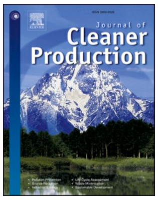
Journal of Cleaner Production 455 (2024) 142313

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Designing regional joint prevention and control schemes of $PM_{2.5}$ based on source apportionment of chemical transport model: A case study of a heavy pollution episode

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ARTICLE INFO

Handling Editor: Zhifu Mi

Keywords:
Fine particular matter
CMAQ
Source apportionment
The Fenhe Plain
Regional joint prevention and control

ABSTRACT

Fine particular matter ($PM_{2.5}$) pollution still occurs frequently in China. Despite recognizing the importance of regional joint prevention and control (RJPC) for mitigating haze pollution, there is still a limited understanding of scheme design and effectiveness. In this study, with the Fenhe Plain in China serving as the case, the Integrated Source Apportionment Method (ISAM), incorporated into the Community Multiscale Air Quality Modeling System (CMAQ), was used to quantitively identify $PM_{2.5}$ sources during a typical heavy pollution episode from Jan. 20th to 25th, 2021. Informed by source apportionment, we designed and assessed multiple RJPC scenarios for eliminating heavy pollution, yielding recommended RJPC schemes. Source apportionment results revealed a substantial increase in the contribution percentage of regions within a 350-km radius during the pollution episode compared to the non-polluted period. Sulfate was predominantly contributed from long-distance transport, whereas nitrate was chiefly contributed from closer regions. Ammonium exhibited higher local contributions than nitrate from the Fenhe Plain. Moreover, Taiyuan and Linfen were identified as $PM_{2.5}$ exporters, whereas Sanmenxia, Jinzhong, and Luliang served as $PM_{2.5}$ importers, and Yuncheng acted as a comprehensive city. The proposed specific RJPC schemes aimed at eliminating heavy pollution for the Fenhe Plain emphasized the importance of controlling emissions of particulate matter, ammonia, nitrogen oxides, and volatile organic compounds in areas within an approximate 350-km radius outside the Fenhe Plain, in addition to strengthening the local emission control. Nevertheless, only through the comprehensive and in-depth implementation of emission control measures across a larger area can $PM_{2.5}$ compliance be achieved.

1. Introduction

Particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) is one of the main pollutants causing air pollution in China (Li et al., 2019b; Gao et al., 2023). $PM_{2.5}$ not only impairs visibility and influences cloud formation (Kuniyal and Guleria, 2019), but also participates in atmospheric chemical processes (Baker et al., 2023), further impacting the concentration of other trace substances in the troposphere (Bao et al., 2018; Li et al., 2019b). Moreover, $PM_{2.5}$ can penetrate the lungs and cardiovascular system (Griggs et al., 2023; Li et al., 2023), posing health risks and increasing mortality (Jiang et al., 2023; Pokharel et al., 2023). Consequently, formulating effective mitigation schemes is crucial

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https://doi.org/10.1016/j.jclepro.2024.142313
Received 16 November 2023; Received in revised form 3 April 2024; Accepted 21 April 2024
Available online 24 April 2024

for continuously improving air quality. Further, potentially substantial mortality benefits can be achieved by pursuing clean air in densely populated areas with high $PM_{2.5}$ levels (Apte et al., 2015).

During the 2013–2017 Air Pollution Prevention and Control Action Plan from 2013 to 2017, the Chinese government implemented measures to reduce emissions, leading to a significant decrease in $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei (BTH)(Cai et al., 2017), Yangtze River Delta (YRD)(Wang et al., 2020), and Pearl River Delta (PRD) regions (Feng et al., 2019). However, in the Fenwei Plain, encompassing the Fenhe Plain, $PM_{2.5}$ concentration rebounded, particularly during autumn and winter (Gao et al., 2023), reaching an annual average of 68 μg/m^3 by 2017 (Zhao et al., 2020). The Fenhe Plain, a prominent center for coal production and consumption in China (Hu et al., 2022; Kou et al., 2023), depends on coal for about 90% of its energy consumption, significantly higher than the national average of 60%. Such high reliance is attributed to the prevalence of heavy industries such as coal coking and steel production (Zhang et al., 2016; Chen et al., 2022). The extensive mining and processing of coal and other minerals, along with the operation of numerous industrial facilities dependent on these resources, have led to substantial air pollutant emissions in the area (Zhang et al., 2023).

In the " Three-Year Action Plan for Winning the Blue Sky Defense Battle" released by the Chinese government in 2018 (https://english.mee.gov.cn/News_service/news_release/201807/t20180713_446624.shtml, last access: Jan. 23, 2024), the Fenwei Plain, including the Fenhe Plain, was listed as one of key regions for pollution prevention and control for the first time. Subsequently, the mitigation of haze pollution in the Fenhe Plain has attracted much attention. For example, research on the sources (Li et al., 2022) and health impacts (Li et al., 2019a) of $PM_{2.5}$, as well as the effects of rural household burning on $PM_{2.5}$ in the Fenhe Plain (Zhang et al., 2022). Given $PM_{2.5}$'s high regional transportability, the magnitude of contributions from various regions/cities and emission categories significantly influences the effectiveness of the regional joint prevention and control (RJPC) scheme. However, the Fenhe Plain currently lacks a precise framework for the RJPC scheme developed based on source identification. Therefore, quantitatively identifying the sources of $PM_{2.5}$ in the Fenhe Plain and developing science-based RJPC schemes are crucial for achieving the goal of reducing $PM_{2.5}$ concentration in the Fenhe Plain.

There are several methods for $PM_{2.5}$ source apportionment, primarily classified into two categories: receptor models (Park et al., 2019) and source-based models. The receptor model determines the contributions of different emission categories to $PM_{2.5}$ concentrations of a specific location, using either emission source profiles or statistical methods (Tao et al., 2016; Srivastava et al., 2021). However, their major limitation lies in the inability to quantitatively attribute $PM_{2.5}$ to specific geographic regions (Chang et al., 2019; Kitagawa et al., 2021). As source-based models, chemical transport models (CTM) including the Community Multiscale Air Quality Modeling System (CMAQ), Comprehensive Air Quality Model with Extensions (CAMx), etc., can reproduce the temporal and spatial distributions of atmospheric $PM_{2.5}$ and its components' concentrations (Han et al., 2020). This capability is attributed to CTM's integration of emission inventories, meteorological fields, and the simulation of all the requisite physical and chemical processes in the atmosphere (Chang et al., 2019; Wang et al., 2023). Furthermore, CTMs can precisely quantify contributions from each emission category and region to $PM_{2.5}$, employing the tracer labeling method, such as the Integrated Source Apportionment Method (ISAM) (Kwok et al., 2013; Sulaymon et al., 2023).

The ISAM approach embedded in CMAQ (https://cmascenter.org) is expected to offer a powerful tool with high efficiency and flexibility in quantitatively determining contributions to $PM_{2.5}$ from various source categories and regions (Napelenok et al., 2014; Kwok et al., 2015). While CTM-based $PM_{2.5}$ source apportionment studies in China have mainly focused on the BTH, YRD, PRD, and Chengdu-Chongqing regions (Li et al., 2019c), there is limited effort on comprehensive quantitative source identification in the Fenhe Plain, particularly those incorporating chemical transport processes based on CTM. This gap remains, although there are a few studies of receptor models (Li et al., 2022) and data analysis based on observations (Zhou et al., 2019; Zhao et al., 2020; Liu et al., 2022). It is highly desired to carry out research on $PM_{2.5}$ source apportionment based on CTM to formulate RJPC schemes to effectively reduce $PM_{2.5}$ concentration levels.

The concentration of $PM_{2.5}$ in any region or city is impacted not just by local emissions (Zhao et al., 2023), but also by the transport contribution from neighboring or distant areas, influenced by meteorological conditions (Wang et al., 2017; Gu et al., 2023). A well-designed RJPC scheme must consider both the impacts of inter-regional transport and the emissions from various source categories. $PM_{2.5}$ source apportionment is vital in identifying the dominant contributors of both regions and emission categories to $PM_{2.5}$ levels in specific areas. It also identifies where emission reduction efforts should be focused to effectively decrease $PM_{2.5}$ concentrations. The results of $PM_{2.5}$ source apportionment are essential for the development of RJPC schemes. However, a gap remains in understanding how to develop specific RJPC schemes through quantitative $PM_{2.5}$ source apportionment based on CTM model, with the goal of effectively mitigating $PM_{2.5}$ levels in targeted regions.

Recent RJPC studies can generally be categorized into two types. The first type includes RJPC schemes derived from statistical analysis or machine learning applied to observational data (Wang and Zhao, 2018; Xie et al., 2018; Wang et al., 2020), which often exhibit basic and imprecise characteristics. The second type involves suggesting RJPC implications based on source apportionment obtained from regional air quality models (Wang et al., 2017; Chang et al., 2019); however, these often result in qualitative RJPC recommendations without quantitative, actionable schemes. The effectiveness of RJPC scheme implementation heavily relies on the specificity, quantification, and clarity of the schemes. This study addresses this issue by proposing a comprehensive framework for developing RJPC schemes characterized by enhanced detail, quantification, and clarity.

In this study, the Fenhe Plain, one of the most polluted regions in China, was taken as a case study to present a framework for designing RJPC schemes. The air quality model system of Weather Research and Forecasting (WRF) and CMAQ was used to perform a comprehensive source apportionment of $PM_{2.5}$, quantitatively determining the contributions from various regions and emission categories during a severe $PM_{2.5}$ pollution episode from January 20th to 25th, 2021. Informed by this source apportionment, multiple RJPC scenarios were specifically designed with the goal of eliminating this type of heavy pollution episode. Then, recommended RJPC schemes were presented, following an evaluation of these scenarios' effectiveness in reducing $PM_{2.5}$ levels in the Fenhe Plain. This study offers valuable insights into the high-efficiency formulation of RJPC schemes, thereby supporting governmental efforts to more effectively combat pollution.

2. Methodology

Improving air quality by eliminating heavy $PM_{2.5}$ pollution was a crucial objective for cities in the Fenhe Plain. This study aimed to tackle this challenge by simulating the chemical and physical processes of the "one-atmosphere" system using WRFv4.0 and CMAQv5.3.2. Its main emphasis was on deriving the most effective RJPC schemes through a combined approach of source apportionment and evaluation.

2.1. Model setup and data

In this modeling system, there were two nested modeling domains with horizontal resolutions of 36 km and 12 km, respectively, as depicted in Fig. 1(a). The innermost domain was the target domain, covering the entire YRD, BTH, Central China, Fenhe Plain, and Weihe Plain. This study specifically targeted the Fenhe Plain, which covers six cities: Taiyuan, Luliang, Jinzhong, Linfen, Yuncheng, and Sanmenxia.

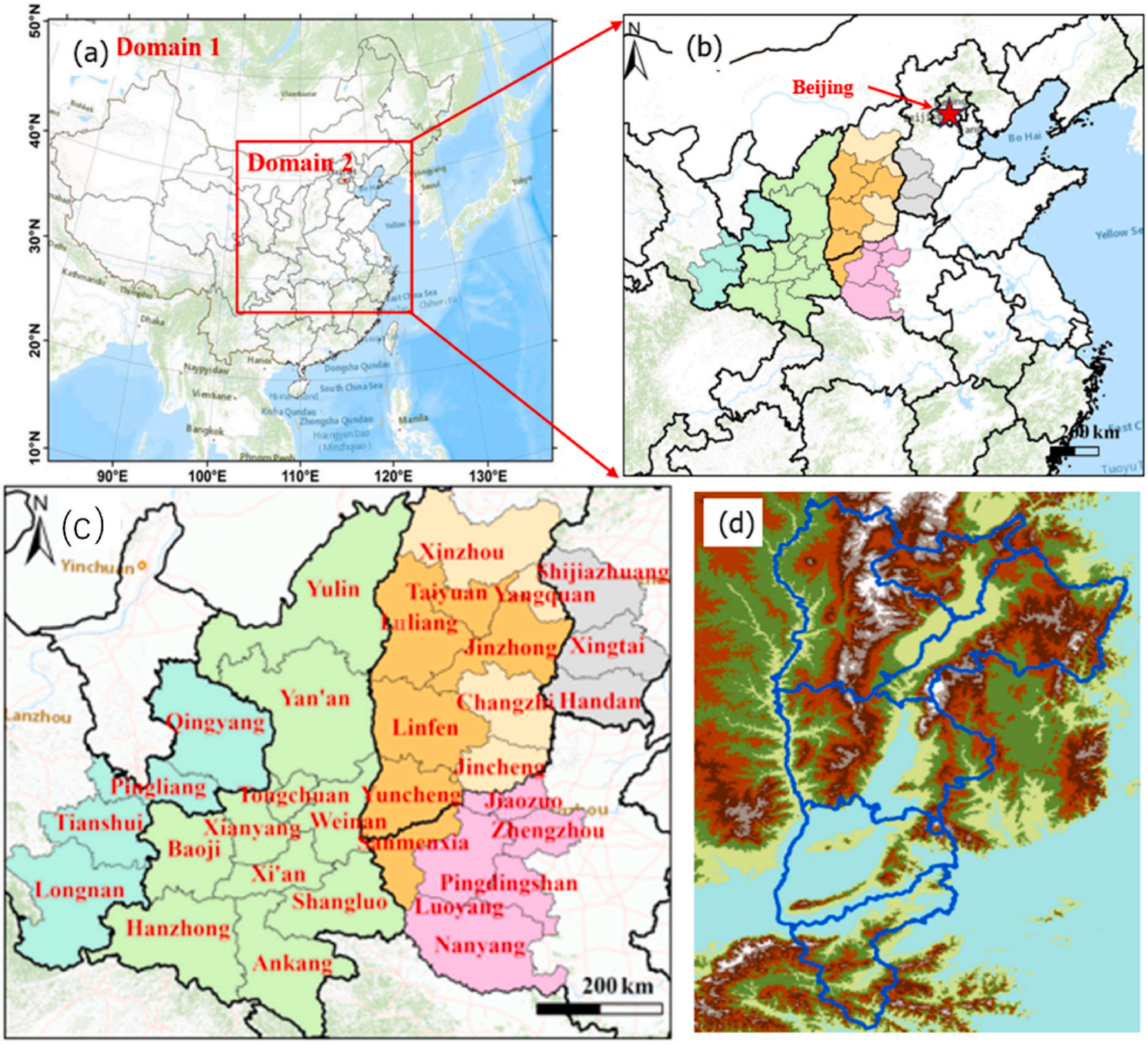

Fig. 1. Modeling domains and geographical features. Panels (a) and (b) illustrate the modeling system's domains. Panel (c) shows the geographical locations of the 32 cities involved in the source apportionment study. Panel (d) highlights the Fenhe Plain's geographical location and topography. The six cities within the Fenhe Plain and their neighboring cities, along with their respective provinces or regions, which were listed as follows: (1) Hebei province: Shijiazhuang, Xingtai, Handan; (2) Shanxi province: Xinzhou, Yangquan, Changzhi, Jincheng; (3) Henan province: Jiaozuo, Zhengzhou, Luoyang, Nanyang, Pingdingshan; (4) Shaanxi province: Ankang, Yanan, Tongchuan, Baoji, Yulin, Xianyang, Hanzhong, Xian, Shangluo, Weinan; (5) Gansu province: Qingyang, Pingliang, Tianshui, Longnan; (6) Fenhe plain: Yuncheng, Luliang, Jinzhong, Taiyuan, Linfen, Shanmenxi.

The geographical location of these cities, along with 26 surrounding cities, are shown in Fig. 1(c). The region's topography is characterized by mountains flanking both sides of the Fenhe Plain.

In this simulation study, the Carbon Bond Mechanism version 06 (CB06) and AERO version 07 (AE07) were used to simulate gas-phase chemistry and aerosols processes, respectively. Both WRF and CMAQ models were initialized with a 15-day spin-up period. The Multi-resolution Emission Inventory of China (http://www.meicmodel.org) of 2019, developed by Tsinghua University, was used as the anthropogenic emission inventories. Natural (biogenic) emission inventories were generated using the Model of Emissions of Gases and Aerosols from Nature (MEGANv3.1). Additionally, CMAQ-ready emission files were prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE). The configurations for both CMAQ and WRF models in this study align with those utilized in a previous study (Wang et al., 2022).

The ISAM method embedded in CMAQ (https://cmascenter.org) was used to quantitatively determine the contributions of various regions and emission categories to $PM_{2.5}$ and its components in six cities of the Fenhe Plain: Taiyuan, Luliang, Linfen, Jinzhong, Yuncheng, and Sanmenxia. During the source apportionment simulation, there were 32 contributing cities across five provinces, including Shanxi, Hebei, Henan, Shaanxi, and Gansu, as shown in Fig. 1 (c). The emission inventory for the innermost domain included seven source categories: Power Plants (PO), Industrial Emissions (IN), Residential Emissions (RE), Transportation Emissions (TR), Agricultural Sources (AR), Natural Sources (NA), Dust Emissions (DU). The ISAM method apportioned pollutant concentrations to these source categories throughout the simulation period.

The transport contribution of $PM_{2.5}$ in the Fenhe Plain cities was categorized in the ISAM simulation based on their approximate distance from each receptor city. The categories were (1) BCON (Ultra-Long-Distance Regions - ULDR), covering areas over 600 km away, outside the second domain; (2) OTH (Long-Distance Regions - LDR), representing regions beyond 350 km but within 600 km, excluding the 32 cities within the second domain; (3) Medium-Distance Regions (MDR), including the remaining 26 cities outsider the Fenhe Plain; and (4) Short-Distance Regions (SDR), comprising the other five cities within the Fenhe Plain, excluding the receptor city.

2.2. Methodological framework

A methodological framework was developed to design RJPC schemes for reducing $PM_{2.5}$ concentrations in the Fenhe Plain, as shown in Fig. 2. Initially, the $PM_{2.5}$ source apportionment was performed using the ISAM method based on the WRF-CMAQ modeling system for a typical $PM_{2.5}$ pollution episode from January 20th to 25th, 2021. Following the principle of prioritizing regions or emission categories with higher contribution rates and greater controllability, fifteen RJPC scenarios were initially designed for this episode to eliminate heavy $PM_{2.5}$ pollution in the Fenhe Plain. The effectiveness of these scenarios in reducing $PM_{2.5}$ was evaluated to formulate the recommended RJPC scheme.

The model performance was evaluated by comparing observed and simulated data in the Fenhe Plain based on various statistical metrics, including the normalized mean error (NME), root mean square error (RMSE), mean bias (MB), normalized MB (NMB), correlation coefficient (R) and the index of agreement (IOA). Detailed equations for these metrics can be found in the Supporting Information file (Equations S1–S6). Hourly air pollutant observations of national control monitoring stations were sourced from the Ministry of Ecology and Environment (MEE) repository (http://datacenter.mep.gov.cn), while meteorological data were sourced from the China Meteorological Administration (CMA). The WRF and CMAQ model simulations generally were in good agreement with observations. More comprehensive details on model performance were included in the support information file.

3. Results and discussion

The heaviest $PM_{2.5}$ pollution in the Fenhe Plain typically occurs during winter, with January emerging as the most polluted month in 2021. It was necessary to analyze concentration observations to understand the characteristics of $PM_{2.5}$ pollution and episodes in the Fenhe Plain.

3.1. Evolution of the $PM_{2.5}$ pollution

From January 13th to 15th, 2021, elevated $PM_{2.5}$ concentrations were observed in the Fenhe Plain and its neighboring cities, mainly caused by sandstorms (Fig. 3). The simulations cannot capture the observed peak value well due to the absence of the dust module in the model system. Subsequently, from 2nd to 4th, the Fenhe Plain experienced $PM_{2.5}$ pollution, but a more widespread and severe $PM_{2.5}$ pollution episode occurred from 20th to 25th. During the latter period, Sanmenxia suffered the heaviest pollution among the six cities of the Fenhe Plain. Daily peak $PM_{2.5}$ concentrations in Sanmenxia, Yuncheng, and Linfen were 219.2, 178.2, and 168.8 $\mu g/m^3$, respectively, all exceeding the limit of heavy pollution in National Ambient Air Quality Standards (NAAQS) of 150 $\mu g/m^3$. Meanwhile, the peaks of daily $PM_{2.5}$ concentrations in Taiyuan, Jinzhong, and Luliang reached 135.1, 100.2, and 90.4 $\mu g/m^3$, respectively, classified as moderate, light, and light pollution according to NAAQS. To improve the air quality in the Fenhe Plain, the primary focus should be on mitigating heavy pollution episodes in Sanmenxia, Yuncheng, and Linfen.

3.2. Source apportionment

During the entire of January, the Fenhe Plain and the ULDR area (i.e., BCO) exhibited higher contribution percentages compared to the pollution episode during the period of 20th –25th, 2021. However, the contribution percentages of both LDR (i.e., OTH) and MDR (i.e., 26 cities around the Fenhe Plain) during the pollution period were significantly higher, as shown in Fig. 4. In other words, during this pollution period, the total contribution from LDR and MDR to the increase in $PM_{2.5}$ concentration was much greater than the contribution from ULDR. Despite this, the Fenhe Plain was still the largest contributor during the pollution period, accounting for 58.3%. Among the local cities in the Fenhe Plain, Taiyuan contributed the most, accounting for 23.7%, while Jinzhong and Linfen also contributed significantly, accounting for 7.8% and 12.0% respectively. Sanmenxia contributed the least. During the pollution period, industrial emissions and dust emissions in the Fenhe Plain were the main contributors, accounting for 21.5% and 15.9%, respectively. Detailed source apportionment results for each city in the Fenhe Plain are shown in Fig. S5, Table S4, and Table S5.

As shown in Fig. 5, sulfate concentrations in the Fenhe Plain in Jan. 2021 were dominated by ULDR (23.2%), followed by Taiyuan contributing 19.1%, and a small contribution (14.3%) from LDR (i.e. OTH). However, compared with the non-polluted period, the ULDR contribution to sulfate decreased during the polluted period; on the contrary, the LDR contribution increased obviously, along with the increased contribution from Hebei and Henan. Specifically, in the non-pollution period, sulfate contributions from the ULDR were substantially higher than those of the LDR. In contrast, during the pollution period, sulfate transport from the LDR was much more pronounced than that from the ULDR.

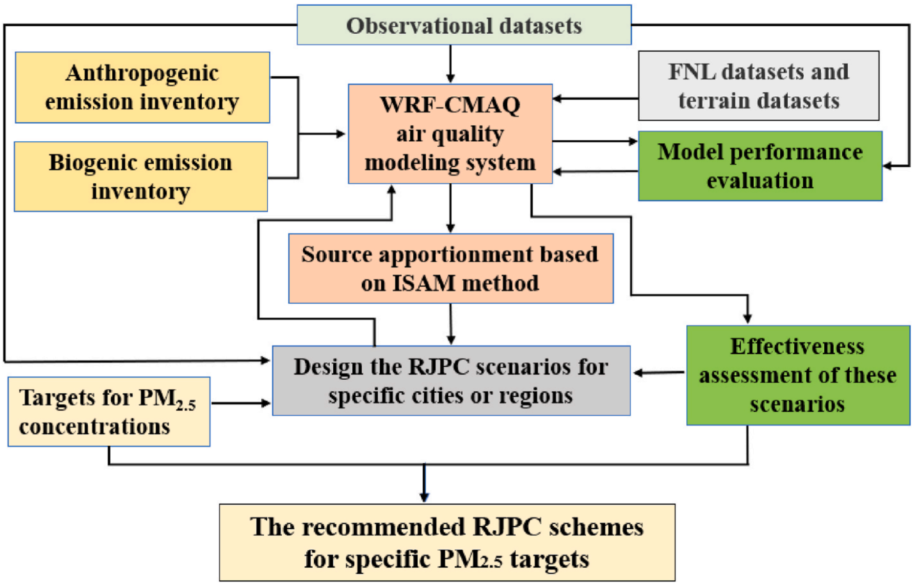

Fig. 2. Methodological framework for designing RJPC schemes.

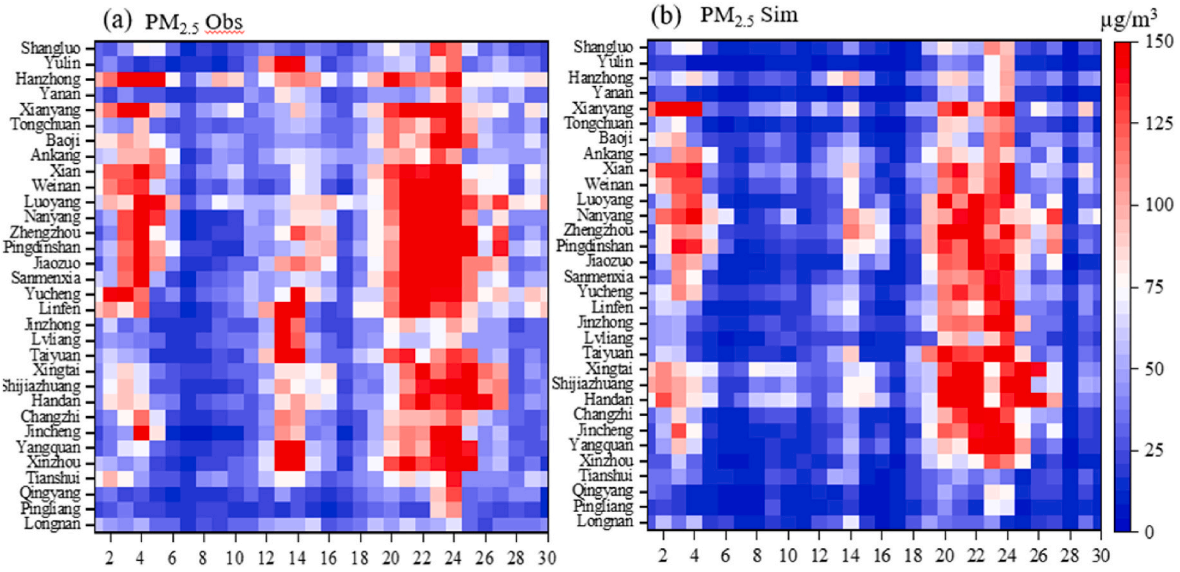

Fig. 3. (**a**) Observed daily $PM_{2.5}$ and (**b**) simulated daily $PM_{2.5}$ concentration in 32 cities of the Fenhe Plain and its surrounding areas for Jan. 2021. Cities were generally ordered based on altitude and longitude The daily average $PM_{2.5}$ concentration limits for light, moderate, and heavy pollution in China's NAAQS are 75, 115, 150, and 200 μg/m^3, respectively. Refer to Fig. 1 for detailed information on the cities.

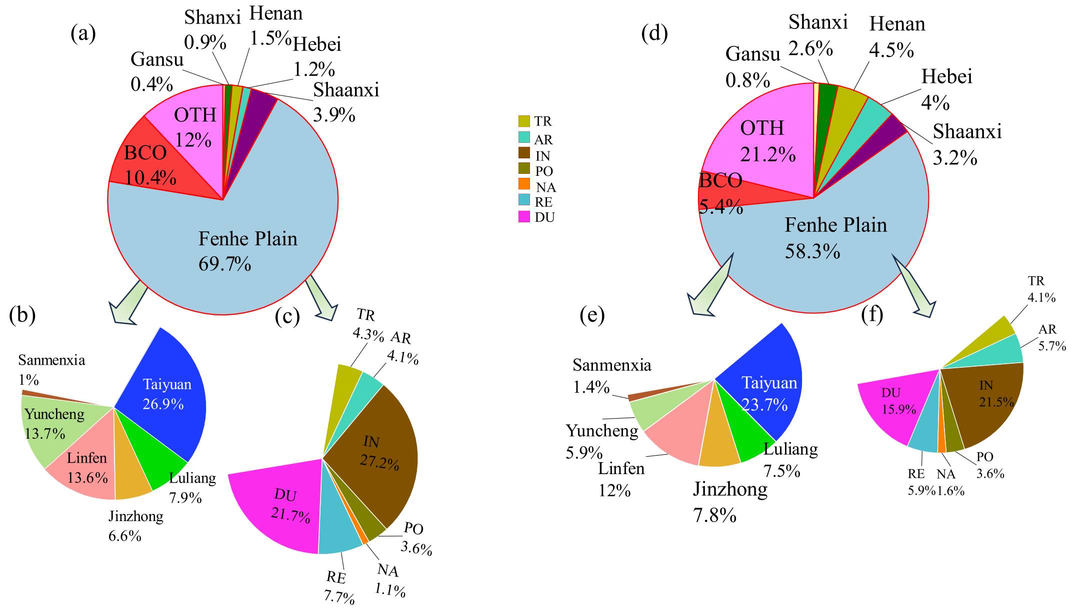

Fig. 4. Contribution percentages of the average concentrations of $PM_{2.5}$ in Fenhe Plain from various emission regions for Jan. 2021 (a,b, and c) and during the pollution episode during the period of 20th –25th, 2021 (d, e, and f). The average concentration of $PM_{2.5}$ in Fenhe Plain contributed from Fenhe Plain local was further apportioned into six cities (b and e) or into emission categories (c and f) of Fenhe Plain. The abbreviations PO, IN, RE, TR, AR, NA, and DU denote the emissions from power plants, industrial emissions, residential emissions, transportation emissions, agricultural sources, natural sources, and dust, respectively.

Compared with sulfate, nitrate contribution in the Fenhe Plain from ULDR in January 2021 was relatively minor (7.1%), while LDR and MDR contributed more, accounting for 30.8% and 62.0%, respectively. The LDR's contribution percentage remained relatively unchanged between pollution and non-pollution periods. However, the MDR's contribution percentage during the pollution period was significantly higher, particularly from Hebei, Henan, and Shaanxi, as part of the MDR.

The local contribution accounted for 78.7% of elemental carbon (EC) in the Fenhe Plain in Jan. 2021. Compared with the non-pollution period, the contribution of MDR during the pollution period increased significantly, accounting for 19.9%, while the SDR contribution decreased, accounting for 64.9%. Similar to EC, organic carbon (OC) displayed a notable local contribution; however, compared with EC, OC had a higher proportion of contributions from LDR.

The source contributions of ammonium and nitrate in the Fenhe Plain in January 2021 exhibited certain similarities. Both showed small ULDR contributions, while LDR and MDR contributions were relatively large. A key distinction, however, was the significantly higher local contribution to ammonium compared to nitrate. During the pollution period, local contribution accounted for 41.0% of ammonium. The contributions from LDR and MDR to ammonium during the pollution period were obviously larger than those during the non-pollution period.

The regional source apportionment results for $PM_{2.5}$ and its components within the Fenhe Plain suggested that effective pollution control

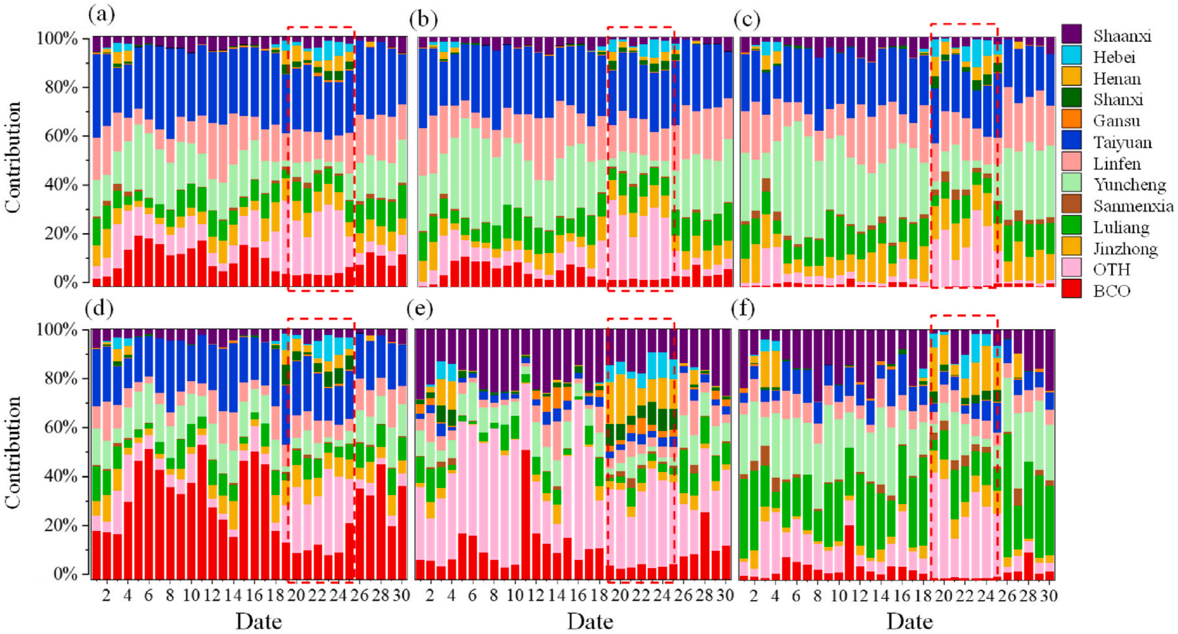

Fig. 5. Temporal variation of regional contribution percentages of $PM_{2.5}$ and its components in the Fenhe Plain in January 2021 (a: $PM_{2.5}$; b: OC; c: EC; d:SO_4^{2-}; e: NO_3^-; f: NH_4^+).

required not just intensified local emission control measures in the Fenhe Plain but also prioritized focus on two critical aspects: (1) controlling SO_2 emission in ULDR, LDR and MDR and (2) controlling NOx and NH_3 emissions in LDR and MDR.

As shown in Fig. 6, the contribution from Taiyuan to $PM_{2.5}$ was relatively large. The biggest contributor to nitrate was Henan and Hebei, followed by Shaanxi. Taiyuan had the highest contribution to $PM_{2.5}$ from the local city, followed by Jinzhong, with Sanmenxia having the smallest contribution. Specifically, a substantial 61% of Taiyuan's $PM_{2.5}$ was attributed to the local city's contribution. The proportions of the local city's contribution for Linfen, Luliang, and Jinzhong were 42%, 38%, and 35%, respectively. Among seven emission categories, the local city's industrial and dust emissions were the biggest contributors to $PM_{2.5}$ in each city within the Fenhe Plain.

As shown in Fig. 7, regarding regional contribution patterns, the six cities can be classified into three distinct types: exporting, importing, and comprehensive cities. Taiyuan and Linfen acted as typical $PM_{2.5}$ exporters, characterized by significant local contributions and a notable impact on other cities. In contrast, Sanmenxia, Jinzhong, and Luliang were identified as $PM_{2.5}$ importers, with their ranking in descending order of contributions received from external regions. Additionally, Yuncheng was a comprehensive city, characterized by both exporting and importing attributes. It significantly contributed to Sanmenxia, primarily as an exporter, while receiving considerable contributions from LDR.

3.3. *Designing RJPC scenarios*

Given the substantial contributions from MDR (i.e., Hebei, Henan, Shanxi, Gansu, and Shaanxi) and LDR (i.e., OTH) to $PM_{2.5}$ in Fenhe Plain during the pollution episode, implementing emission controls in these areas was crucial. Notably, Sanmenxia, located in the Fenhe Plain, recorded the highest $PM_{2.5}$ concentrations. Its unique geographical features — a narrow, elongated terrain at the Fenhe Plain's edge — made it particularly vulnerable to emissions from neighboring areas, especially Henan, Shaanxi, and Hebei. Therefore, stringent measures of

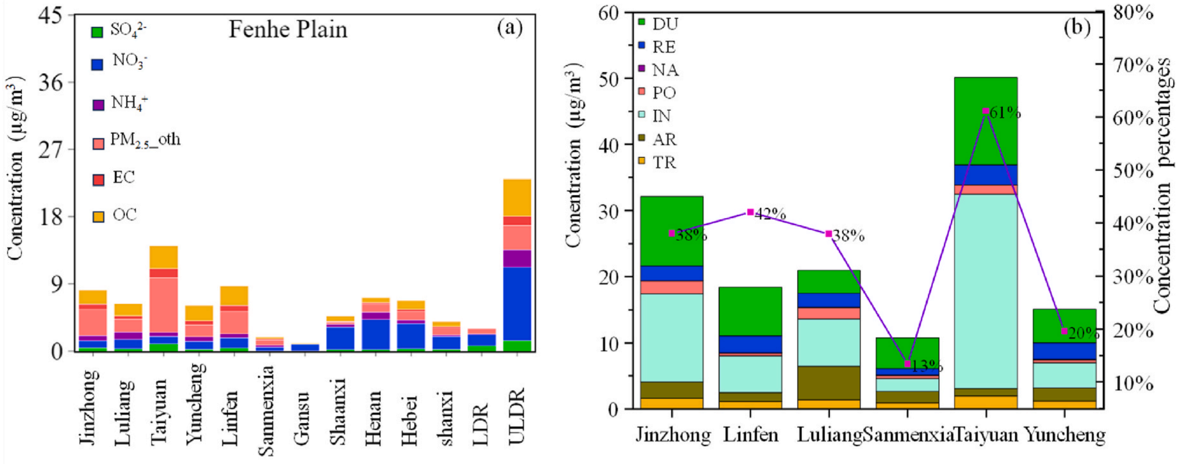

Fig. 6. (a) Average concentrations of $PM_{2.5}$ components in the Fenhe Plain contributed from different cities or regions during the pollution episode. (b) $PM_{2.5}$ contribution concentration (colored bar) and contribution percentage (line) from each city's own emissions during the pollution episode.

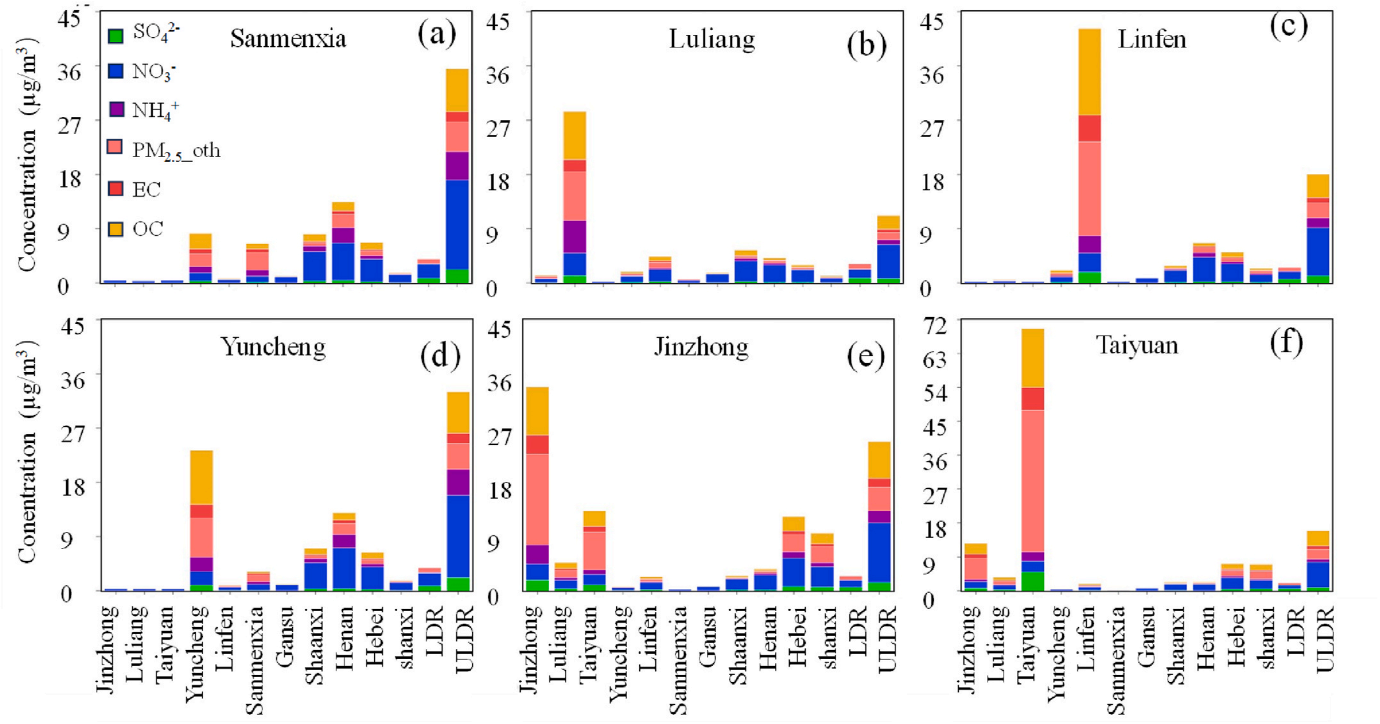

Fig. 7. Contributions from various regions to $PM_{2.5}$ components in individual cities of the Fenhe Plain during the pollution period of Jan. 20th-25th, 2021

emission control in both MDR and LDR were essential for mitigating $PM_{2.5}$ levels in Sanmenxia. Accordingly, an RJPC scenario was proposed, which set a low emission ratio of 10% for both MDR and LDR, specifically to aid Sanmenxia in achieving NAAQS compliance.

It was evident that dust and industrial emissions held greater significance compared to transportation (mobile sources) and residential emissions. Furthermore, the control measures for dust and industrial emissions were relatively easy to implement. Consequently, the emission rates for dust and industrial sources in some RJPC scenarios, e.g., S10–S13 as shown in Table 1, were specially set lower than for the other two emission categories. Notably, China's power plants already complied with ultra-low emission standards, offering minimal further reduction potential. Thus, in the RJPC scenarios, their emission rates remained unchanged (100%), indicating no reduction. Emissions from natural sources, inherently beyond human control, were also not reduced in these scenarios. Additionally, there were no recommended emission control measures for mitigating emissions from agricultural sources so far, so agricultural sources were also set to have no emission reduction in the scenario design.

In order to eliminate heavy pollution and even achieve $PM_{2.5}$ compliance, 15 RJPC scenarios were initially designed, as shown in Table 1. Power plants, natural sources, and agricultural sources were excluded from Table 1 as their emission ratios were kept at 100%. It is worth mentioning that emission control in other regions (MDR and LDR) may be more challenging than that of the Fenhe Plain. This was particularly true for the ULDR, where emission reduction was significantly more difficult. As a result, in the majority of RJPC scenarios, the emission ratios for these regions, especially the ULDR, were set higher than those assigned to cities within the Fenhe Plain.

Table 1
RJPC scenarios with various emission ratios of regions or categories during the pollution episode from Jan. 20th to 25th, 2021 (Units: %).

Regions or emission categories		Names of RJPC scenarios														
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Taiyuan and Linfen	IN	10	25	40	40	40	40	25	40	50	40	60	60	75	75	75
	DU	10	25	40	40	40	40	25	40	50	40	20	60	75	75	75
	RE	10	25	40	40	60	60	50	40	50	60	80	80	90	75	75
	TR	10	25	40	40	60	60	50	40	50	60	80	80	90	75	75
Yuncheng	IN	10	25	40	40	40	40	25	40	50	40	60	60	75	75	75
	DU	10	25	40	40	40	40	25	40	50	40	20	60	75	75	75
	RE	10	25	40	40	80	80	50	40	50	60	80	80	90	75	75
	TR	10	25	40	40	80	80	50	40	50	60	80	80	90	75	75
Jinzhong, Luliang, and Sanmenxia	IN	10	25	40	40	40	40	25	40	50	40	60	60	75	75	75
	DU	10	25	40	40	40	40	25	40	50	40	20	60	75	75	75
	RE	10	25	40	40	40	40	50	40	50	60	80	80	90	75	75
	TR	10	25	40	40	40	40	50	40	50	60	80	80	90	75	75
Hebei		10	25	40	25	25	40	40	40	50	50	60	60	75	75	100
Henan		10	25	40	25	25	40	40	40	50	50	60	60	75	75	100
Shanxi		10	25	40	25	25	40	40	40	50	50	60	60	75	75	100
OTH, Gansu, and Shaanxi		10	25	40	25	25	40	40	40	50	50	60	60	75	75	100
ULDR		25	25	25	50	50	50	50	50	50	75	75	75	75	100	100

3.4. *Effectiveness assessment of these scenarios*

The effectiveness of $PM_{2.5}$ reduction in each city within the Fenhe Plain under the RJPC scenarios during the pollution episode from Jan. 20th to 25th, 2021 was evaluated. Detailed $PM_{2.5}$ concentration reductions and corresponding reduction ratios for each city were presented in Fig. 8 and Table S6. In scenario S15, featuring a 75% emission ratio exclusively within the Fenhe Plain (equivalent to a 25% emission reduction), Taiyuan exhibited the highest reduction in $PM_{2.5}$ concentration, amounting to 13.3%. This was closely followed by Linfen, Jinzhong, and Luliang, with reductions of 9.4%, 8.9%, and 9.5%, respectively. In contrast, Sanmenxia and Yuncheng showed comparatively modest decreases, at 1.9% and 5%, respectively. Sanmenxia's notably low reduction ratio can be primarily attributed to minimal local contributions from the Fenhe Plain and substantial contributions from regional transport beyond the Fenhe Plain.

In scenario (S14), where the ULDR emission ratio remained at 100%, and the emission ratios for all other regions were set to 75%, a $PM_{2.5}$ reduction ratio of 20% was achieved in Taiyuan. Reducing this ratio further to 50% from 75%, significantly increased Taiyuan's reduction to 38.4% in scenario S9. Under the condition that the emission rates for all regions except ULDR were set at 40%, a scenario (S3) with a 25% emission rate in ULDR, in comparison to a scenario (S8) where ULDR's emission rate was 50%, results in a 6.1% increase in the $PM_{2.5}$ reduction ratio for Luliang. However, this change led to less than a 5% increase in $PM_{2.5}$ reduction ratios for the other cities in the Fenhe Plain. With an emission rate of 25% in ULDR, the $PM_{2.5}$ concentration reduction rates in the Fenhe Plain decreased successively in alignment with the scenarios featuring emission ratios of 10% (S1), 25% (S2), and 40% (S3) in all regions except ULDR. As an example, the $PM_{2.5}$ reduction ratios for Sanmenxia in these three scenarios were 72.1%, 57.5%, and 44.0%, respectively.

A comparison between the S4 and S5 scenarios revealed that emission reductions from residential and transportation sources had a relatively minor impact on reducing $PM_{2.5}$ concentrations. In contrast, the comparisons between the S6 and S7 scenarios, as well as between the S11 and S12 scenarios, illustrated that emission reductions from industrial and dust sources had a more pronounced effect on $PM_{2.5}$ concentration reduction, with the exception of Sanmenxia.

Comparison of S5 and S6 scenarios underscores those changes in emissions from LDR and MDR had the most pronounced impact on the $PM_{2.5}$ reduction ratio in Sanmenxia, resulting in an increase of 12.2% reduction in S5 compared to S6. Conversely, the shift in the reduction ratio of $PM_{2.5}$ concentration in Taiyuan was relatively modest, only amounting to 4.8%. This suggested that changes in emission in LDR and MDR had the most substantial influence on the reduction of $PM_{2.5}$ concentration in Sanmenxia, which was consistent with the above source apportionment results.

Moreover, the comparison of scenarios S10, S12, and S13 implied that strengthening emission control in the Fenhe Plain, MDR, and LDR regions can significantly promote the reduction of $PM_{2.5}$ concentrations in cities within the Fenhe Plain during the pollution episode, and it was of great significance for eliminating $PM_{2.5}$ pollution episode in cities of the Fenhe Plain.

During this pollution episode, $PM_{2.5}$ concentrations in Sanmenxia, Linfen, and Yuncheng exceeded the NAAQS heavy pollution threshold of 150 $\mu g/m^3$. Taiyuan experienced moderate pollution levels, while Jinzhong and Luliang were affected by light pollution. Fig. 9 illustrates the simulated $PM_{2.5}$ concentrations for all RJPC scenarios during the two most polluted days in each Fenhe Plain city, clearly indicating which scenarios can achieve the goal of eliminating heavy pollution.

For Linfen, a city with heavy pollution, the S15 scenario, which involved a 25% emissions reduction across the six cities in the Fenhe Plain, was insufficient to completely eliminate heavy pollution. However, by further reducing emissions in the MDR region by 25% (S14), heavy pollution can be effectively eliminated. Another effective scenario was S13, which involved differentiated emission reduction schemes. Specifically, S13 scenario included a 25% emission reduction outside the Fenhe Plain, a 10% emission reduction in residential and transportation sources, and a 25% emission reduction in industrial and dust sources in the six cities of the Fenhe Plain. The S13 scenario featured lower emission reduction ratios for residential and transportation sources, due to the greater challenge in controlling emissions from these two categories compared to industrial and dust sources. As a result, the S13 scenario was relatively easy to implement and can serve as a recommended RJPC scenario, as shown in Fig. 10(b).

For Yuncheng, neither the S15 nor the S13 scenario was effective in eliminating heavy pollution. However, both the S14 and S12 scenarios had the potential to eliminate heavy pollution. Compared with S14, S12 was a more balanced and reasonable scenario. Under the S12 scenario, LDR and MDR emissions were reduced by 40%, which was greater than ULDR, and industrial and dust emissions were reduced by 40%, which was greater than residential and traffic sources. S12 can be considered as a recommended RJPC scenario for Yuncheng as shown in Fig. 10 (a). For Sanmenxia, none of the S9-15 scenarios can eliminate heavy pollution. However, scenarios S6, S7, and S8 can eliminate heavy pollution and have similar $PM_{2.5}$ reduction effects. Compared to S8, scenarios S6 and S7 were differentiated scenarios and more reasonable, but S7 was much stricter in emission control. Thus, S6 can be the recommended scenario for Sanmenxia, as shown in Fig. 10 (c).

Nonetheless, the Fenhe Plain still faced a big challenge in fully meeting NAAQS standards. Achieving $PM_{2.5}$ compliance across the

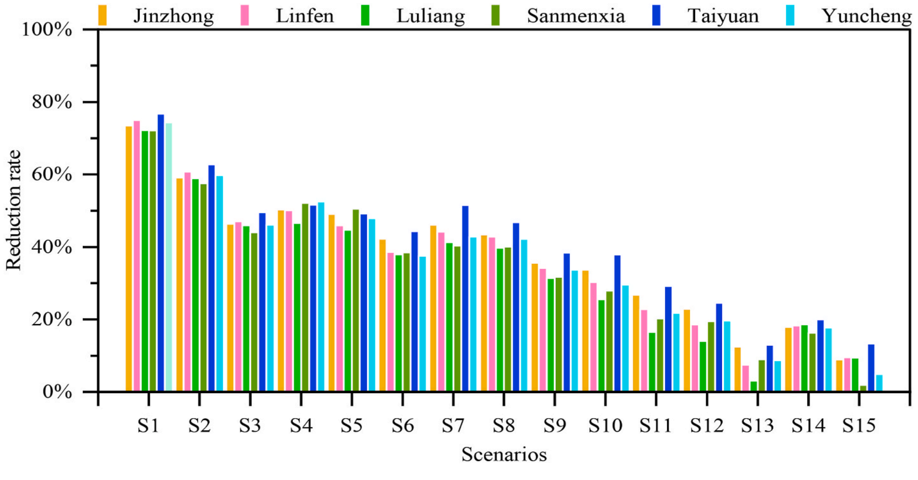

Fig. 8. Reduction ratios of $PM_{2.5}$ concentrations in the Fenhe Plain cities during the pollution episode under various emission reduction scenarios.

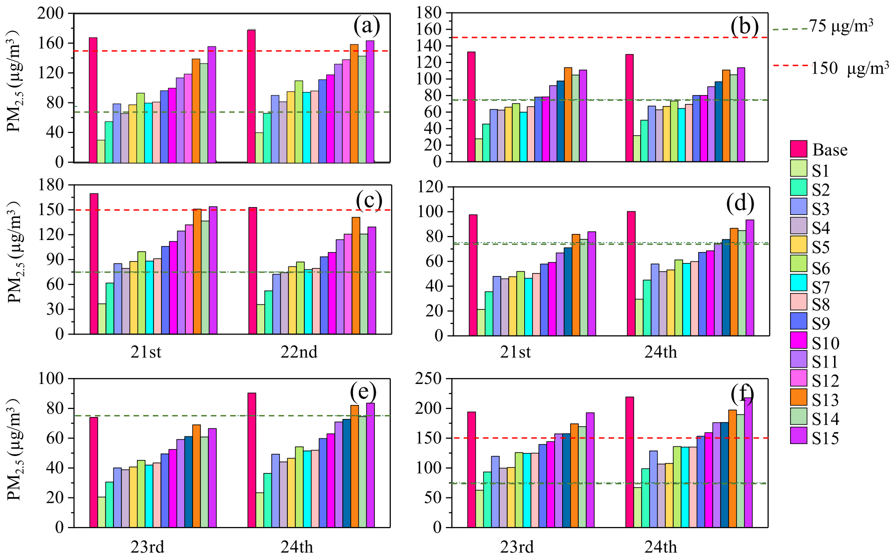

Fig. 9. $PM_{2.5}$ simulations of cities in the Fenhe Plain under 15 emission scenarios during the two most polluted days of the pollution period. (a:Yunchen; b:Taiyuan; c: Linfen; d: Jinzhong; e: Luliang; f: Sanmenxia). The green and red dashed lines represented the $PM_{2.5}$ limits for light and heavy pollution levels, respectively, according to the NAAQS. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

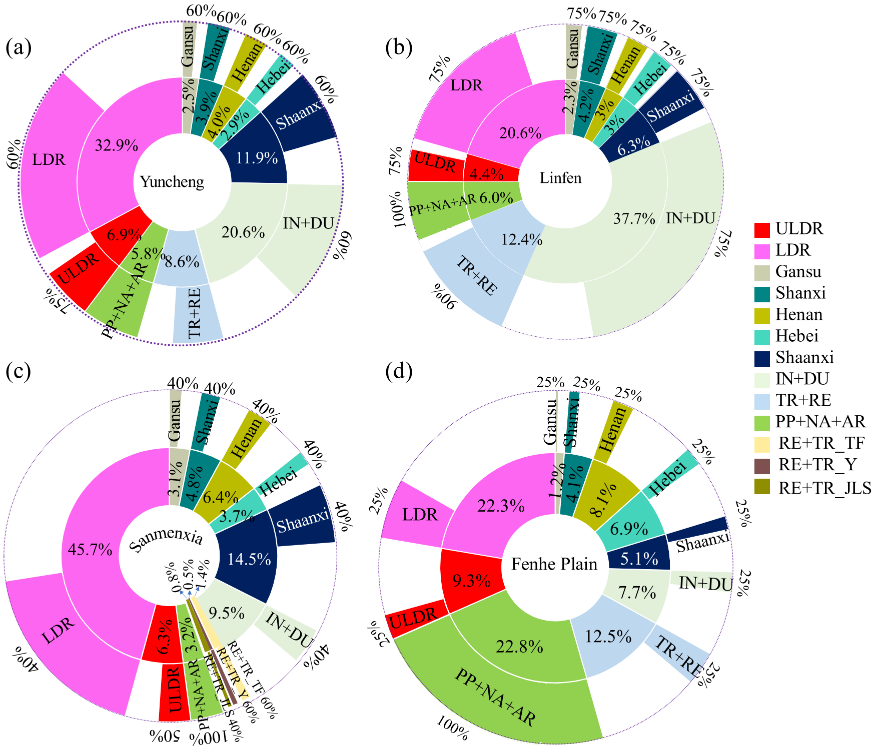

Fig. 10. Source contribution percentages and the recommended RJPC schemes during the pollution episode. The outer rings depict the recommended RJPC schemes with varying emission ratios of different emission regions or emission categories for the purpose of eliminating heavy pollution in Yuncheng (a), Linfen (b), and Sanmenxia (c), as well as achieving NAAQS compliance in the Fenhe Plain (d). The inner rings illustrate contributions percentages of $PM_{2.5}$ from various emission regions or emission categories for Yuncheng (a), Linfen (b), Sanmenxia (c), and the Fenhe Plain (d) during the pollution period. RE + TR_TF denotes the residential and transportation emissions from Taiyuan and Linfen, while RE + TR_Y denotes the residential and transportation emissions from Yuncheng. Similarly, RE + TR_JLS represents the residential and transportation emissions of Jinzhong, Luliang, and Sanmenxia.

region was only feasible through the implementation of broader and more intensive emission control measures, akin to those in the S1 scenario, as depicted in Fig. 10(d).

4. Conclusions

This study employed a typical heavy pollution episode (January

20th–25th, 2021) in the Fenhe Plain as a case study to present a framework for developing the $PM_{2.5}$ RJPC scheme. This was based on detailed source apportionment of $PM_{2.5}$ and a thorough evaluation aimed at eliminating heavy pollution and attaining $PM_{2.5}$ compliance goals during this type of heavy haze pollution episode. This study leads to several main conclusions.

During the pollution episode, emissions from LDR and MDR contributed more to $PM_{2.5}$ in Fenhe Plain than from ULDR, although Fenhe Plain was the largest contributor, accounting for 58.3%. Notably, the contribution of areas within a 350-km radius to $PM_{2.5}$ in the Fenhe Plain increased significantly during this period compared to non-pollution episodes. Moreover, Taiyuan and Linfen served as typical $PM_{2.5}$ exporters, while Sanmenxia, Jinzhong, and Luliang acted as $PM_{2.5}$ importers.

Prioritizing the emission control of particulate matter, ammonia, nitrogen oxides, and volatile organic compounds within a 350-km radius, along with reinforcing local emission control measures within the Fenhe Plain, was essential for eliminating heavy $PM_{2.5}$ pollution in the region during this type of heavy pollution episode.

The formulation of a successful $PM_{2.5}$ RJPC scheme should be based on scientific source apportionment, taking into account the differing challenges in implementing emission control measures in various sources. Furthermore, conducting a thorough scientific evaluation of the RJPC scheme should not be neglected.

In China's Air Quality Continuous Improvement Action Plan released at the end of 2023, reducing $PM_{2.5}$ concentration and eliminating heavy pollution were still essential tasks. The framework for formulating specific RJPC schemes proposed in this study strongly supports this. Mitigating ozone pollution remains another essential task for many cities in China. Due to the strong nonlinearity of ozone's response to precursors, the formulation of RJPC schemes aimed at reducing ozone must be based on reliable ozone source apportionment studies to ensure the effectiveness of the RJPC schemes.

CRediT authorship contribution statement

Yangjun Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Miao Ning:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Qingfang Su:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Lijuan Wang:** Methodology, Funding acquisition, Conceptualization. **Sen Jiang:** Visualization, Validation, Software, Methodology. **Yueyi Feng:** Visualization. **Weiling Wu:** Visualization. **Qian Tang:** Visualization. **Shiyu Hou:** Visualization. **Jinting Bian:** Visualization, Validation, Software, Methodology. **Ling Huang:** Software. **Guibin Lu:** Software. **Kasemsan Manomaiphiboon:** Methodology. **Burcak Kaynak:** Methodology. **Kun Zhang:** Writing – review & editing. **Hui Chen:** Writing – review & editing. **Li Li:** Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgment

This study was financially supported by the National Key R&D Program of China (No. 2019YFC0214205), the Open Research Subject of State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex (No. SCAPC202003), and the National Natural Science Foundation of China (No. 42075144, 42005112). We also appreciate the High-Performance Computing Center of Shanghai University and Shanghai Engineering Research Center of Intelligent Computing System (No. DZ2252600) for providing computing resources and technical support. We are grateful for the anonymous comments of reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142313.

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