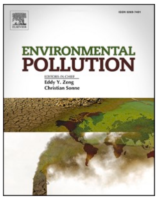
Environmental Pollution 398 (2026) 128060

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol



Concentration-oriented vs. health-oriented strategies: future anthropogenic sectoral emission reductions for $PM_{2.5}$ and ozone control over eastern China

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ARTICLE INFO

Keywords:
Anthropogenic sectoral emission reduction
Synergistic control
Air pollutant
Health benefit

ABSTRACT

In the field of environmental governance and health protection, coordinated management of $PM_{2.5}$ and ozone has become a critical priority in China. Previous research primarily evaluated the synergistic benefits of mitigating anthropogenic sources based on concentration regulations. This study extends the analysis to health-oriented outcomes using WRF-Chem simulations of reduced emissions from five different anthropogenic sectors under the most stringent carbon neutrality pathway over eastern China, emphasizing that although achieving synergistic improvements in concentrations of $PM_{2.5}$ and ozone may be challenging in future, potential health benefits are substantial. Results show that emission reductions in industry, thermal power, residential, transportation, and agriculture sectors from 2018 to 2060 can lead to co-control of $PM_{2.5}$ and ozone air quality in 62%, 31%, 42%, 59%, and 41% of analyzed regions, respectively. Substantial health benefits are projected with reduced total short-term exposure premature deaths of 1329–40910 persons by various sectors, and the changes in $PM_{2.5}$-related risk dominate the improvement in health outcomes with contributions of 87%–121%. Compared with traditionally concentration-oriented results, health-oriented anthropogenic source abatement shows that up to twelve additional provinces can achieve coordinated improvement in $PM_{2.5}$-related and ozone-related health risks. For the dual control of concentration and health, it will be achieved in 52% of the analyzed provinces under the reduction in IND, followed by TRA (44%), AGR (41%), RES (19%), and POW (4%), respectively. All these imply that future clean air action based on public health intervention may achieve greater benefits at the same or potentially lower emission reduction cost.

1. Introduction

China has been grappling with a complex array of environmental challenges, including $PM_{2.5}$ and ozone pollution, and their associated health impacts. Since 2013, strict emission reduction measures have been implemented by Chinese government for improving fine particulate matter air quality (Cheng et al., 2019; Wang et al., 2019; Zheng et al., 2018). However, the annual mean concentration of $PM_{2.5}$ still exceeds the WHO's standard of 5 $\mu g\ m^{-3}$ (Jiang et al., 2022; Geng et al., 2021; Wang et al., 2020). Meanwhile, ozone (O_3) concentrations continue to rise year by year (Li et al., 2019). $PM_{2.5}$ and O_3 have emerged as the predominant pollutants in China, posing a significant threat to public health (Zheng et al., 2024; Guo et al., 2023; Ma et al., 2023; Dong et al., 2024; Guan et al., 2021). Therefore, under the national strategic goal of carbon neutrality, it is necessary to adopt effective emission reduction measures to improve air quality and promote public health.

To enhance air quality, the impact of sectoral emission reductions on $PM_{2.5}$ and O_3 concentrations is emphasized (Zhang et al., 2023; Duan et al., 2021; Cheng et al., 2021). Conibear et al. (2022) utilized the WRF-Chem model to quantify the contribution of different human-induced emissions to air quality in China, and found that emissions from industrial sector led to a decrease in $PM_{2.5}$ concentrations of up to 11.3 $\mu g\ m^{-3}$ from 2012 to 2020. Cao et al. (2022) conducted source

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https://doi.org/10.1016/j.envpol.2026.128060
Received 22 December 2025; Received in revised form 26 March 2026; Accepted 1 April 2026

analysis by using the CMAQ model and discovered that the primary contributor to the increase in maximum daily 8-h average O_3 (MDA8 O_3) concentrations over North China Plain during 2012–2017 was the transport sector with contribution of 1.2–18.1 μg m^{-3}. He et al. (2022) used WRF-Chem to simulate the impact of emission reduction from different anthropogenic sectors on $PM_{2.5}$ and O_3 in Beijing, and found that reductions in the power sector from 2014 to 2019 resulted in a 4.3% decrease in $PM_{2.5}$ concentrations, while O_3 concentration was increased by 0.4%. Given that $PM_{2.5}$ and O_3 share common precursors, coordinated multi-sectoral control offers a viable strategy for air quality improvement (Dong et al., 2023; Wang et al., 2023; Li et al., 2021; Peng et al., 2017). However, the synergistic outcomes remain highly complex due to the heterogeneous chemical compositions and spatial distributions of emissions across various sectors. This uncertainty in collaborative control underscores the need for granular assessments of future sector specific emission reductions to ensure the balanced mitigation of both pollutants.

Reducing anthropogenic emissions is critical not only for improving air quality but also for realizing substantial public health co-benefits (Liu et al., 2022). As demonstrated by Cohen et al. (2017) using satellite data and numerical simulations, the 20% rise in global $PM_{2.5}$-attributable mortality from 1990 to 2015 significantly outpaced the 11.2% increase in $PM_{2.5}$ concentrations. Driven by factors like population aging, this pronounced non-linear response underscores the urgent need to evaluate and compare concentration-oriented versus health-oriented control strategies.

Recent studies have underscored these complex dynamics. For instance, Qin et al. (2024) utilized WRF-Chem to project that achieving carbon neutrality in China by 2060 could reduce $PM_{2.5}$ concentrations by 39 μg m^{-3} and prevent 1.13 million associated premature deaths compared with that in 2015. Similarly, Liu et al. (2024) employed machine learning to estimate that short-term exposure to $PM_{2.5}$ and O_3 accounted for 713.5 and 496.3 thousand global premature deaths in 2019, respectively, with 12.5% stemming from the transport, energy, and industrial sectors. Crucially, the health risk landscape is shifting. Analyzing Tracking Air Pollution in China (TAP) data, Xiao et al. (2022) found that since 2018, short-term O_3 attributable mortality has surpassed that caused by $PM_{2.5}$ in China. Despite existing efforts to evaluate synergistic pollutant control and overall health burdens, there is a notable lack of research on the consistency of concentration-oriented versus health-oriented pathways across anthropogenic sectoral emission reductions.

This study employs the WRF-Chem model to systematically analyze the synergistic effects of future clean air actions on $PM_{2.5}$, MDA8 O_3, and their associated health burdens in eastern China. The analysis is conducted under DPEC's (Dynamic Projection for Emission in China) most stringent carbon neutrality scenario driven by sector-specific anthropogenic emission reductions. Meanwhile, a detailed comparison between concentration-oriented (i.e., both the concentrations of $PM_{2.5}$ and MDA8 O_3 are decreased) and health-oriented (i.e., the premature mortalities attributable to exposure to $PM_{2.5}$ and MDA8 O_3 are both decreased) anthropogenic sectoral abatement measures is also conducted, with the aim to imply that air pollution prevention based on public health intervention will enhance the environment-health benefits of China's clean air action.

2. Data and methods

2.1. Model configuration

A fully coupled online meteorology–chemistry model, Weather Research and Forecasting model coupled to Chemistry (WRF-Chem v4.2.2), is used in this study. This air quality model can simulate meteorological fields and concentrations of gases and aerosols simultaneously (Grell et al., 2005). The simulation domain covers central and eastern China (96–124°E, 17–51°N) with the grid points of 115 (west-east) × 140 (south-north) at the horizontal resolution of 27 km. The model contains 30 vertical levels, with the first 15 layers located below the bottom 2 km to resolve fine boundary layer processes. Simulation periods are integrated during January, April, July, and October in the year of 2018, representing the winter, spring, summer, and autumn, respectively. The results averaged among the four seasons are used to represent the annual mean, following the method by Zhang et al. (2018), Sun et al. (2022), and Qin et al. (2024). To avoid potential deviations caused by long-term model integration, each simulation is re-initialized every 15 days, with the first 5 days as the model spin-up. The MOZART gas-phase scheme and MOSAIC aerosol module are employed to represent complex gas-phase chemistry and secondary aerosol formation, aiming to provide accurate simulations of $PM_{2.5}$ and O_3 concentrations over eastern China. Detailed model parameterization schemes used in this study are summarized in Table S1.

Meteorological initial and lateral boundary conditions (denoted as met_em files) are generated from ERA5 (European Center for Medium-Range Weather Forecasts Fifth Generation Reanalysis) with the spatial resolution of 0.25° and the temporal resolution of 3-h. The BASE experiment listed in Table 1 is designed to evaluate model performance against observations, and is driven by ERA5 reanalysis data for 2018. Meteorological variables exhibit inter-annual fluctuations. Therefore, the utilization of met_em files from different years will exert a substantial influence on the synergistic results of anthropogenic source abatement. In order to minimize this impact, climatological met_em files are created by averaging the met_em files from 2013 to 2023, and the final 3-h resolution climatological met_em files are used for sensitivity experiment simulations of CTL, IND, POW, RES, TRA, and AGR (Table 1) to quantify the impacts of different anthropogenic sectoral emission reductions on air quality and health burden. These climatological initial and lateral boundary conditions can mitigate the influence of different meteorological fields at different simulation years to some extent (Liu et al., 2019; Wu et al., 2019; Ritter et al., 2013). The chemical initial and boundary conditions for WRF-Chem are taken from the outputs of CAM-Chem (Community Atmosphere Model with Chemistry).

Anthropogenic emissions in the year of 2018 are derived from MEIC v1.4 (Multi-resolution Emission Inventory model for Climate and air pollution research) (http://meicmodel.org.cn) (Geng et al., 2024). Future anthropogenic emissions at year 2060 are collected from DPEC v1.2 (Dynamic Projection model for Emissions in China) with the most rigorous emission reduction scenario of early peak-net zero-clean air (Cheng et al., 2023). Fig. S1 presents the relative changes in anthropogenic emissions from 2018 to 2060 by each sector of industrial (IND), thermal power (POW), residential (RES), transport (TRA), and agriculture (AGR), with large reductions in emissions of SO_2 (−43 to −29%), primary $PM_{2.5}$ (−45 to −35%), and NH_3 (−30 to −17%) in sectors of

Table 1
Sensitivity experiments.

Experiment	Meteorological condition	Anthropogenic emission
BASE	2018 ERA5	2018 MEIC
CTL	Climatological mean ERA5 averaged over 2013-2023	2018 MEIC
IND		Same as CTL, but emissions of industrial sector are replaced by 2060 DPEC
POW		Same as CTL, but emissions of thermal power sector are replaced by 2060 DPEC
RES		Same as CTL, but emissions of residential sector are replaced by 2060 DPEC
TRA		Same as CTL, but emissions of transport sector are replaced by 2060 DPEC
AGR		Same as CTL, but emissions of agricultural sector are replaced by 2060 DPEC

IND and RES, and large reductions in emissions of VOCs (−44 to −14%) and NOx (−35% to −34%) from IND and TRA sectors.

In order to assess the impacts of future anthropogenic sectoral emission reductions, six sets of sensitivity experiments are designed (Table 1). CTL represents the control experiment, in which the simulation is driven by the 11-year-averaged meteorological field while anthropogenic emissions are fixed at the 2018 level. For other experiments (i.e., IND, POW, RES, TRA, and AGR), taking IND as an example, all the settings in IND are the same as CTL, but the anthropogenic emissions of industrial sector are replaced by DPEC. Therefore, by comparing IND with CTL, we can quantitatively evaluate the impacts of future anthropogenic emission reductions in industrial sector on air quality and their related health burden.

Biogenic emissions are calculated with MEGAN (Model of Emissions of Gases and Aerosols from Nature) v2.04. The emissions of biomass burning are sourced from FINN (Fire INventory from NCAR) v2.0 (Wiedinmyer et al., 2010). To isolate the impacts of anthropogenic emission changes, emissions of biogenic sources and biomass burning in the six sensitivity experiments are both fixed at year 2018.

2.2. Observation data

Hourly meteorological data collected by the University of Wyoming are used (http://weather.uwyo.edu/surface/meteorogram/seasia.shtml), including 2-m temperature (T_2), 2-m relative humidity (RH_2), 10-m wind speed (WS_{10}), and 10-m wind direction (WD_{10}), along with hourly $PM_{2.5}$ and MDA8 O_3 monitoring observations from China National Environmental Monitoring Center (CNEMC, https://air.cnemc.cn:18007/) to evaluate model simulations. Fig. 1 and Fig. S2 present the spatial-temporal comparison of simulation results against observed data. Or meteorological parameters, the correlation coefficients (Rs) for T_2, RH_2, and WS_{10} range from 0.83 to 0.99, with normalized mean biases (NMBs) within the range of −1.6% to +17.6%. The R and NMB values are 0.92 and −3.4% for $PM_{2.5}$, and 0.89 and −6.5% for MDA8 O_3. These results indicate that the WRF-Chem model can reliably reproduce the spatial-temporal evolution of both meteorological parameters and air pollutant concentrations.

2.3. Health impact assessment

This study focuses on the health risks of all-cause disease from short-term exposures to $PM_{2.5}$ and MDA8 O_3, following Eq. (1) and Eq. (2) that have been widely used in many other studies (Guan et al., 2022; Xiao et al., 2022; Liu et al., 2021; Gasparrini and Leone, 2014):

$$\mathrm{Mort}_{i,j,a} = \mathrm{POP}_{i,j,a} \times y_{0j,a} \times \left(1 - \frac{1}{\exp\left(\beta\left(C_{i,j} - C0\right)\right)}\right) \quad (1)$$

$$\mathrm{Mort} = \sum_{i}\sum_{j}\sum_{a}\mathrm{Mort}_{i,j,a} \quad (2)$$

where *i*, *j* and *a* represent grid point, time, and age-specific group, respectively. *Mort* is all-cause premature mortality attributable to short-term exposure to $PM_{2.5}$ concentrations (MDA8 O_3 concentrations). y_0 is the age-specific daily baseline mortality rate. *POP* represents the age-specific population data. *C* is $PM_{2.5}$ concentrations (MDA8 O_3 concentrations) from numerical simulation. *C*0 means the theoretical minimum risk exposure. β denotes the change in daily mortality associated with an increase of 10 $\mu g\ m^{-3}$ for $PM_{2.5}$ (10 $\mu g\ m^{-3}$ for MDA8 O_3). The 95% confidence intervals (95%CI) for health risks are derived from 1000 Monte Carlo simulations by randomly sampling the exposure-response coefficient (β) from its normal distribution to propagate statistical uncertainty to the final health risk estimates.

Age-specific group (i.e., 0–4, 5–39, 10–14, 15–19, 20–24, 25–29, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, and 85+) gridded population data for China in 2018 are obtained from LandScan (https://landscan.ornl.gov/). Age-specific daily baseline mortality rates for all-cause diseases in 2018 are collected from Global Burden of Disease (GBD) (https://vizhub.healthdata.org/gbd-results/). We use 0.000648 (95% CI: 0.000439, 0.000856) (15 $\mu g\ m^{-3}$) and 0.000429 (95%CI: 0.000339, 0.000519) (100 $\mu g\ m^{-3}$) as the β (*C*0) values for $PM_{2.5}$ and MDA8 O_3, respectively (Orellano et al., 2020). By calculating the daily premature mortality, the total number of premature deaths caused by short-term exposure to $PM_{2.5}$ and MDA8 O_3 during the simulation period can be estimated. Furthermore, by comparing the results of sensitivity experiments with the CTL experiment, the impacts of future anthropogenic sectoral emission reductions on $PM_{2.5}$-related and O_3-related premature deaths can be quantified.

3. Results and discussion

3.1. Coordinated impact of future anthropogenic source abatement on $PM_{2.5}$ and ozone air quality

Changed $PM_{2.5}$ and MDA8 O_3 concentrations due to anthropogenic emission reductions by each sector from 2018 to 2060 are shown in Fig. 2. Emission reductions in each individual sector contribute to a

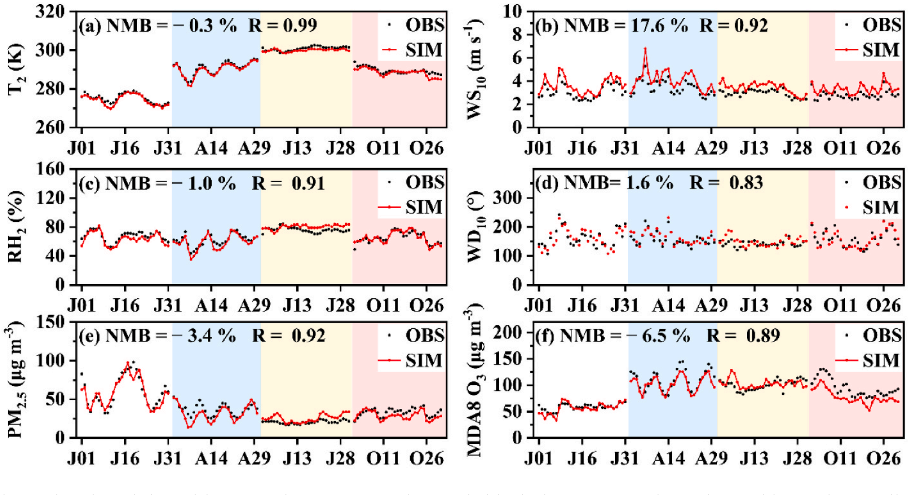


Fig. 1. Time series of model simulated (red dotted lines) and monitoring observed (black dots) meteorological variables and air pollutants during January, April, July and October in 2018. **(a)** 2 m Temperature (T_2), **(b)** 10 m wind speed (WS_{10}), **(c)** 2 m relative humidity (RH_2), **(d)** 10 m wind direction (WD_{10}), **(e)** $PM_{2.5}$, and **(f)** MDA8 O_3. Statistics of NMB (normalized mean bias) and R (correlation coefficient) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

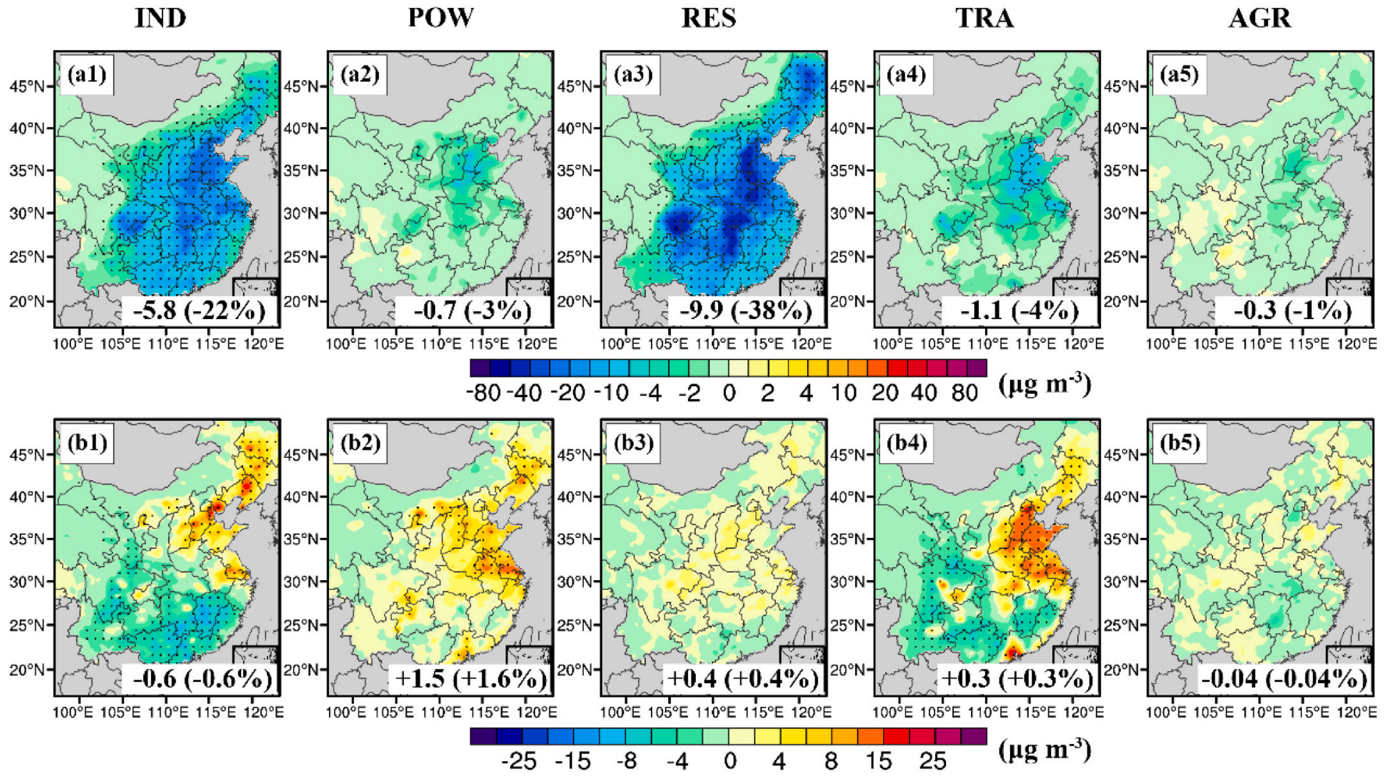


Fig. 2. Spatial distribution of changed $PM_{2.5}$ (upper) and MDA8 O_3 (bottom) concentrations due to future anthropogenic emission reductions by each sector of industry (IND, a1-b1), thermal power (POW, a2-b2), residential (RES, a3-b3), transportation (TRA, a4-b4), and agriculture (AGR, a5-b5) relative to that in 2018. Dotted areas indicate grid cells where the concentration differences pass the 90% significance level based on a student t-test. The mean change averaged over the whole domain is also shown in the bottom right corner of each panel.

decrease in $PM_{2.5}$ concentrations across China. The most substantial improvement is driven by the RES sector (−9.9 μg m^{-3}, −38%), followed by IND (−5.8 μg m^{-3}, −22%), TRA (−1.1 μg m^{-3}, −4%), POW (−0.7 μg m^{-3}, −3%), and AGR (−0.3 μg m^{-3}, −1%) sectors. While future changes in MDA8 O_3 concentrations averaged over the simulation area caused by emission reductions in various anthropogenic sectors are relatively small (−0.6–+1.5 μg m^{-3}), the spatial heterogeneity variations are obvious. Specifically, reductions in IND and TRA will lead to a decrease of 3–5% in MDA8 O_3 concentrations over the south region, whereas an increase of 7–9% over North China Plain (NCP) and 2–8% over Yangtze River Delta (YRD). Seasonal analysis (Fig. S3) reveals that during summer with high concentrations of MDA8 O_3, future anthropogenic emission reductions can improve ozone air quality, but during other seasons, anthropogenic source abatement will worsen MDA8 O_3 concentration, with the maximum increase of 20 μg m^{-3} over NCP and YRD. Similar spatial-temporal variation characteristics in MDA8 O_3 concentrations due to anthropogenic emission reductions are also reported by Yang et al. (2025). The O_3 increases in the NCP and YRD regions are primarily due to the larger reduction in NOx emissions compared to that in VOCs. Since these regions are under a VOC-limited regime (Wang et al., 2022), such unbalanced emission reductions will lead to a rise in O_3 concentrations.

Synergistic controls of air pollutants of $PM_{2.5}$ and MDA8 O_3 due to reductions in anthropogenic emissions by the five sectorial scenarios from 2018 to 2060 are shown in Fig. 3. According to Fig. 3(a1-a5) we can find that emission reductions in sectors of IND and TRA will simultaneously improve $PM_{2.5}$ and MDA8 O_3 over 62% and 59% of the simulated region, respectively. Although future emission control in AGR sector can result in co-control of $PM_{2.5}$ and MDA8 O_3 in 41% of the simulation grid cells, the improvement in these concentrations is very limited (Fig. 2(a5) and (b5)). Future reductions in POW sector will decrease $PM_{2.5}$ but worsen MDA8 O_3 concentrations resulting in the discordant effect over nearly the whole provinces (Fig. 3(b2)). The superior synergistic control in the IND sector is attributed to the simultaneous large-scale reduction of both $PM_{2.5}$ and O_3 precursors. In contrast, the TRA sector demonstrates limited synergy in major urban clusters due to the disproportionate reduction in NOx relative to that in VOCs. Therefore, future air quality strategies should implement differentiated management based on the emission characteristics of various sectors to achieve the optimal synergistic reduction of $PM_{2.5}$ and O_3.

The impacts of future anthropogenic emission reductions on $PM_{2.5}$ and MDA8 O_3 are reflected not only in the coordinated control of air pollutant concentrations but also in the compliance rates according to 24-hr $PM_{2.5}$ and MDA8 O_3 air quality standards (75 μg m^{-3} for daily average $PM_{2.5}$ concentration and 160 μg m^{-3} for MDA8 O_3). Fig. 3(c1-c5) clearly shows that anthropogenic source abatement in IND and RES sectors will effectively enhance the synergistic attainment rates of $PM_{2.5}$ and MDA8 O_3. Although the concentrations of MDA8 O_3 are increased due to reductions in emissions of precursors, the significant decreases in $PM_{2.5}$ concentrations dominate the decline in number of exceedance days. Results discussed above suggest that future anthropogenic emissions reductions in IND, RES and TRA sectors will lead to synergistic improvements in $PM_{2.5}$ and MDA8 O_3 air quality, especially for the provinces over southern China.

3.2. Coordinated impact of future anthropogenic source abatement on $PM_{2.5}$-related and ozone-related health burden

Although emission reduction measures can improve air quality, their impacts on the health burden of $PM_{2.5}$ and ozone may not be consistent. Therefore, a detailed analysis of the health impacts related to these factors independently in each province is further conducted in Fig. 4. Decreased $PM_{2.5}$ concentrations dominate the improvement in health burden under all sectoral reductions. Specifically, reductions in RES

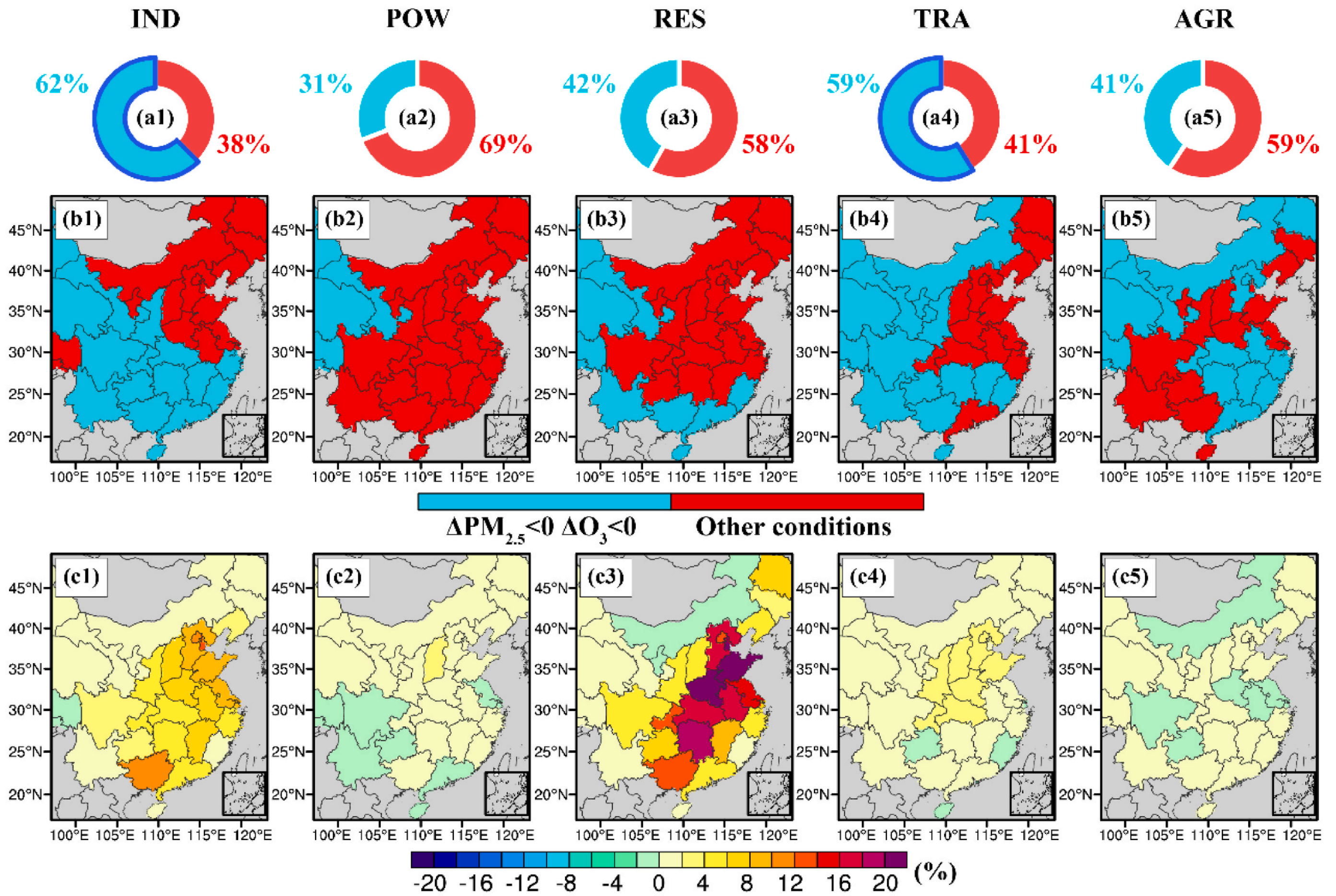


Fig. 3. Synergistic controls in concentrations (upper, middle) and compliance status for 24-hr standards (bottom) of $PM_{2.5}$ and MDA8 O_3 air quality due to reductions in anthropogenic emission by each sector of industry (IND, a1-c1), thermal power (POW, a2-c2), residential (RES, a3-c3), transportation (TRA, a4-c4), and agriculture (AGR, a5-c5) from 2018 to 2060. The cyan (red) number beside circular ring represents the proportion of whole analyzed region where decreased conditions (other conditions) for both $PM_{2.5}$ and MDA8 O_3 concentration are simulated. The thick blue outline in circular ring indicates the co-control of $PM_{2.5}$ and MDA8 O_3 at the national scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from 2018 to 2060 maximize the health benefits (−40172 [95%CI: −52342, −27592] persons), followed by those in the IND (−26164 [95%CI: −34137, −17938] persons), TRA (−5231 [95%CI: −6830, −3591] persons), POW (−2786 [95%CI: −3623, −1920] persons), and AGR (−1314 [95%CI: −1702, −910] persons), respectively.

Increased MDA8 O_3 concentrations induced by reductions in POW sector worsen ozone-related health risks by +481 (95%CI: +380, +581) persons over the simulation region, especially in Shanghai (+104 [95% CI: +83, +126] persons) and Jiangsu (+267 [95%CI: +221, +322] persons) provinces, where the adverse impacts of ozone even outweigh the concurrent $PM_{2.5}$ benefits. However, future reductions in sectors of IND and TRA will alleviate ozone-related health burden by −4041 (95% CI: −4873, −3202) and −2286 (95%CI: −2756, −1812) persons, respectively, even though the concentrations of MDA8 O_3 are increased over north China. Overall, changes in health burden due to exposure to MDA8 O_3 induced by anthropogenic source abatement in various sectors are relatively small. When considering the net changes in $PM_{2.5}$-related and ozone-related deaths (denoted as all-related deaths) as presented in Fig. S4, premature deaths related to $PM_{2.5}$ drive the overall reduction, accounting for the vast majority (70–121%) of the decrease in all-related deaths under various sectoral reductions over the simulation region. Furthermore, Fig. S5 shows that reductions in RES from 2018 to 2060 result in the largest overall health benefits, followed by IND, TRA, POW, and AGR.

From Fig. 4 and Fig. S4 we can also conclude the characteristics of synergistic improvement (i.e., both $PM_{2.5}$-related and ozone-related premature deaths are decreased) and net improvement (i.e., all-related deaths are decreased) in health burden. Future reductions in IND, RES and TRA sectors will realize net improvement in health burden over all analyzed provinces. While for synergistic improvement, 96% of the provinces are simulated by the reduction in the IND sector, followed by TRA of 78%, AGR of 52%, RES of 48%, and POW of 44%, respectively.

All these indicate that future emission reductions in various anthropogenic sectors will decrease $PM_{2.5}$ concentrations which dominate the improvement in health burden, and the impacts of changed MDA8 O_3 on health risk should not be neglected. Despite the complex effects on public health due to inconsistent changes in $PM_{2.5}$ and MDA8 O_3 concentrations, synergistic improvement in health burden can be found in most provinces.

3.3. *Comparative analysis of concentration-oriented and health-oriented future anthropogenic source abatement*

Traditional research typically evaluated the effectiveness of anthropogenic source abatement based on concentration-centric regulation. This study goes further by targeting health-based emission reduction strategies. Compared with concentration-oriented results (e.g., collaborative improvement in $PM_{2.5}$ and ozone air quality can be achieved by reductions in sectors of IND and TRA, but these improvements are mainly located in south China, such as Fujian, Yunnan, Guangxi, and

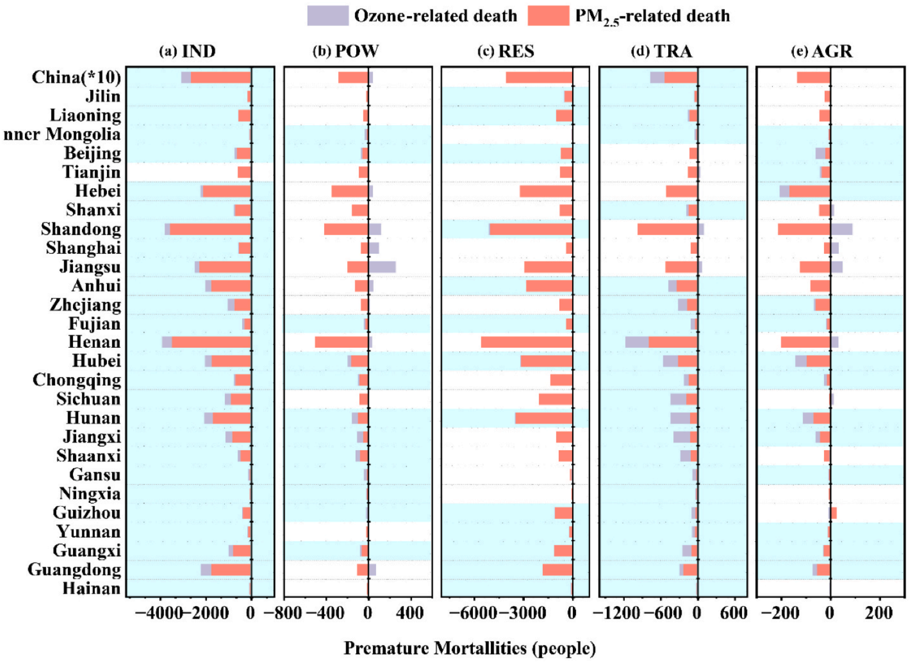


Fig. 4. Changes in premature deaths associated with short-term exposure to $PM_{2.5}$ and MDA8 O_3 for each province in China due to reductions in anthropogenic emission by sectors of industry (IND, **a**), thermal power (POW, **b**), residential (RES, **c**), transportation (TRA, **d**), and agriculture (AGR, **e**) from 2018 to 2060. Purple (red) bar means changes in ozone-related ($PM_{2.5}$-related) premature deaths. The light cyan backgrounds indicate synergistic improvement in health burden, which mean both ozone-related and $PM_{2.5}$-related premature deaths are decreased. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Hainan provinces), health-oriented results present more pronounced benefits. As Fig. 5 shows, when the emissions of IND (POW, RES, TRA, AGR) sectors are reduced, a synergistic improvement in $PM_{2.5}$-related and ozone-related health risks will be achieved in twelve (eleven, eight, ten, one) more provinces than the results based on the strategy of synergistically improving $PM_{2.5}$ and MDA8 O_3 air quality.

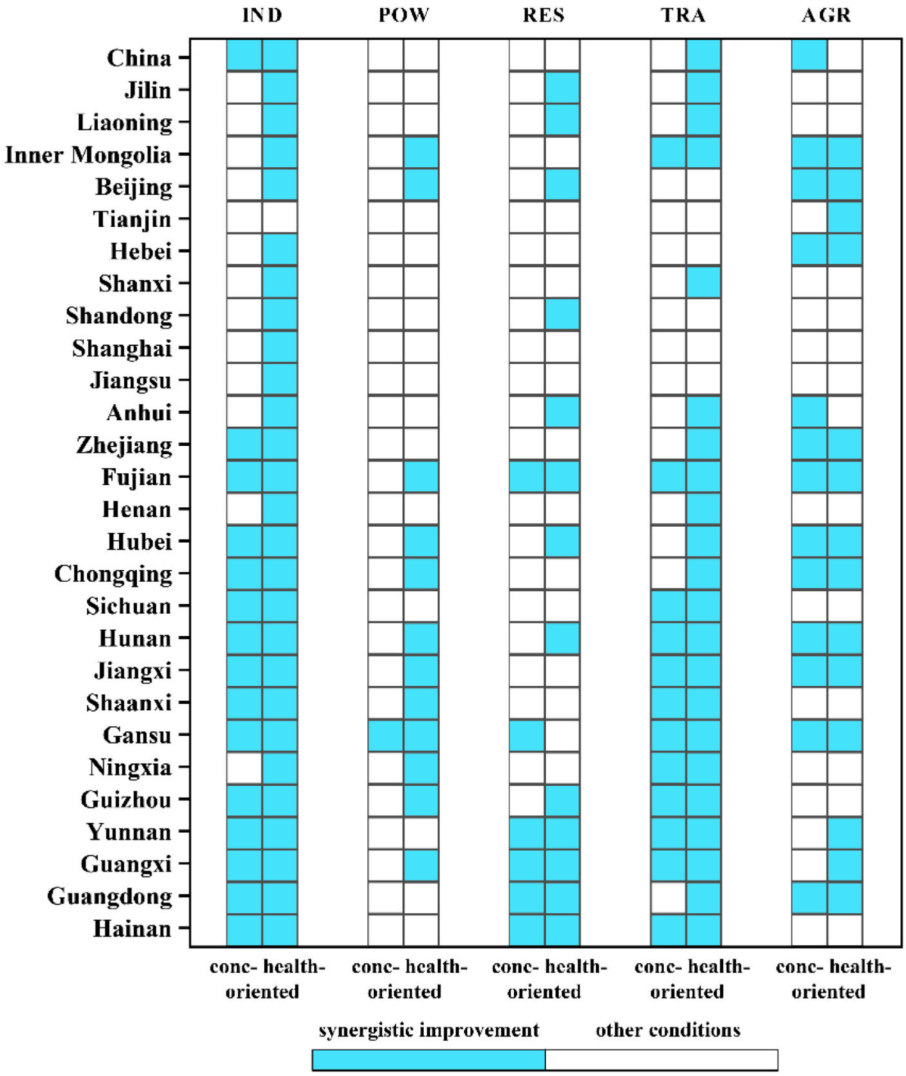
Further comparisons between concentration-oriented and health-oriented results reveal that emission reductions in sector of IND will enable win-win results (i.e., both concentration-oriented and health-oriented anthropogenic source abatement can be achieved) over 52% of the analyzed provinces, followed by TRA of 44%, AGR of 41%, RES of 19%, and POW of 4%, but these provinces are mainly located over south China.

3.4. Limitations

There are also many limitations in this study. (1) Air pollutants of $PM_{2.5}$ and ozone share the same origin and can interact with each other, often trigger overlapping cardiovascular and respiratory diseases within the same vulnerable populations. Therefore, simply summing the premature deaths attributable to $PM_{2.5}$ and ozone independently may result in substantial bias due to double-counting shared health risks, particularly for all-related premature deaths. Consequently, these combined mortality estimates should be regarded as the theoretical upper limit of the total health burden. However, it does not affect our conclusions regarding synergistic control analysis. This study emphasizes a directional and qualitative comparison among different scenarios instead of absolute quantification. Nonetheless, future research should apply co-exposure or multi-pollutant risk models for more accurate assessments. (2) The health risk coefficients (β) are taken from the latest World Health Organization (WHO) guidelines. Although these guidelines can provide a reliable benchmark, future localized investigations are essential to refine these coefficients for the specific health context of China. To account for statistical uncertainty, 1000 Monte Carlo simulations are conducted focusing on β. Although uncertainty from model parameterizations is not quantified, these systematic biases are expected to largely cancel out as this study emphasizes the relative differences between sensitivity experiments. (3) Zheng et al. (2025) have shown significant differences in the toxicity of $PM_{2.5}$ from various anthropogenic sectors. However, this research assumes that the toxicity of $PM_{2.5}$ per unit mass is the same across all sectors. This simplification may overlook the unique toxicological profiles of different components in different sectors. (4) The results in this study are based on the simulations during January, April, July, and October. Although these data to some extent can present the seasonal characteristics of concentrations of $PM_{2.5}$ and ozone and their related health burden, they cannot fully reflect the concentration in each month and even the number of premature deaths throughout the year. Given the above limitations, future research should consider conducting detailed simulations of each month to more accurately capture the changes in $PM_{2.5}$ and ozone air quality throughout the whole year, and further explore how specific environmental factors in different regions affect air pollutants and their associated health outcomes to tackle complex environment-health issues.

4. Conclusions

Coordinating the control of air pollutants of $PM_{2.5}$ and ozone constitutes a crucial strategy within China's clean air action. A fully coupled online air quality model of WRF-Chem is applied to estimate the impacts of emission reductions in different anthropogenic sources (i.e., IND, POW, RES, TRA, and AGR) on $PM_{2.5}$ and MDA8 O_3, and their related health risks over eastern China under the most stringent carbon neutrality pathway (i.e., early peak-net zero-clean air) from the DPEC. Previous research evaluated the effectiveness of anthropogenic source abatement primarily based on concentration-centric regulation. This study goes further by targeting health-based results, aiming to illustrate that although achieving synergistic improvements in $PM_{2.5}$ and ozone air quality may be challenging in future, the potential health benefits are expected to be substantial. It also highlights that future clean air action based on public health intervention will enhance the environment-



	IND		POW		RES		TRA		AGR	
	conc-	health-oriented	conc-	health-oriented	conc-	health-oriented	conc-	health-oriented	conc-	health-oriented
China	🟦	🟦	☐	☐	☐	☐	☐	🟦	🟦	☐
Jilin	☐	🟦	☐	☐	☐	🟦	☐	🟦	☐	☐
Liaoning	☐	🟦	☐	☐	☐	🟦	☐	🟦	☐	☐
Inner Mongolia	☐	🟦	☐	🟦	☐	☐	🟦	🟦	🟦	🟦
Beijing	☐	🟦	☐	🟦	☐	🟦	☐	☐	🟦	🟦
Tianjin	☐	☐	☐	☐	☐	☐	☐	☐	☐	🟦
Hebei	☐	🟦	☐	☐	☐	☐	☐	☐	🟦	🟦
Shanxi	☐	🟦	☐	☐	☐	☐	☐	🟦	☐	☐
Shandong	☐	🟦	☐	☐	☐	🟦	☐	☐	☐	☐
Shanghai	☐	🟦	☐	☐	☐	☐	☐	☐	☐	☐
Jiangsu	☐	🟦	☐	☐	☐	☐	☐	☐	☐	☐
Anhui	☐	🟦	☐	☐	☐	🟦	☐	🟦	🟦	☐
Zhejiang	🟦	🟦	☐	☐	☐	☐	☐	🟦	🟦	🟦
Fujian	🟦	🟦	☐	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Henan	☐	🟦	☐	☐	☐	☐	☐	🟦	☐	☐
Hubei	🟦	🟦	☐	🟦	☐	🟦	☐	🟦	🟦	🟦
Chongqing	🟦	🟦	☐	🟦	☐	☐	☐	🟦	🟦	🟦
Sichuan	🟦	🟦	☐	☐	☐	☐	🟦	🟦	☐	☐
Hunan	🟦	🟦	☐	🟦	☐	🟦	🟦	🟦	🟦	🟦
Jiangxi	🟦	🟦	☐	🟦	☐	☐	🟦	🟦	🟦	🟦
Shaanxi	🟦	🟦	☐	🟦	☐	☐	🟦	🟦	☐	☐
Gansu	🟦	🟦	🟦	🟦	🟦	☐	🟦	🟦	🟦	🟦
Ningxia	☐	🟦	☐	🟦	☐	☐	🟦	🟦	☐	☐
Guizhou	🟦	🟦	☐	🟦	☐	🟦	🟦	🟦	☐	☐
Yunnan	🟦	🟦	☐	☐	🟦	🟦	🟦	🟦	☐	🟦
Guangxi	🟦	🟦	☐	🟦	🟦	🟦	🟦	🟦	☐	🟦
Guangdong	🟦	🟦	☐	☐	🟦	🟦	☐	🟦	🟦	🟦
Hainan	🟦	🟦	☐	☐	🟦	🟦	🟦	🟦	☐	☐

🟦 synergistic improvement ☐ other conditions

Fig. 5. Comparison between concentration-oriented (left column) and health-oriented (right column) anthropogenic source abatement in sectors of industry (IND), thermal power (POW), residential (RES), transportation (TRA), and agriculture (AGR) from 2018 to 2060 for each province of China. "conc-" means "concentration-". Light green box in the left (right) column indicates synergistic improvement in $PM_{2.5}$ and MDA8 O_3 air quality, which means both the concentrations of $PM_{2.5}$ and MDA8 O_3 are decreased (synergistic improvement in $PM_{2.5}$-related and ozone-related death, which means both $PM_{2.5}$-related and ozone-related deaths are decreased). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

health benefits. Detailed conclusions are summarized as follows:

(1) Synergistic impacts of emission reductions from various anthropogenic sectors on $PM_{2.5}$ and MDA8 O_3 concentrations are first investigated. RES emission reductions from 2018 to 2060 improve national $PM_{2.5}$ most significantly (−38%), followed by IND (−22%) and TRA (−4%). The variation in MDA8 O_3 concentration is relatively small (−0.6–+1.5 $\mu g\ m^{-3}$), but the spatial heterogeneity is obvious. Future anthropogenic emissions reductions in sectors of IND, POW, RES, TRA, and AGR will lead to synergistic improvements in 62%, 31%, 42%, 59%, and 41% of the analyzed regions.

(2) Although it is challenging to achieve synergistic improvements in $PM_{2.5}$ and MDA8 O_3, future anthropogenic emission reductions can generate substantial health benefits, with decreased short-term exposure premature deaths of −40910 (95%CI: −53315, −28090) persons in RES, followed by that in sectors of IND (−30350 [95%CI: −39198, −21242] persons), TRA (−7599 [95%CI: −9689, −5464] persons), POW (−2332 [95%CI: −3075, −1560] persons), and AGR (−1329 [95%CI: −3168, −82] persons). The decreased concentrations of $PM_{2.5}$ dominate the improvement in health burden, while changes in O_3-related deaths are relatively small.

(3) Compared with traditional concentration-oriented results, health-oriented anthropogenic source abatement presents more pronounced benefits, with twelve (eleven, eight, ten, and one) more provinces achieving synergistic improvements in $PM_{2.5}$-related and ozone-related health risks through emission reductions in IND (POW, RES, TRA, and AGR) sectors, implying that focusing on health can enhance the effectiveness of reduced emissions.

(4) Future strict emission reductions in IND sector will enable dual coordinated control of air quality and health in 52% of the analyzed provinces, followed by TRA of 44%, AGR of 41%, RES of 19%, and POW of 4%.

CRediT authorship contribution statement

Ziyu Long: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Lei Chen:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Ke Li:** Visualization, Funding acquisition, Formal analysis. **Jia Zhu:** Visualization, Formal analysis. **Xi Chen:** Visualization, Formal analysis. **Wenhao Qiao:** Visualization, Formal analysis. **Zhenjiang Yang:** Visualization, Formal analysis. **Yang Yang:** Writing – review & editing, Validation. **Xu Yue:** Writing – review & editing, Validation. **Hong Liao:** Writing – review & editing, Validation.

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.

Acknowledgment

This research was supported by National Key Research and Development Program of China (grant no. 2022YFE0136100), and National Natural Science Foundation of China (grant no. 42305121, 42293320).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.128060.

Data availability

Data will be made available on request.

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