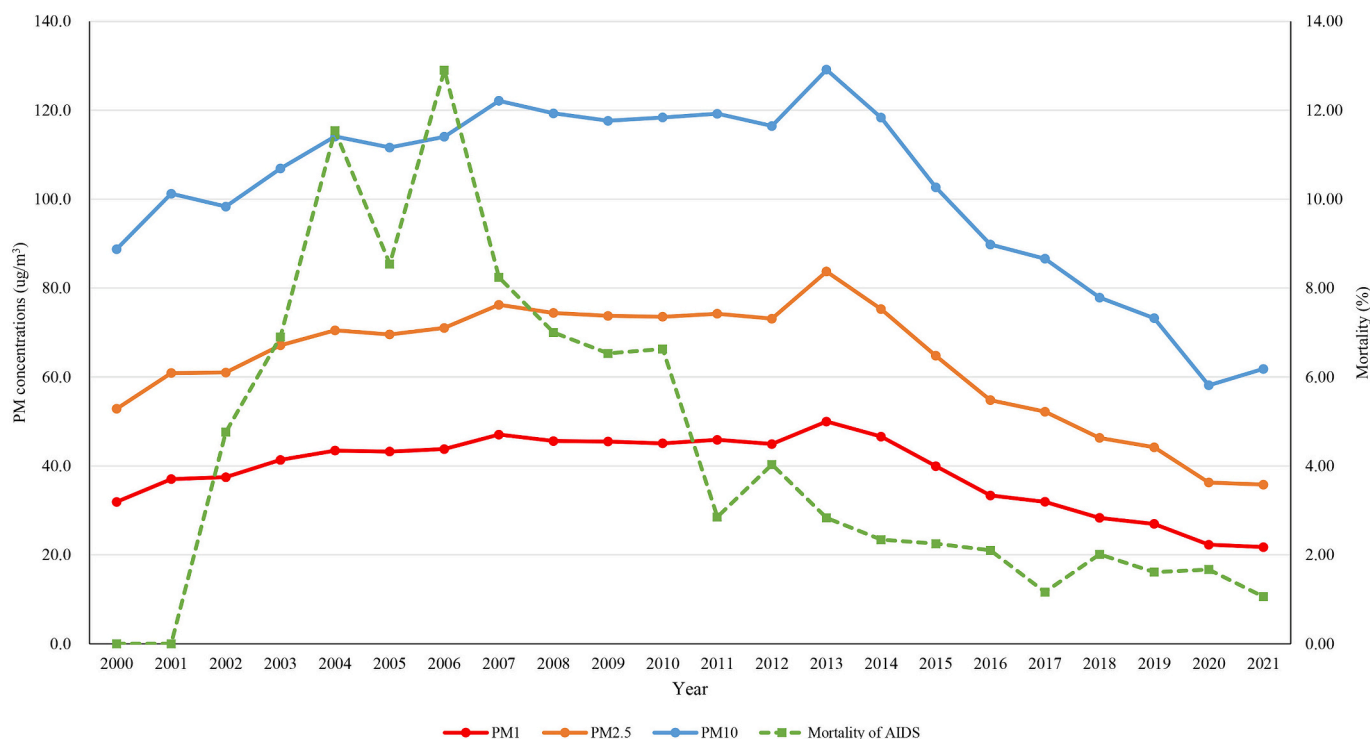
Fig. 2. The levels of particulate matter and mortality of AIDS in Wuhan from 2000 to 2021.

Table 2
Associations of long-term particulate matter exposures with risk of AIDS-related deaths and complications in people with HIV/AIDS.

Outcomes	Pollutants	Model 1	Model 2	Model 3
HR of AIDS-related deaths (95 % CI)	PM_1	1.050 (1.039, 1.061)	1.031 (1.019, 1.043)	1.021 (1.009, 1.033)
	$PM_{2.5}$	1.031 (1.024, 1.037)	1.019 (1.012, 1.026)	1.012 (1.005, 1.020)
	PM_{10}	1.023 (1.018, 1.027)	1.014 (1.010, 1.020)	1.010 (1.005, 1.015)
HR of AIDS-related complications (95 % CI)	PM_1	1.074 (1.065, 1.083)	1.053 (1.038, 1.070)	1.049 (1.034, 1.064)
	$PM_{2.5}$	1.043 (1.038, 1.048)	1.031 (1.022, 1.040)	1.029 (1.020, 1.038)
	PM_{10}	1.038 (1.034, 1.042)	1.032 (1.026, 1.038)	1.031 (1.024, 1.037)

Results are presented for the following increments: 1 μg/m^3 for PM_1, 1 μg/m^3 for $PM_{2.5}$, and 1 μg/m^3 for PM_{10}.
Model 1 did not adjust for any covariant.
Model 2 adjusted for age, sex, body mass index, education, marital status, occupation, smoking status, drinking status, temperature, and relative humidity.
Model 3 adjusted for age, sex, body mass index, education, marital status, occupation, smoking status, drinking status, temperature, relative humidity, infection status, treatment program, CD4 + T cell count, hypertension, diabetes, and coronary heart disease.
Abbreviation: PM_1: particulate matter with an aerodynamic diameter of ≤1 μm; $PM_{2.5}$, particulate matter with an aerodynamic diameter of ≤2.5 μm; PM_{10}: particulate matter with an aerodynamic diameter of ≤10 μm; HR, hazard ratio; CI, confidence intervals.

adjusted HRs (95%CIs) of AIDS-related deaths were 1.021 (1.009, 1.033), 1.012 (1.005, 1.020), and 1.010 (1.005, 1.015), respectively; and the fully adjusted HRs (95%CIs) for AIDS-related complications were 1.049 (1.034, 1.064), 1.029 (1.020, 1.038), and 1.031 (1.024, 1.037), respectively. RCS showed the exposure-response relationship curves between the PM concentrations and AIDS-related deaths showed decreasing trends at the low concentrations and then showed increasing trends with increasing concentrations. On the other hand, the exposure-response relationship curves between the PM concentrations and AIDS-related complications showed slowly increasing trends at the low concentrations but sharply increasing trends after the concentrations above a certain threshold (Fig. 3).

3.3. Mediation analysis and effect modification

Our mediation analysis revealed that AIDS-related complications mediated 18.38 % and 18.68 % of the association of exposure to PM_1 and $PM_{2.5}$ with AIDS-related deaths, respectively (Fig. 4A and B); however, had no mediating effects on the association of PM_{10} with AIDS-

related deaths (Fig. 4C). The results of effect modification analyses stratified by sex, age, and BMI are presented in Fig. 5. We observed that the relationship between PM exposure and AIDS-related deaths was more significant in older PWHA compared with younger PWHA, with corresponding HRs (95%CI) of 1.052 (1.032, 1.073) versus 1.024 (1.011, 1.037) for PM_1, 1.031 (1.019, 1.043) versus 1.015 (1.007, 1.023) for $PM_{2.5}$, and 1.023 (1.014, 1.032) versus 1.011 (1.006, 1.017) for PM_{10}. Furthermore, the associations of PM_1, $PM_{2.5}$, and PM_{10} with the risk of AIDS-related complications were stronger in PWHA with BMI ≥24 kg/m^2 compared to those with BMI < 24 kg/m^2 (P-interaction <0.05).

3.4. Sensitivity analyses

We performed several sensitivity analyses to evaluate the reliability and consistency of our results based on different statistical models, treatment programs, changes in residential address, length of follow-up, and adjustment of gaseous pollutants. The results of this study remain robust and the details can be obtained in Tables S2–S6.
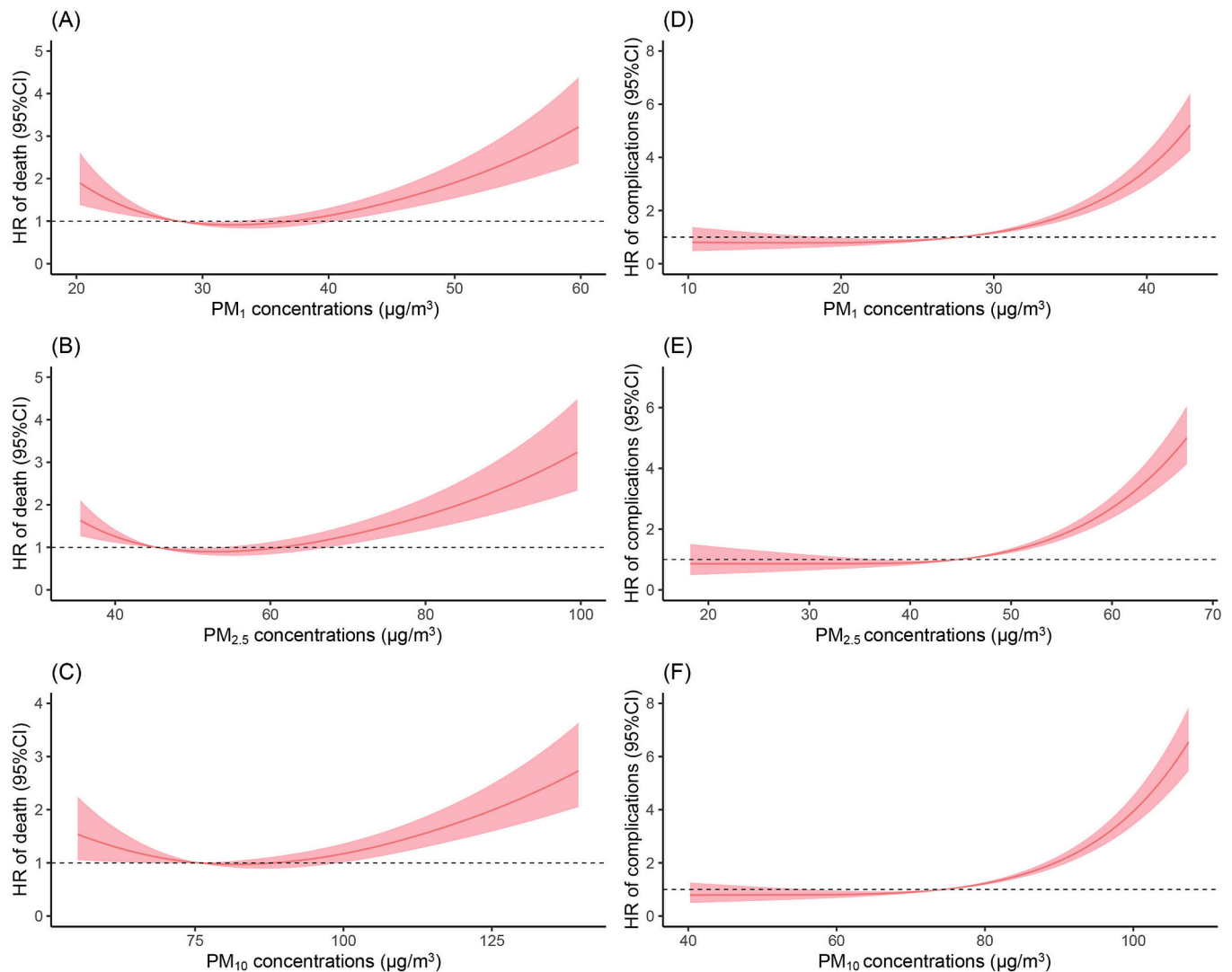
Fig. 3. Exposure-response curves for the association between particulate matter exposures and outcome indicators. The effect estimate is presented as a red line, and pink areas represent 95%CI. Models were adjusted for age, sex, body mass index, education, marital status, occupation, smoking status, drinking status, temperature, relative humidity, infection status, treatment program, CD4 + T cell counts, hypertension, diabetes, and coronary heart disease.

4. Discussion

To our knowledge, this was the first large-sample longitudinal study to examine the association between long-term exposure to PM and prognosis in PWHAs. Our results showed that long-term exposure to PM_1, $PM_{2.5}$, and PM_{10} was positively related to the incidence of AIDS-related deaths and complications. The AIDS-related complications partially mediated the association of exposure to PM_1 and $PM_{2.5}$ with the incidence of AIDS-related deaths. Notably, PM_1 showed a more pronounced effect size compared to $PM_{2.5}$ and PM_{10}. Moreover, the associations of PM exposure with AIDS-related deaths and complications were more significant in older PWHA. Meanwhile, the associations of PM exposure with AIDS-related complications were stronger in PWHA with a BMI $\geq$24 kg/m^2.

Over the past two decades, Wuhan has experienced rapid industrialization. Concurrently, PM concentrations in Wuhan exhibited a gradual increase from 2000 to 2013, followed by a subsequent decline. This trend change was attributed to the introduction of the Air Pollution Prevention and Control Action Plan in 2013 (The State Council of China, 2013). Owing to the relatively low total number of PWHAs, the mortality of AIDS in Wuhan showed a fluctuating yet gradual upward trajectory until 2006. China implemented the widespread distribution of

free antiretroviral therapy in 2005 and the effective AIDS prevention and control regulations in January 2006. Following these interventions, the consistently decreased AIDS mortality was observed over time (The State Council of China, 2006); furthermore, a consistent pattern emerged in Wuhan where the AIDS mortality and the ambient PM concentrations showed simultaneous declines. The fluctuation trajectory of ambient PM was partially consistent with variations in the AIDS mortality.

Our study observed a positive association of long-term exposure to $PM_{2.5}$ and PM_{10} with the risk of AIDS-related deaths and also provided evidence that long-term exposure to PM_1 significantly increased the risk of AIDS-related deaths. A previous study conducted in Spain revealed that the elevated PM_{10} concentrations were related to the mortality due to PCP in HIV-infected patients between 1997 and 2011 (Alvaro-Meca et al., 2015). Likewise, another study conducted in China showed that each 1 μg/m^3 increase in the 1-year average $PM_{2.5}$ (1.65 %, 95%CI: 1.14, 2.17) and PM_{10} (0.90 %, 95%CI, 0.56, 1.24) concentrations were associated with the increased risk of AIDS-related deaths (Zhang et al., 2023b). Furthermore, a study in the southeastern US reported that the mortality risk for the elderly, a vulnerable group, increased by 2.1 % with each 1 μg/m^3 increase in the annual average $PM_{2.5}$ concentrations between 2000 and 2013 (Wang et al., 2017). Since PWHAs have weaker
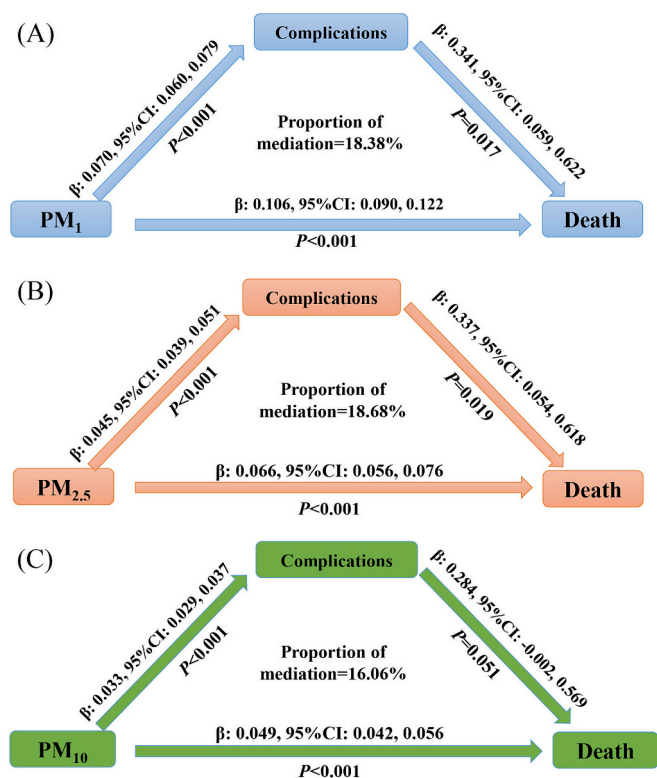
Fig. 4. The mediation effect of AIDS-related complications on the association of PM$_1$ PM$_{2.5}$, and PM$_{10}$ and with AIDS-related deaths. Models were adjusted for age, sex, body mass index, education, marital status, occupation, smoking status, drinking status, temperature, relative humidity, infection status, treatment program, CD4 + T cell counts, hypertension, diabetes, and coronary heart disease.

immune systems, they are more susceptible to the harmful effects of PM exposure. Our findings reported that AIDS-related complications partially mediated the association of exposure to PM$_1$ (18.38 %) and PM$_{2.5}$ (18.68 %) with the elevated risk of AIDS-related deaths. Exposure to PM has been linked to an increase in HIV replication, exacerbating the compromise of the immune systems of PWHAs (Liang et al., 2023). This heightened viral replication, in turn, contributes to an elevated incidence of opportunistic infections and various complications, thereby amplifying the risk of AIDS-related deaths. Based on this, the susceptibility of PWHAs to the hazards caused by PM exposure is higher, which calls for urgent action to mitigate the adverse effects. Reducing PM exposure can potentially improve prognosis in PWHAs. Therefore, our findings highlight the urgent need for policymakers to implement appropriate measures for reducing the PM levels and promoting the PWHAs' health.

Studies on the association between PM exposure and AIDS-related complications in PWHAs are rare. In the limited number of studies, Toe observed that HIV-positive patients exposed to the high PM$_{2.5}$ levels increased the risk of atheromatous lesions (Toe et al., 2022). Besides, another study showed that PM$_{10}$ (each 10 μg/m^3 increase) was linked to the decreased IgM response to the Pneumocystis jirovecii Mgs (β: 35 %, 95%CI: 9.1 %, 61 %) (Blount et al., 2013). Our study found the positive associations of PM$_1$, PM$_{2.5}$, and PM$_{10}$ exposures with the risk of AIDS-related complications. For each 1 μg/m^3 increase in PM$_1$, PM$_{2.5}$, and PM$_{10}$, the HRs for AIDS-related complications increased by 4.9 %, 2.9 %, and 3.1 %, respectively. The biological mechanisms underlying the increased risk of AIDS-related complications in PWHAs exposed to PM have not been fully clarified. Previous studies have reported that PM exposure may induce oxidative stress and systemic inflammation, consequently resulting in respiratory symptoms and adverse

cardiovascular diseases (Lu et al., 2022; Sierra-Vargas et al., 2023; Wang et al., 2021). Additionally, exposure to PM may potentially disrupt the normal immunoglobulin levels, triggering overactivation of the Notch signaling pathway, thus leading to immune dysfunction. (Gu et al., 2017). One study based on HIV/AIDS patients reported that PM exposure may lead to reduced immunity in PWHAs (Liang et al., 2023), thereby contributing to the development of opportunistic infections in PWHAs (Zhanget al., 2022a). In brief, PM can impair the immune function of PWHAs via a series of mechanisms, ultimately increasing the risk of AIDS-related complications.

In addition, we found that PM$_1$ had stronger associations with AIDS-related deaths and complications than PM$_{2.5}$ and PM$_{10}$, which was consistent with the growing evidence suggesting that smaller size fractions were associated with more severe health effects (Chen et al., 2017; Lin et al., 2016). For instance, research conducted in 11 cities in China demonstrated that PM$_1$ was significantly linked to an increased risk of all-cause mortality, as well as the mortality of cardiovascular disease, stroke, respiratory disease, and chronic obstructive pulmonary disease compared to PM$_{2.5}$ and PM$_{10}$ (Hu et al., 2018). Meanwhile, Chen observed that co-exposure to ambient PM$_1$ and PM$_{2.5}$ was significantly associated with the increasing number of visits to the emergency department of hospitals, and PM$_1$ accounted for the primary health effects among PM$_{2.5}$ components (Chenet al., 2017). Possible reasons for this phenomenon could be explained by the smaller diameter of PM$_1$ makes it more easily deposited in the alveoli, penetrates blood vessels, and enters the circulation, leading to a stronger inflammatory response and oxidative stress (Kan, 2017). In addition, the smaller diameter of PM$_1$ allows it to remain suspended in the atmosphere for a longer period and attach more toxic components (Izhar et al., 2016; Song et al., 2022). Therefore, it is crucial for the government to recognize the harmful effects of PM$_1$ and incorporate it into environmental monitoring indicators.

In age-stratified analyses, the associations between PM exposure and AIDS-related deaths were stronger in older PWHA compared with younger PWHA, with corresponding HRs of 1.052 versus 1.024 for PM$_1$, 1.031 versus 1.015 for PM$_{2.5}$, and 1.023 versus 1.011 for PM$_{10}$, which was in line with previous study (Zhang et al., 2023a; Zhanget al., 2023b). Elderly individuals, burdened by a spectrum of underlying health conditions, including but not limited to cardiovascular diseases, diabetes, and hypertension, exhibit diminished resilience, rendering them more susceptible to the adverse effects of atmospheric PM. Furthermore, our results showed that the association of PM with AIDS-related complications was more significant in overweight PWHAs. Previous research revealed that overweight persons were more susceptible to PM compared with normal-weight persons (Dubowsky et al., 2006; Li et al., 2021; Wu et al., 2023; Zhang et al., 2022b). This difference in susceptibility could be attributed to the inherent inflammatory state and the higher inhalation rate in obese persons (Brochu et al., 2014; Dubowsky et al., 2006). Obesity-induced chronic inflammation caused by macrophage infiltration into adipose tissue is believed to be a crucial mechanism by which PM affects human health (Cinti, 2009; Sacks et al., 2011). Moreover, overweight individuals may increase tidal and minute ventilation at rest, leading to inhalation of more PM (Bennett and Zeman, 2004). Therefore, overweight PWHAs may inhale more PM, which can exacerbate the inflammatory response and ultimately increase the risk of AIDS-related complications. Our findings emphasize the significance of protecting vulnerable populations, especially overweight populations, from the adverse effects of PM. Accordingly, targeted interventions must be developed to reduce PM exposure in overweight PWHAs.

Some limitations in this study must be mentioned. Firstly, the utilization of high-resolution satellite-based spatiotemporal models in evaluating PM exposure data, despite their advantages in handling large samples and extended follow-up periods, introduces a possible misclassification. For example, the inability to precisely measure indoor and outdoor exposures, compounded by variations in personal
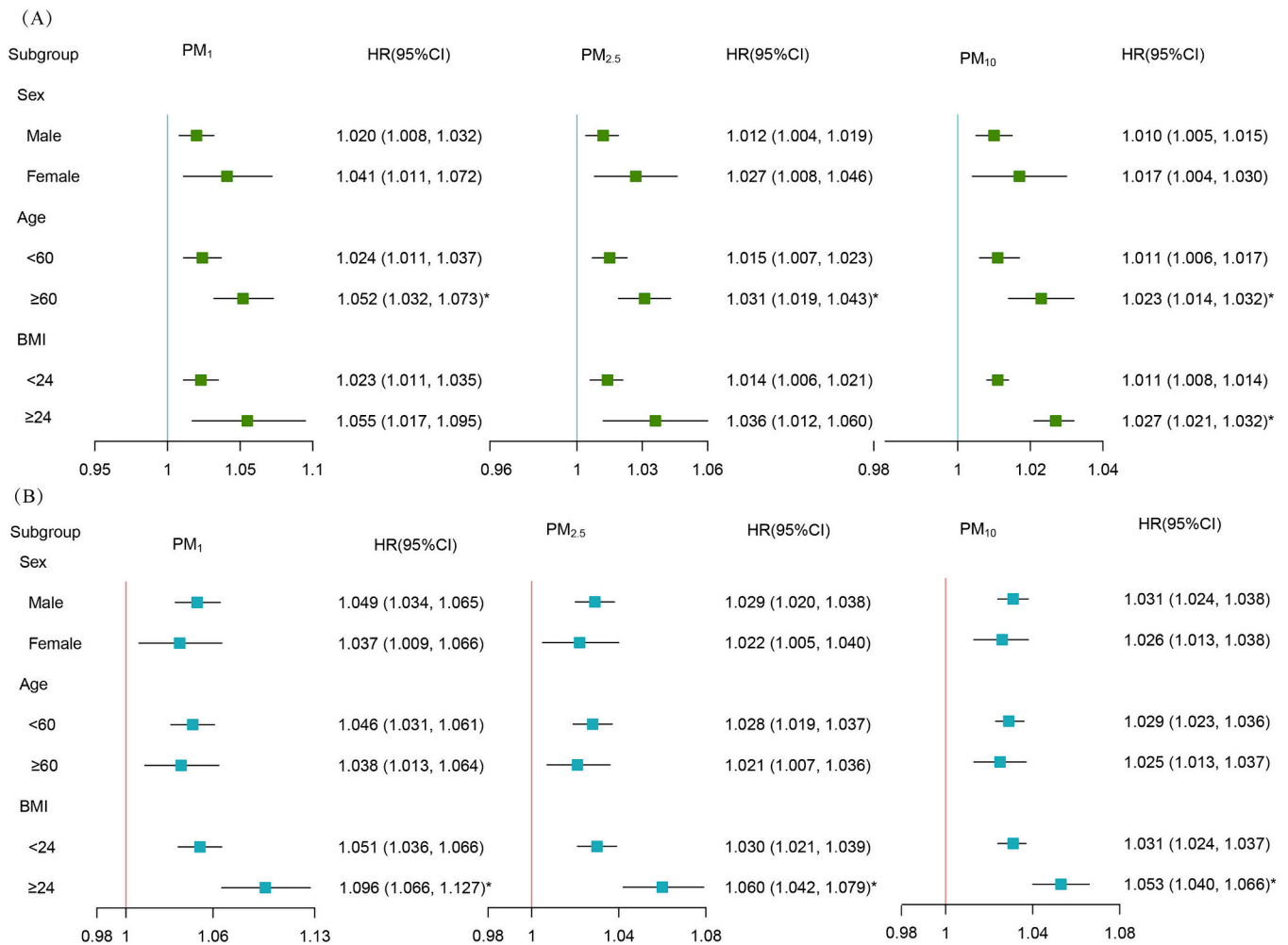
（A）

Subgroup	PM$_1$	HR(95%CI)	PM$_{2.5}$	HR(95%CI)	PM$_{10}$	HR(95%CI)
Sex						
Male		1.020 (1.008, 1.032)		1.012 (1.004, 1.019)		1.010 (1.005, 1.015)
Female		1.041 (1.011, 1.072)		1.027 (1.008, 1.046)		1.017 (1.004, 1.030)
Age						
<60		1.024 (1.011, 1.037)		1.015 (1.007, 1.023)		1.011 (1.006, 1.017)
≥60		1.052 (1.032, 1.073)*		1.031 (1.019, 1.043)*		1.023 (1.014, 1.032)*
BMI						
<24		1.023 (1.011, 1.035)		1.014 (1.006, 1.021)		1.011 (1.008, 1.014)
≥24		1.055 (1.017, 1.095)		1.036 (1.012, 1.060)		1.027 (1.021, 1.032)*

（B）

Subgroup	PM$_1$	HR(95%CI)	PM$_{2.5}$	HR(95%CI)	PM$_{10}$	HR(95%CI)
Sex						
Male		1.049 (1.034, 1.065)		1.029 (1.020, 1.038)		1.031 (1.024, 1.038)
Female		1.037 (1.009, 1.066)		1.022 (1.005, 1.040)		1.026 (1.013, 1.038)
Age						
<60		1.046 (1.031, 1.061)		1.028 (1.019, 1.037)		1.029 (1.023, 1.036)
≥60		1.038 (1.013, 1.064)		1.021 (1.007, 1.036)		1.025 (1.013, 1.037)
BMI						
<24		1.051 (1.036, 1.066)		1.030 (1.021, 1.039)		1.031 (1.024, 1.037)
≥24		1.096 (1.066, 1.127)*		1.060 (1.042, 1.079)*		1.053 (1.040, 1.066)*

Fig. 5. The stratified analyses of the associations of long-term particulate matter exposure with the risk of AIDS-related deaths and complications based on the main model. (A) Stratified analyses between PM and AIDS-related deaths. (B) Stratified analyses between PM and AIDS-related complications. * indicates that P for interaction is statistically significant ($P < 0.05$).

protective measures, further complicates accurate exposure assessment. Secondly, although we adjusted for many potential confounders in this study, we lacked information regarding family income, dietary habits, and physical activity, which could potentially introduce bias. However, we mitigated this limitation to some extent by including occupation and education level in our adjustments, as these factors are highly correlated with the above variables. Thirdly, throughout the duration of our study's follow-up period, we only identified 488 new instances of AIDS-related complications. Consequently, we chose not to divide AIDS-related complications into specific subtypes to achieve statistical power. Fourthly, the majority of participants in this study are men, and there are recognized differences in the morbidity and mortality of many diseases between women and men, so these findings must be applied with caution to women infected with HIV. Fifthly, we acknowledge that our analysis fails to account for certain factors, such as medical advances and changes in socioeconomic conditions, and this limitation may have introduced bias into our results.

5. Conclusion

In summary, our study found the positive associations of long-term exposure to PM with AIDS-related complications and deaths. Moreover, the AIDS-related complications partially mediated the association of exposure to PM$_1$ and PM$_{2.5}$ with AIDS-related deaths. Our evidence emphasizes that developing measures to enhance protection against PM

exposure for PWHAs is an additional mitigation strategy to reduce AIDS-related deaths and complications. For vulnerable populations such as HIV/AIDS patients, policy measures could include restricting their employment in industries with high exposure to air pollutants. Through the use of television, text messaging, and electronic bulletin boards, vulnerable groups can be alerted to areas experiencing high pollution levels, with advisories to avoid these areas. The present study opens a new perspective for studying prognostic factors in PWHAs. In the future, the biological mechanisms of PM exposure and prognosis in PWHAs should be further investigated in depth based on the evidence from this longitudinal study, thereby clarifying the associations of PM exposure with AIDS-related complications and deaths.

CRediT authorship contribution statement

Wei Liang: Conceptualization, Formal analysis, Writing –original draft. **Ruihan Li**: Writing – review & editing, Software, Data curation. **Gongbo Chen**: Project administration, Formal analysis. **Hongfei Ma**: Investigation. **Aojing Han**: Data curation. **Qilin Hu**: Data curation. **Nianhua Xie**: Data curation. **Jing Wei**: Methodology. **Huanfeng Shen**: Supervision. **Xia Wang**: Supervision, Conceptualization, Validation. **Hao Xiang**: Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.172453.

References

Alvaro-Meca, A., Palomares-Sancho, I., Diaz, A., Resino, R., De Miguel, A.G., Resino, S., 2015. Pneumocystis pneumonia in HIV-positive patients in Spain: epidemiology and environmental risk factors. J. Int. AIDS Soc. 18, 19906.

Bennett, W.D., Zeman, K.L., 2004. Effect of body size on breathing pattern and fine-particle deposition in children. J. Appl. Physiol. (1985) 97, 821–826.

Blount, R.J., Djawe, K., Daly, K.R., Jarlsberg, L.G., Fong, S., Balmes, J., et al., 2013. Ambient air pollution associated with suppressed serologic responses to Pneumocystis jirovecii in a prospective cohort of HIV-infected patients with Pneumocystis pneumonia. PloS One 8, e80795.

Bo, Y., Yu, T., Chang, L.Y., Guo, C., Lin, C., Zeng, Y., et al., 2022. Combined effects of chronic PM2.5 exposure and habitual exercise on cancer mortality: a longitudinal cohort study. Int. J. Epidemiol. 51, 225–236.

Brochu, P., Bouchard, M., Haddad, S., 2014. Physiological daily inhalation rates for health risk assessment in overweight/obese children, adults, and elderly. Risk Anal. 34, 567–582.

Bu, X., Xie, Z., Liu, J., Wei, L., Wang, X., Chen, M., et al., 2021. Global PM2.5-attributable health burden from 1990 to 2017: estimates from the Global Burden of disease study 2017. Environ. Res. 197, 111123.

Chen, G., Li, S., Zhang, Y., Zhang, W., Li, D., Wei, X., et al., 2017. Effects of ambient PM(1) air pollution on daily emergency hospital visits in China: an epidemiological study. Lancet Planet Health 1, e221–e229.

Chen, J., Ma, W.M., Yuan, J.L., Cui, L.Q., 2019. PM2.5 exposure aggravates left heart failure induced pulmonary hypertension. Acta Cardiol. 74, 238–244.

Cherie, S., Workie, H., Kassie, T., Bitew, A., Samuel, T., 2022. Pregnant women's knowledge, attitude, and practice towards the prevention of mother to child transmission of HIV/AIDS in Dil Chora Referral Hospital, Dire Dawa, Eastern Ethiopia: a cross-sectional study. HIV AIDS (Auckl) 14, 45–60.

Cinti, S., 2009. Transdifferentiation properties of adipocytes in the adipose organ. Am. J. Physiol. Endocrinol. Metab. 297, E977–E986.

Dubowsky, S.D., Suh, H., Schwartz, J., Coull, B.A., Gold, D.R., 2006. Diabetes, obesity, and hypertension may enhance associations between air pollution and markers of systemic inflammation. Environ. Health Perspect. 114, 992–998.

GBD 2017 Causes of Death Collaborators, 2018. Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392, 1736–1788.

GBD 2019 Diseases and Injuries Collaborators, 2020. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lance 396, 1204–1222.

Ghosh, R., Causey, K., Burkart, K., Wozniak, S., Cohen, A., Brauer, M., 2021. Ambient and household PM2.5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories. PLoS Med. 18, e1003718.

Glencross, D.A., Ho, T.R., Camiña, N., Hawrylowicz, C.M., Pfeffer, P.E., 2020. Air pollution and its effects on the immune system. Free Radic. Biol. Med. 151, 56–68.

Global Burden of Disease Health Financing Collaborator Network, 2018. Spending on health and HIV/AIDS: domestic health spending and development assistance in 188 countries, 1995–2015. Lancet 391, 1799–1829.

Govender, R.D., Hashim, M.J., Khan, M.A., Mustafa, H., Khan, G., 2021. Global epidemiology of HIV/AIDS: a resurgence in North America and Europe. J Epidemiol Glob Health 11, 296–301.

Gu, X.Y., Chu, X., Zeng, X.L., Bao, H.R., Liu, X.J., 2017. Effects of PM2.5 exposure on the Notch signaling pathway and immune imbalance in chronic obstructive pulmonary disease. Environ. Pollut. 226, 163–173.

Hayes, R.B., Lim, C., Zhang, Y., Cromar, K., Shao, Y., Reynolds, H.R., et al., 2020. PM2.5 air pollution and cause-specific cardiovascular disease mortality. Int. J. Epidemiol. 49, 25–35.

Hemelaar, J., Elangovan, R., Yun, J., Dickson-Tetteh, L., Kirtley, S., Gouws-Williams, E., et al., 2020. Global and regional epidemiology of HIV-1 recombinants in 1990-2015: a systematic review and global survey. Lancet HIV 7, e772–e781.

Ho, T.H., Van Dang, C., Pham, T.T.B., Thi Hien, T., Wangwongwatana, S., 2023a. Ambient particulate matter (PM2.5) and adverse birth outcomes in Ho Chi Minh City. Vietnam. Hygiene and Environmental Health Advances 5, 100049.

Ho, T.H., Van Dang, C., Pham, T.T.B., Wangwongwatana, S., 2023b. Assessment of health and economic benefits of reducing fine particulate matter (PM2.5) concentration in Ho Chi Minh City, Vietnam. Hygiene and Environmental Health Advances 6, 100045.

Hu, K., Guo, Y., Hu, D., Du, R., Yang, X., Zhong, J., et al., 2018. Mortality burden attributable to PM(1) in Zhejiang province. China. Environ Int. 121, 515–522.

Izhar, S., Goel, A., Chakraborty, A., Gupta, T., 2016. Annual trends in occurrence of submicron particles in ambient air and health risk posed by particle bound metals. Chemosphere 146, 582–590.

Kan, H., 2017. The smaller, the worse? Lancet Planet Health 1 e210-e211.

Khomenko, S., Cirach, M., Pereira-Barboza, E., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., et al., 2021. Premature mortality due to air pollution in European cities: a health impact assessment. Lancet Planet Health 5, e121–e134.

Li, X., Wang, M., Song, Y., Ma, H., Zhou, T., Liang, Z., et al., 2021. Obesity and the relation between joint exposure to ambient air pollutants and incident type 2 diabetes: a cohort study in UK Biobank. PLoS Med. 18, e1003767.

Li, F.D., Tong, Z.D., Chang, Y., Li, K.F., Gu, X., Zhang, T., et al., 2022. Eggs consumption in relation to lower risk of cognitive impairment in elderly: findings from a 6-year cohort study. J. Nutr. Health Aging 26, 771–777.

Liang, W., Wang, X., Xie, N., Yan, H., Ma, H., Liu, M., et al., 2023. Short-term associations of PM2.5 and PM2.5 constituents with immune biomarkers: a panel study in people living with HIV/AIDS. Environ. Pollut. 317, 120743.

Lin, H., Tao, J., Du, Y., Liu, T., Qian, Z., Tian, L., et al., 2016. Particle size and chemical constituents of ambient particulate pollution associated with cardiovascular mortality in Guangzhou. China. Environ Pollut. 208, 758–766.

Lu, X., Gong, C., Lv, K., Zheng, L., Li, B., Zhao, Y., et al., 2022. Impacts of combined exposure to formaldehyde and PM(2.5) at ambient concentrations on airway inflammation in mice. Environ. Pollut. 315, 120234.

North, C.M., MacNaughton, P., Lai, P.S., Vallarino, J., Okello, S., Kakuhikire, B., et al., 2019. Personal carbon monoxide exposure, respiratory symptoms, and the potentially modifying roles of sex and HIV infection in rural Uganda: a cohort study. Environ. Health 18, 73.

Pun, V.C., Kazemiparkouhi, F., Manjourides, J., Suh, H.H., 2017. Long-term PM2.5 exposure and respiratory, cancer, and cardiovascular mortality in older US adults. Am. J. Epidemiol. 186, 961–969.

Rasking, L., Vanbrabant, K., Bové, H., Plusquin, M., De Vusser, K., Roels, H.A., et al., 2022. Adverse effects of fine particulate matter on human kidney functioning: a systematic review. Environ. Health 21, 24.

Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S., et al., 2011. Particulate matter-induced health effects: who is susceptible? Environ. Health Perspect. 119, 446–454.

Sierra-Vargas, M.P., Montero-Vargas, J.M., Debray-García, Y., Vizuet-de-Rueda, J.C., Loaeza-Román, A., Terán, L.M., 2023. Oxidative stress and air pollution: its impact on chronic respiratory diseases. Int. J. Mol. Sci. 24, 853.

Song, J., Ding, Z., Zheng, H., Xu, Z., Cheng, J., Pan, R., et al., 2022. Short-term PM(1) and PM(2.5) exposure and asthma mortality in Jiangsu Province, China: What's the role of neighborhood characteristics? Ecotoxicol. Environ. Saf. 241, 113765.

Sun, L., Yu, Z., Ye, X., Zou, S., Li, H., Yu, D., et al., 2010. A marker of endotoxemia is associated with obesity and related metabolic disorders in apparently healthy Chinese. Diabetes Care 33, 1925–1932.

Suter, M.K., Karr, C.J., John-Stewart, G.C., Gómez, L.A., Moraa, H., Nyatika, D., et al., 2018. Implications of combined exposure to household air pollution and HIV on neurocognition in children. Int. J. Environ. Res. Public Health 15, 163.

The State Council of China, 2006. AIDS Prevention and Control Regulations.

The State Council of China, 2013. Air Pollution Prevention and Control Action Plan. The State Council of China.

Toe, S., Nagy, M., Albar, Z., Yu, J., Sattar, A., Nazzinda, R., et al., 2022. Ambient air pollution is associated with vascular disease in Ugandan HIV-positive adolescents. Aids 36, 863–870.

Wang, Y., Shi, L., Lee, M., Liu, P., Di, Q., Zanobetti, A., et al., 2017. Long-term exposure to PM2.5 and mortality among older adults in the southeastern US. Epidemiology 28, 207–214.

Wang, Y., Xiong, L., Yao, Y., Ma, Y., Liu, Q., Pang, Y., et al., 2021. The involvement of DRP1-mediated caspase-1 activation in inflammatory response by urban particulate matter in EA.hy926 human vascular endothelial cells. Environ. Pollut. 287, 117369.

Wei, J., Li, Z., Guo, J., Sun, L., Huang, W., Xue, W., et al., 2019. Satellite-derived 1-km-resolution PM(1) concentrations from 2014 to 2018 across China. Environ. Sci. Technol. 53, 13265–13274.

Wei, J., Li, Z.Q., Cribb, M., Huang, W., Xue, W.H., Sun, L., et al., 2020. Improved 1 km resolution PM2.5 estimates across China using enhanced space-time extremely randomized trees. Atmospheric Chemistry and Physics 20, 3273–3289.

Wei, J., Li, Z., Xue, W., Sun, L., Fan, T., Liu, L., et al., 2021a. The ChinaHighPM(10) dataset: generation, validation, and spatiotemporal variations from 2015 to 2019 across China. Environ. Int. 146, 106290.

Wei, J., Li, Z.Q., Lyapustin, A., Sun, L., Peng, Y.R., Xue, W.H., et al., 2021b. Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications. Remote Sens. Environ. 252, 112136.

Wei, J., Li, Z.Q., Li, K., Dickerson, R.R., Pinker, R.T., Wang, J., et al., 2022. Full-coverage mapping and spatiotemporal variations of ground-level ozone (O3) pollution from 2013 to 2020 across China. Remote Sens. Environ. 270, 112775.

Wei, J., Li, Z.Q., Wang, J., Li, C., Gupta, P., Cribb, M., 2023. Ground-level gaseous pollutants (NO2, SO2, and CO) in China: daily seamless mapping and spatiotemporal variations. Atmos. Chem. Phys. 23, 1511–1532.

Wu, Y., Gasevic, D., Wen, B., Yu, P., Xu, R., Zhou, G., et al., 2023. Association between air pollution and telomere length: a study of 471,808 UK Biobank participants. The Innovation Medicine 1, 100017.

Zhang, F., Tang, H., Zhao, D., Zhang, X., Zhu, S., Zhao, G., et al., 2022a. Short-term exposure to ambient particulate matter and mortality among HIV/AIDS patients: case-crossover evidence from all counties of Hubei province. China. Sci Total Environ 857, 159410.

Zhang, W., Liu, J., Hu, D., Li, L., Cui, L., Xu, J., et al., 2022b. Joint effect of multiple air pollutants on lipid profiles in obese and normal-weight young adults: the key role of ozone. Environ. Pollut. 292, 118247.

Zhang, W., Pan, L., Li, H., Xu, J., Yang, X., Dong, W., et al., 2022c. Effect of indoor coarse particulate matter on blood pressure and lung function of male patients with chronic obstructive pulmonary disease: perspectives of constituent, source and season. Hygiene and Environmental Health Advances 3, 100013.

Zhang, F., Wan, Y., Tang, H., Zhao, D., Zhu, S., Ruan, L., et al., 2023a. Submicronic particulate matter (PM(1)), a "neglected killer" for HIV/AIDS patients in Hubei, China: results from a cohort study from 2001 to 2020. Sci. Total Environ. 905, 167093.

Zhang, F., Zhu, S., Tang, H., Zhao, D., Zhang, X., Zhao, G., et al., 2023b. Ambient particulate matter, a novel factor hindering life spans of HIV/AIDS patients: evidence from a ten-year cohort study in Hubei. China. Sci Total Environ 875, 162589.