Environment, Development and Sustainability
https://doi.org/10.1007/s10668-024-05400-z

# Construction of a high-resolution city-level emission inventory based on multiple methods: a case study of Cangzhou City, China

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Received: 21 May 2024 / Accepted: 3 September 2024
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**Abstract**
Cangzhou is an important city in the Beijing-Tianjin-Hebei (BTH) region for assessing air quality. Based on the data from the Continuous Emissions Monitoring System (CEMS) and other sources, in this study, we used a combination of bottom-up and top-down approaches to establish an emission inventory of nine atmospheric pollutants in Cangzhou City in 2018. The results showed that the emission of nitrogen oxides (NOx), sulfur dioxide ($SO_2$), particulate matter with aerodynamic diameters less than 10 μm and 2.5 μm ($PM_{10}$ and $PM_{2.5}$), volatile organic compounds (VOCs), carbon monoxide (CO), ammonia ($NH_3$), black carbon (BC), and organic carbon (OC) were 20.29, 82.67, 116.41, 54.87, 702.81, 87.66, 62.00, 4.15, and 3.83 kt, respectively. Most of the emitted pollutants were concentrated in the eastern and southern areas of Cangzhou, but $NH_3$ was emitted the most in the eastern region. In this study, we revealed the emission characteristics of air pollutants and put forward the air pollution control suggestions, which can not only provide a scientific basis for pollution control efforts in the city and similar industrial structure of the city but also offer valuable insights and references for environmental governance across the BTH region. Analyzing emission characteristics and mitigation measures in Cangzhou enhanced understanding of pollution status and management needs in the BTH region, thereby supporting regional coordinated governance with data-backed policy recommendations.

**Keywords** Emission inventory · Characteristics of air pollution emissions · Comprehensive sources attribution · Continuous emissions monitoring system (CEMS) · Cangzhou · Air quality

Extended author information available on the last page of the article

Published online: 10 January 2025

## 1 Introduction

With rapid economic development and accelerated industrialization and urbanization, air quality has decreased considerably (Yao et al., 2019). In 2018, among the 338 major cities in China, 64.2% of them failed to meet the air quality standards (MEE, 2013), and the concentration of $O_3$ increased considerably compared to that in 2017 (MEE, 2019). Poor air quality is extremely harmful to human health, and it also affects economic growth (Dong et al., 2021; Wu et al., 2021). According to the World Health Organization (WHO), ambient air pollution is responsible for causing the premature death of approximately seven million people annually (WHO, 2021). In 2016, 18.34 million people suffered health damage due to $PM_{10}$ pollution in Hebei Province (Fan et al., 2019). Therefore, improving the air quality is extremely important. Constructing an accurate and comprehensive emission inventory is a crucial step for controlling air pollution.

China has established emission inventories of different scales to provide valuable data on emissions in recent years. Multi-resolution Emission Inventory for China (MEIC, http://www.meicmodel.org/) and China High Resolution Emission Database 3.0 A (CHRED3.0 A, http://www.ieimodel.org/) were established to assess the emission characteristics of air poll utants in China (Gao et al., 2022; Li et al., 2017). In addition, regional emission inventories have been established, such as the BTH region and the Yangtze River Delta, to understand the pollutant characteristics of urban agglomerations with large populations, developed industries and dense road networks (Fan et al., 2016; Qi et al., 2017; Yang et al., 2020). However, due to the general emission source data, excessive research scale of emission inventory will reduce the accuracy of urban pollutant emissions, distribution of space, and air quality modeling. Some studies have demonstrated the advantages of smaller scale emission inventories with more detailed local data. For example, Hong et al. (2016) found that the atmospheric pollutant emissions calculated by China's provincial energy statistics are generally higher than those calculated by national energy statistics. In China, Zheng et al. (2014) found that vehicle emission inventories at the county level, rather than the provincial level, could better support air quality modeling for smaller areas. Timmermans et al. (2013) concluded that, compared to a downscaled emission inventory, simulated concentrations of $PM_{10}$ and $NO_2$ using a local emission inventory for Paris were more consistent with the observed data from monitoring stations in Paris. Large differences were found between sectoral contributions by comparing global and local emission inventories for five cities in South America (Huneeus et al., 2020). And this highlighted the importance of establishing accurate city-level emission inventories to formulate control policies for local air pollution characteristics. Despite the importance of city-level emission inventories, most of them focused on a single emission source or pollutant (Gong et al., 2017; Liu et al., 2017; Wu & Zheng, 2023; Zhang et al., 2013), or were limited to large cities, such as Beijing, Shanghai, and Tianjin (Chen et al., 2019; Liu et al., 2020; Sun et al., 2021). Very few inventories covered all pollutants and emission sources for medium-sized cities. Moreover, to support national industrial emission standards, China also implemented a continuous emissions monitoring system for high-emitting facilities in 2007 to obtain more precise and real-time data on the emission of atmospheric pollutants (Bo et al., 2021). However, studies on the development of city-level emission inventories that use the CEMS data are limited. To fill in these research gaps, in this study, we selected Cangzhou, a representative medium-sized

industrial city to firstly formulate an emission inventory with multi-type pollutants and data on the CEMS for 2018.

Cangzhou, as a key industrial city in the BTH region and a crucial part of the regional air pollution transmission corridor, holds significant representativeness. In 2018, Cangzhou ranked third in gross domestic product (GDP) within the province, with the secondary industry GDP reaching 43% (CBS, 2019). This rapid industrialization has aggravated air pollution, particularly due to its traditional heavy industry base in iron and steel, petrochemicals, chemicals, and construction materials, which are high-emission sectors contributing substantially to regional air quality issues. Besides, Cangzhou's strategic position as a transportation hub within the BTH region, with an extensive network of highways, railways, and waterways, makes transportation emissions a major component of its air pollution profile (Qi, 2019). Additionally, its economic development relies heavily on resource-based industries, a common trait in the BTH region, and its pollution control experiences offer valuable insights for similar cities. The city's proximity to Beijing, just 200 km away, means its air pollution can easily affect the air quality of the capital. Furthermore, the relocation of many polluting enterprises from Beijing and Tianjin to Cangzhou has increased the pressure on local pollution management. Additionally, 2018 was the year of assessing the achievements of the "Action Plan for Air Pollution Prevention and Control" and the commencement of the "Three-Year Action Plan to Win the Blue Sky Defense Battle" (CPG, 2018a, b; MEE, 2018). Hence, establishing a high-resolution and comprehensive emission inventory in Cangzhou for the year 2018 can not only provide scientific support for local pollution control but also offers critical insights for the subsequent steps in air pollution co-control, cross-boundary transfer, and management across the BTH region and beyond.

In our previous study, aiming at the foundry and the iron and steel industries in Cangzhou, we selected representative enterprises and carried out VOCs sampling and testing analysis on key emission links to construct the VOCs composition spectrum and localized VOCs emission factors of these industries in Cangzhou (Gao et al., 2021; Wang et al., 2022). Based on the findings of that study, in this study, we established an emission inventory with high resolution in Cangzhou City for 2018, focusing on nine pollutants with spatial and temporal allocation. Additionally, we confirmed the reliability of the results by comparing them with other inventories, including those established for Cangzhou, and used Monte Carlo simulation to assess the uncertainties. This inventory with a greater number of pollutants and emission sources can more comprehensively reflect the spatial distribution characteristics than the inventories formulated in other studies. Additionally, we also used CEMS data from the thermal power industry and iron and steel industry (Bo et al., 2021; Qu et al., 2020), which increased the accuracy of the results and the geographical distribution through a combination of top-down and bottom-up approaches.

## 2 Methods and data

### 2.1 Study area

Cangzhou is located in the southeast of Hebei Province, bordering the Bohai Sea in the east, Beijing and Tianjin in the north, and Shandong in the south. It extends from 115° 42′ E to 117° 50′ E longitudes and from 37° 29′ N to 38° 57′ N latitudes. The study area included 19

counties (Fig. 1), with a resident population of 7,544,300, an urbanization rate of 53.64%, and a total area of approximately 14,000 km$^2$. In 2018, the average annual GDP of Cangzhou City was 361.64 billion yuan, ranking third among 13 cities in Hebei Province (NBSC, 2019).

## 2.2 Classification of the sources of emission

To ensure the accuracy of the inventory, a comprehensive and scientific classification of emission sources needs to be performed (Zhong et al., 2018). There were 10 first-level categories based on the socioeconomic conditions of Cangzhou and studies in recent years (He, 2018; Jiang et al., 2020; Krecl et al., 2022; Lei, 2020). Each category was then reclassified guided by product use, the types of fuel, and the control technology of air pollution. Unlike other emission inventories that sufferred from data availability limitations resulting in incomplete source representation (Gao et al., 2022; Li et al., 2017; Liu et al., 2018a, b),

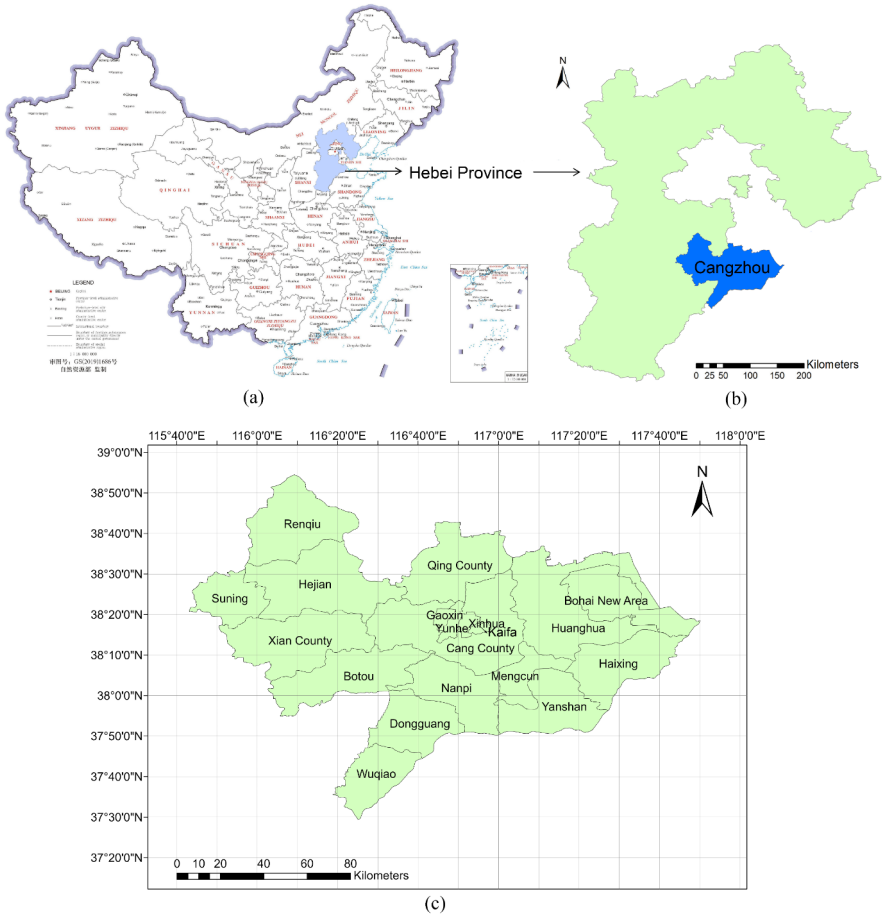



**Fig. 1** Location and administrative division of Cangzhou City: (**a**) location of Hebei Province in China, (**b**) location of Cangzhou City in Hebei Province, (**c**) administrative division of Cangzhou City

this study included both catering and fugitive dust sources. The details about the classification of emission sources are provided in Table S1 of Supplementary Material.

### 2.3 Data collection and calculation method

Cangzhou City has many industrial enterprises with a complex industrial structure. For point sources, such as industrial and residential boilers, cement plants, and petrochemical enterprises, a bottom-up approach was utilized to calculate emissions. This involved collecting and calculating emissions data at the facility level (such as boiler type, CEMS data, removal efficiency, and activity data) for each source, and then aggregating these to form an emission inventory for the entire sector, which enhanced the accuracy and reliability of the results. Among them, power plants and the iron and steel industry utilized the CEMS data (direct, detailed, real-time, and latest actual measurements) to address limitations concerning the use of indirect, invariable, uniform, and obsolete average emission factors. CEMS typically consists of flue gas sampling probes, analyzers, data acquisition systems, data processing systems, data storage systems, and data transmission systems. It enables real-time monitoring and upload of actual emission concentrations and emission rates of pollutants such as $SO_2$, NOx, and $PM_{10}$, as well as data on oxygen content, flue gas temperature, and other parameters during the operation of emission sources. After rigorous quality control of CEMS data, emissions were calculated based on theoretical flue gas volume and emission concentrations combined with activity levels, significantly enhancing the accuracy of emission estimation. Emission factors for other pollutants were derived from the mass fraction of various particulate matter components ($PM_{2.5}$, BC, and OC) in $PM_{10}$ and literature (VOCs and CO). For more detailed methodological description about QA/QC and estimation for CEMS data, please refer to our previous studies (Bo, 2020; Bo et al., 2021; Tang et al., 2019) and Section S2. Environmental management data for point sources, such as pollutant discharge permits and environmental impact assessment reports, were used for Quality Assurance/Quality Control (QA/QC) to obtain more accurate data. Companies with an error rate of 60% or higher between the reported data and the environmental management data were categorized as suspected problematic enterprises. Following this method, the suspected problematic enterprises were screened from the > 8,000 industrial enterprises in Cangzhou, from which a sample was selected for on-site investigations to review the data, which led to the generation of a new set of baseline data.

For non-point sources difficult to obtain individual emission information one by one, such as transportation and agriculture, a top-down approach was used. This approach relies on relatively macro-level statistical data from various sectors at the district or county level to estimate emissions based on activity levels. Combining bottom-up and top-down approaches yields a more comprehensive and accurate emission inventory, providing high-precision and multi-level emission data. This combined methodology offered a scientific basis for formulating more effective and targeted pollution control and emission reduction policies. Flow chart is shown in Fig. 2. More information about the calculation methods, emission factors, and spatial and temporal allocation are listed in **Sections S1–S3** of Supplementary Material.

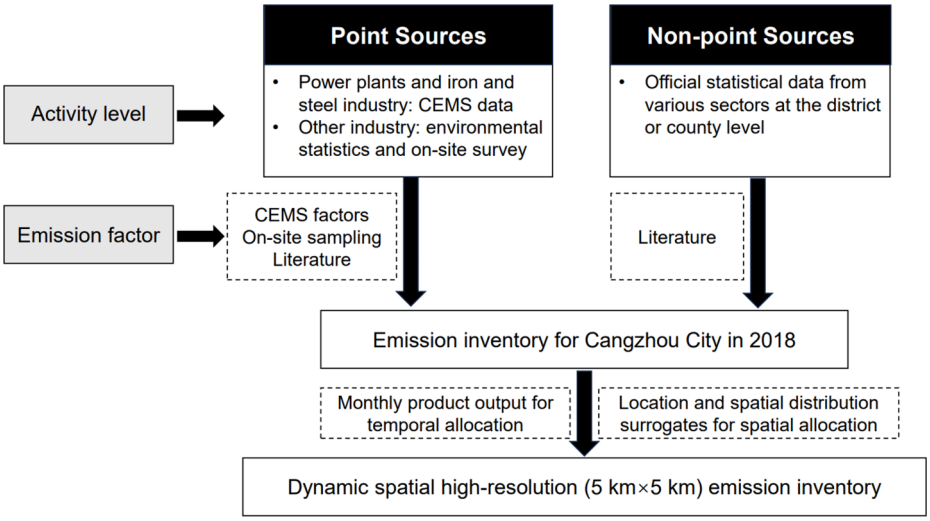



**Fig. 2** Flow chart of high spatial and temporal resolution emission inventory compilation

**Table 1** Emission inventory of nine pollutants in Cangzhou City for 2018 (unit: kt)

| Sources | $SO_2$ | NOx | CO | $PM_{10}$ | $PM_{2.5}$ | BC | OC | VOCs | $NH_3$ |
|---|---|---|---|---|---|---|---|---|---|
| Fossil fuel combustion | 8.36 | 14.1 | 188.16 | 15.09 | 11.76 | 2.11 | 0.44 | 5.60 | 0.00 |
| Industrial processes | 10.21 | 15.21 | 442.67 | 37.35 | 21.9 | 0.71 | 1.19 | 51.61 | 7.71 |
| Mobile | 1.58 | 51.93 | 88.09 | 2.48 | 2.32 | 1.24 | 0.42 | 13.11 | 0.77 |
| Solvent use | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13.06 | 0 |
| Agriculture | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 50.50 |
| Fugitive dust | 0 | 0 | 0 | 58.30 | 16.31 | 0 | 0 | 0 | 0 |
| Storage and transportation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.47 | 0 |
| Biomass burning | 0.14 | 0.91 | 3.89 | 0.20 | 0.18 | 0.02 | 0.10 | 0.21 | 0.11 |
| Waste treatment | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 2.88 |
| Others(catering) | 0 | 0 | 0 | 2.99 | 2.39 | 0.05 | 1.68 | 2.09 | 0 |
| **Sum** | **20.29** | **82.67** | **702.81** | **116.41** | **54.87** | **4.15** | **3.83** | **87.66** | **62.00** |

## 3 Results

### 3.1 Total emissions and the contribution of various sources

The emission inventory in Cangzhou for 2018 is summarized in Table 1. The total, $SO_2$, NOx, VOCs, $PM_{10}$, $PM_{2.5}$, BC, OC, CO, and $NH_3$ emissions were 20.29, 82.67, 87.66, 116.41, 54.87, 4.15, 3.83, 702.81, and 62.00 kt, respectively. The $SO_2$, CO, $PM_{10}$, $PM_{2.5}$, and VOCs emissions from industrial sources accounted for 62.4%, 35.3%, 44.6%, 35.5%, and 56.2% of the total pollutants emitted, respectively.

The contribution of the subcategory to the total emissions of nine pollutants is shown in Fig. 3. The contribution of each county is shown in Fig. 4.

Fossil fuel combustion sources and industrial processes contributed the most to total $SO_2$ emissions (41.2% and 50.3%, respectively), among which power plants, residential com-

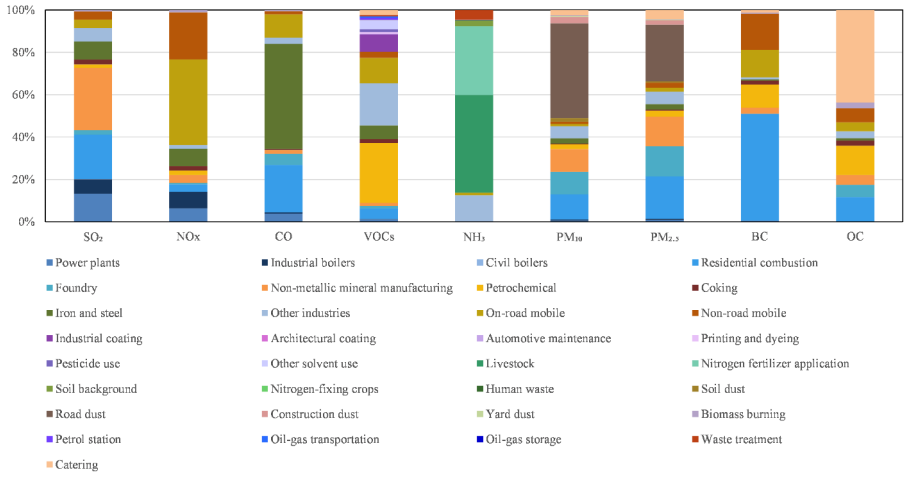



**Fig. 3** The contribution of the emission of sub-sources to Cangzhou in 2018

bustion, and non-metallic mineral manufacturing were the dominant contributors of $SO_2$, accounting for 13.2%, 21.0%, and 29.5% of the total emissions, respectively. For spatial contribution, Bohai New Area (21.1%) was the highest $SO_2$ emitting county with numerous power plants and industries that consumed large quantities of fuel, followed by the counties Hejian (15.1%), Huanghua (9.4%), and Xian (8.7%).

Mobile was the largest source of NOx emissions (62.8% of the total NOx emissions), followed by industrial processes (18.4%). On-road mobile sources accounted for 64.6% of mobile sources. Among industrial processes, the iron and steel industry contributed the most to NOx emissions, accounting for 44.6% of the sources. The spatial contribution of NOx emissions in Bohai New Area (20.6%), Huanghua (12.6%), and Cang County (7.9%) was higher than that in other counties.

Carbon monoxide emissions were mainly caused by the incomplete combustion of fuel. Industrial processes contributed the most to CO emissions (60.1%), followed by fossil fuel sources (26.8%). Among subcategories, the iron and steel industry and residential combustion produced the largest emissions, accounting for 49.7% and 22.3% of the total emissions, respectively. For spatial contribution, Bohai New Area emitted the largest quantity of CO (55.8% of the total CO emissions).

Industrial processes contributed significantly to VOCs emissions (58.9% of the total), followed by mobile sources (15.0%) and solvent use (14.9%). Within subcategories, petrochemical sources accounted for 28.3% of the total VOCs emissions, followed by on-road mobile (12.1%) and industrial coating (8.2%). Regarding spatial contribution, Bohai New Area was the county responsible for the highest emission of VOCs (25.8%) in Cangzhou City.

Fugitive dust and industrial processes contributed the most to $PM_{10}$ (50.4% and 32.1% of the total) and $PM_{2.5}$ (29.7% and 39.9% of the total) emissions, respectively. Among subsources, PM emissions were mainly from foundry, non-metallic mineral manufacturing, and road dust. Huanghua County produced the highest emissions contributing 11.1% of the total $PM_{10}$ emissions and 10.2% of the total $PM_{2.5}$ emissions, respectively.

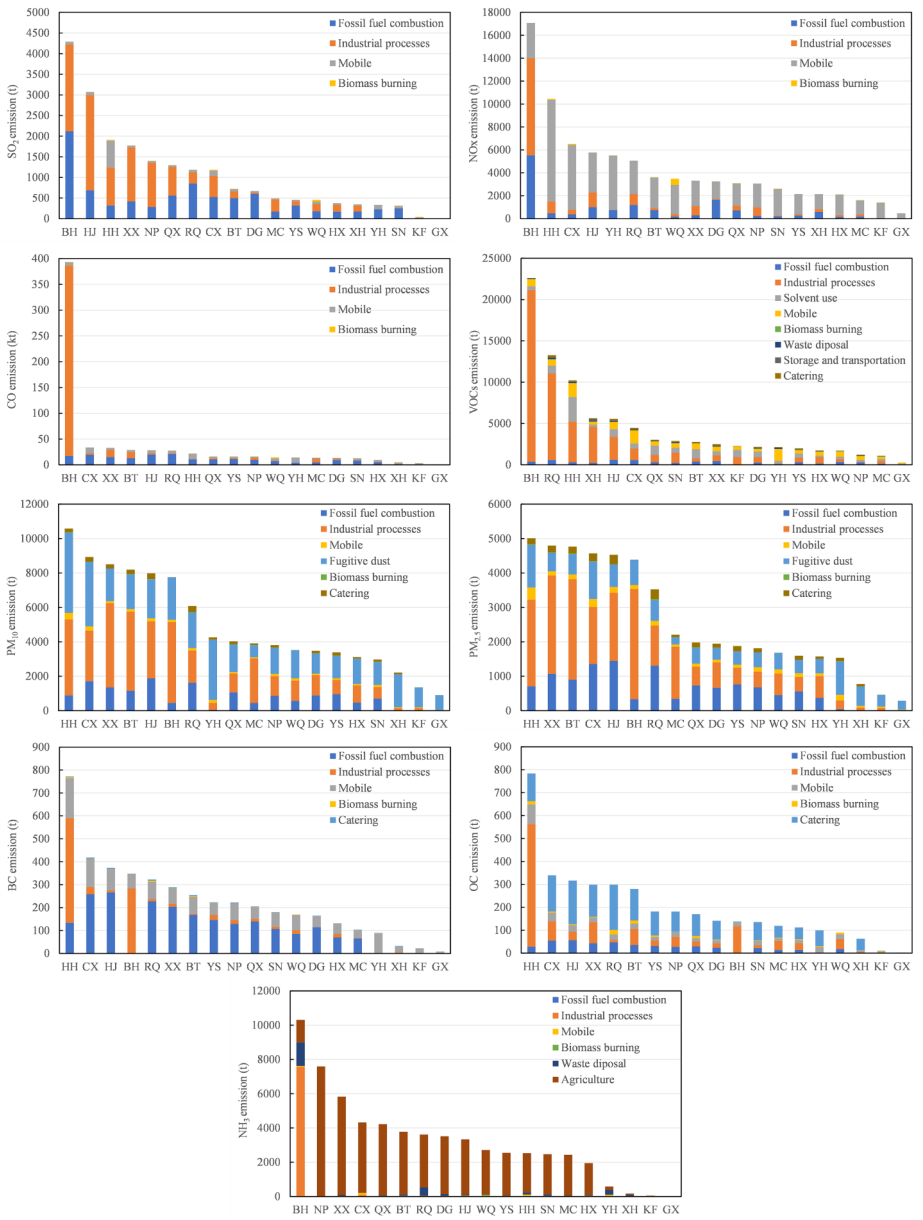



**Fig. 4** City-level contributions to the total emissions for nine pollutants in Cangzhou City

Fossil fuel combustion contributed the most to BC emissions (51.0%), followed by mobile sources (30.0%). Among fossil fuel combustion sources, residential combustion contributed 50.5% of the total BC emissions, followed by non-road mobile sources (17.1% of the total). Huanghua (17.8%) contributed the most to BC emissions, followed by Cang County (9.7%) and Hejian County (8.6%).

The catering industry contributed the most to OC emissions, at 43.8%. Industrial processes and fossil fuel combustion sources contributed 31.0% and 11.6% of the OC emissions. The major sub-sources for OC emissions were petrochemical and residential combustion which contributed 13.8% and 11.5% to the total OC emissions, respectively. Huanghua (20.8%) was the highest OC emitting county, followed by Cang County (9.0%).

Unlike other pollutants, $NH_3$ was mainly emitted from agricultural sources, which accounted for 81.5% of the total $NH_3$ emitted owing to the significant growth in the agricultural and livestock scales. Thus, livestock, the main sub-sector, accounted for 46.0% of the total $NH_3$ emitted, followed by N-fertilizer (32.5%). High $NH_3$ emissions were mainly concentrated in Bohai New Area (16.6%), Nanpi (12.2%), and Xian County (9.4%).

### 3.2 Temporal and spatial distribution characteristics

Power plants experienced peak electricity generation primarily in July and August, mainly due to an increase in the use of cooling appliances, such as refrigerators and air conditioners (Fig. 5). High electricity generation also occurred in the winter months, primarily driven by the heating requirements of thermal power enterprises (Bo et al., 2017). Similar changes were associated with the production of iron and steel, cement, and coke, i.e., with an increase in spring and autumn and a decrease in summer and winter. The increase in production from February might be attributed to the resuming of normal operations in factories after the Spring Festival and the production ban for winter or heating season (Tang et al., 2022).

Cangzhou City was divided into 5 km × 5 km grids based on the emission of NOx, $SO_2$, CO, VOCs, $PM_{10}$, $PM_{2.5}$, OC, BC, and $NH_3$ in 2018 (Fig. 6). Large quantities of pollutants (except $NH_3$) were mainly emitted in the eastern and western areas of the city, like Bohai, Huanghua, Xian County, and Hejian County, which are industrial clusters above the city level. These counties have heavy traffic, high population density (Fig. S1), and developed

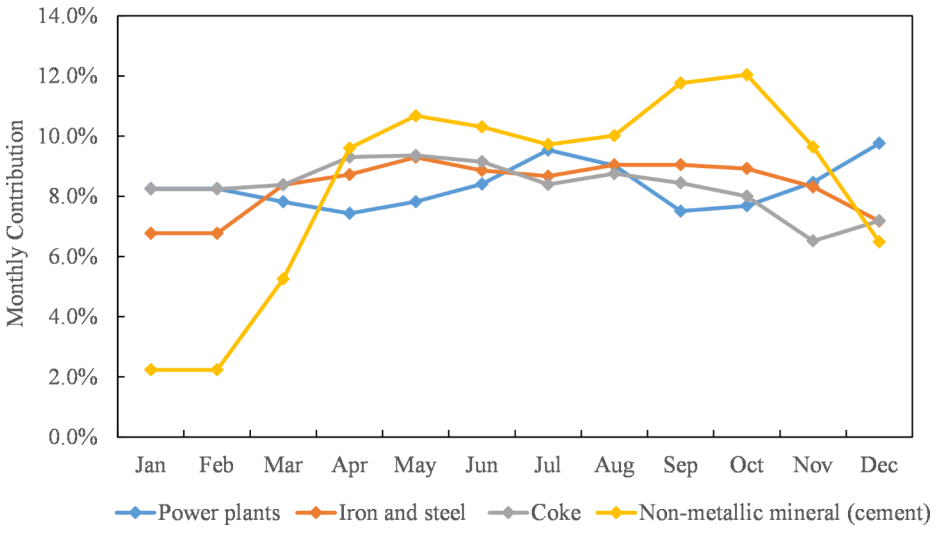



**Fig. 5** Monthly variations in power plants and major subcategories of industrial processes in Cangzhou in 2018

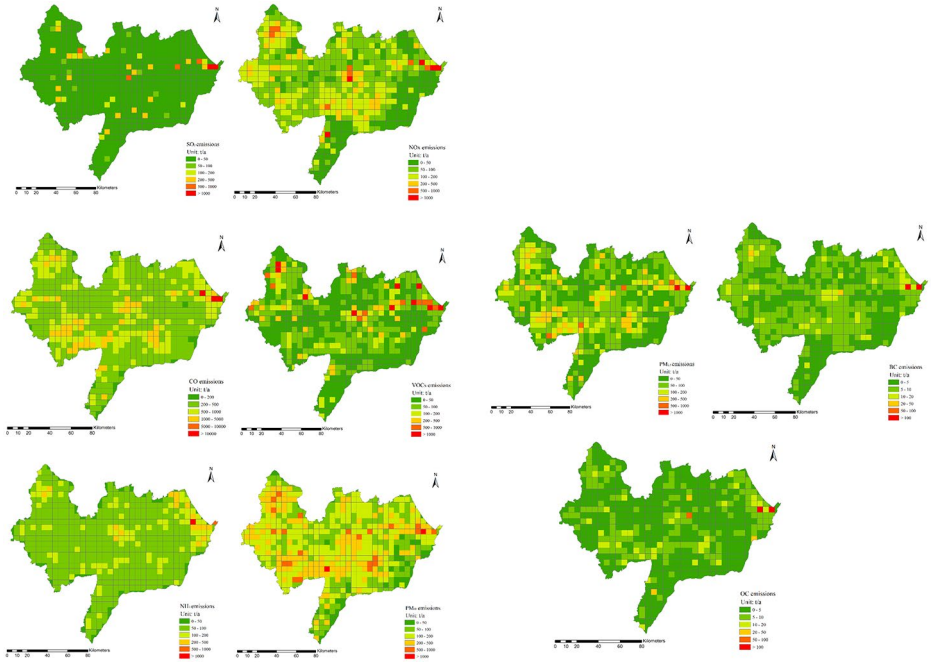


**Fig. 6** Spatial distribution characteristics of the emission of atmospheric pollutants in Cangzhou (2018)

industries. High $SO_2$ emissions occurred in Bohai New Area, Hejian, and Huanghua due to the consumption of large quantities of fossil fuels and the presence of many industrial plants. Bohai New Area has the main thermal power plants in Cangzhou and an iron and steel enterprise. The use of large quantities of coal as fuel by these large-scale enterprises was the primary contributor to the large quantities of $SO_2$ emitted. The high-emission areas for CO were Bohai New Area, Cang County, and Xian County; the latter two areas also served as the main concentration areas for residential combustion. The emission of $PM_{10}$, $PM_{2.5}$, and NOx was predominantly concentrated in Bohai New Area, Huanghua, and Cang County, which served as the gathering areas for foundry enterprises, non-metallic mineral manufacturing enterprises, and road networks. The emission of VOCs was the highest in Bohai New Area, Renqiu, and Huanghua, which were gathering areas for petrochemical companies. Additionally, these areas were characterized by the presence of various manufacturing industries that use large quantities of solvents in their production processes, resulting in the significant emission of VOCs. Large quantities of $NH_3$ were emitted in Bohai New Area with dense manufacturing enterprises, and in Nanpi and Xian County, which have high agricultural and livestock farming activities.

**Table 2** A comparison of the estimated emissions between this study and previous studies (unit: kt)

| Reference | Year | Spatial resolution | $SO_2$ | NOx | $PM_{10}$ | $PM_{2.5}$ | CO | $VOC_S$ | $NH_3$ | BC | OC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MEIC | 2018 | 0.25°×0.25° | 69.46 | 170.18 | 63.59 | 45.85 | 1202.39 | 157.46 | 43.51 | 8.03 | 12.52 |
| CHRED 3.0 A | 2018 | 10 km×10 km | 46.67 | 70.20 | 35.02 | 28.45 | 766.60 | 96.68 | 59.91 | 5.74 | 12.35 |
| This study | 2018 | 5 km×5 km | 20.29 | 82.67 | 116.41 | 54.87 | 702.81 | 87.66 | 62.00 | 4.15 | 3.83 |

## 4 Discussion

### 4.1 Comparison with other emission inventories

To evaluate the accuracy of our results, we compared our emission results with the results obtained for the same region of MEIC and CHRED 3.0 A for 2018 (shown in Table 2).

Except for the $NH_3$ and PM emissions, the estimated results of other pollutants in MEIC were significantly higher than those reported in our study, while the emissions of these pollutants in CHRED 3.0 A were similar to the inventory results in this study. One of the reasons is that the emissions of iron and steel enterprises and power plants in this study and CHRED 3.0 A were calculated based on CEMS data, which were lower and closer to the actual emissions than the results of MEIC calculated by the unlocalized emission factor method. As for the OC emissions, the results of this study were significantly lower than those of MEIC and CHRED 3.0 A, mainly due to differences in biomass burning, civil boilers, and residential combustion sources. This study was based on precise to detailed and more reliable point source information (location, combustion mode, fuel consumption, pollutant removal information, etc.) and municipal environmental statistics. However, MEIC and CHRED 3.0 A calculated emissions mostly based on provincial data and literature, then allocated them to cities through population and other data, which overestimated the emissions of cities (Zhao et al., 2015). The classification system of MEIC and CHRED 3.0 A (five emission sources) was different from that followed in this study (ten emission sources), which also influenced the results. For example, fugitive dust, one of the major sources of PM ($PM_{10}$ and $PM_{2.5}$), was not listed in MEIC but was included in this study. Therefore, this emission inventory described the characteristics of pollutant emissions in Cangzhou City more comprehensively and accurately.

### 4.2 Implications of air pollution control policy

The emission inventory established in this study allowed us to more precisely analyze the sources of pollutants that significantly affect human health, primarily PM, NOx, and VOCs; the latter two are the precursors of ozone ($O_3$). This information can help the government implement targeted measures to control pollution and reduce its effect on human health. The energy in Cangzhou City is mainly obtained from coal, petroleum fuel, and natural gas, among which coal is the main source. Thus, at the government level, Cangzhou Municipal Government should actively promote the adjustment of energy structure, improve the coordinated emission reduction of pollutants, and formulate stricter pollutant emission standards. For the civil sectors and industrial coal-fired boilers, measures such as coal to gas and coal to electricity should be taken. At the industry level, the management of scattered

coal should be promoted for the combustion and processing of fossil fuels. Foundry enterprises should strengthen rectification and upgrade equipment to reduce pollution. Combustion devices and environmental protection equipment should be improved and enhanced to increase efficiency while improving the management of unorganized emissions. Regarding mobile sources, the use of outdated vehicles, which have lower emission standards, reduced fuel efficiency, and diminished safety features, should be discontinued, fuel quality should be improved, and the adoption of new energy vehicles should be promoted. Additionally, fine-grained management should be implemented for dust sources. To prevent the large amount of $NH_3$ emitted from agricultural sources, Cangzhou should promote the reduction of pesticide and fertilizer application and improve the resource utilization of livestock and poultry breeding wastes.

With the promotion of the CEMS model and the strict QA/QC of the CEMS data, the pollutants emitted calculated by the CEMS data have become more accurate than those calculated by traditional emission inventory compilation methods. This study standardized how to develop an emission inventory with the CEMS model, so that this method can be extended to more regions and industries of the whole country. Therefore, the quality of emissions data can be greatly improved, more accurate emission inventories can be obtained, and more targeted management measures might be developed.

### 4.3 Uncertainty analysis and limitations

The removal efficiency, activity data, and emission factor are the main sources of uncertainty that reduce the accuracy of the emission inventory. The uncertainties of emission estimation were quantitatively evaluated by the Monte Carlo simulation using the R software (version 3.5.1). Further details on uncertainty analysis are provided in studies conducted by Hua et al. (2019) and Qi et al. (2017).

The probability distribution data are presented in Tables S4–S11.

We performed 10,000 Monte Carlo simulations with a 95% confidence interval to describe the uncertainty. The ranges of estimated pollutant emissions were -16–17% for $SO_2$, -10–11% for NOx, -12–13% for CO, -24–29% for $PM_{10}$, -19–22% for $PM_{2.5}$, -12–11% for VOCs, -6–18% for $NH_3$, -11–12% for BC, and -10–11% for OC. Compared to other sources, biomass burning, construction dust, and industrial processes had larger uncertainties. Because the localized emission factors were missing and the activity data of the residential biomass source were taken from the Statistical Yearbook, which has high inherent uncertainties, pollutants emissions from biomass burning were found to be associated with higher levels of uncertainty, especially $PM_{10}$ and $PM_{2.5}$. The uncertainty of construction dust mainly occurred due to the lack of construction time data. The uncertainty of industrial processes was caused by incomplete emission factors of various types of products.

Point sources were the main contributors of $SO_2$ and NOx; thus, they had low uncertainties. However, $PM_{10}$, $PM_{2.5}$, VOC, and CO emissions had relatively high uncertainties, which were mainly caused by industrial processes, biomass burning, and mobile sources. For $NH_3$, factors like fertilization time, local weather conditions, and different disposal of waste led to the uncertainties of N-fertilizer application and livestock.

Besides the quantitative uncertainties, this inventory had some limitations. Firstly, the emission factors of some sources, such as mobile sources and agricultural sources, were derived from the guidelines issued by the Ministry of Ecology and Environment (MEE,

2014a, b, c, 2016) rather than local emission factors, and thus, the values might differ from actual emissions. Besides, according to Hua (2023), the average annual concentration of $PM_{2.5}$ in Tianjin in 2018 was 52 μg/m$^3$, and the estimated number of deaths from cardiovascular and respiratory diseases caused by $PM_{2.5}$ was 1084–1569 (Hua et al., 2023). Similarly, the $PM_{2.5}$ concentration in Cangzhou in 2018 was 59 μg/m$^3$ (CEEB, 2019), and the number of deaths from these two diseases caused by $PM_{2.5}$ was preliminarily estimated to be 1230–1780. However, due to the lack of long-term disease data and meteorological data, we could not establish a detailed air pollution-health model to comprehensively analyze the effect of air pollution on human health in Cangzhou City. Future studies need to address these limitations.

## 5 Conclusions

In this study, a city-scale anthropogenic emission inventory with high resolution has been established for Cangzhou for the year 2018. In particular, estimates of emission factors, temporal emission distributions, and total emissions from the key industries (power plants, foundry, and iron and steel) were improved through CEMS data after quality control and on-site sampling. Fossil fuel combustion was the main source of BC emissions (51.0% of the total BC emissions). The main contributor to NOx emissions was mobile sources (62.8% of the total NOx emissions). Industrial processes were the major sources of $SO_2$ (50.3% of the total quantity emitted), VOCs (60.1%), CO (58.9%), and $PM_{2.5}$ (39.9%). Fugitive dust sources contributed the most to $PM_{10}$ emissions (50.4%). The catering industry emitted most of the OC (43.8%). Agricultural sources like livestock (46.0%) and N-fertilizer (32.5%) were the main sources of $NH_3$ emissions. Concerning temporal and spatial distribution, the emissions of power plants and major subcategories of industrial processes showed obvious seasonal characteristics; except for $NH_3$, all pollutants emitted were concentrated in the southern and eastern regions of Cangzhou City. Compared with the national-level inventory, the activity level, spatial resolution and completeness and accuracy of this emission inventory were greatly improved, which can better support the policymakers' fine management of local atmospheric environmental quality. Moreover, our findings offer valuable insights and practical references for enhancing environmental governance throughout the broader BTH region. Through detailed analysis of emission profiles and effective mitigation strategies in Cangzhou, our research contributes to a deeper understanding of pollution dynamics and management priorities in the BTH area. These insights facilitate informed policy recommendations and support coordinated regional initiatives aimed at improving environmental quality. Future improvements of the Cangzhou City emission inventory should focus on the incorporation of local emission factors, the accuracy of the activity data, and the enhancement of spatial distribution surrogates.

**Funding** This research was supported by Fundamental Research Funds for the Central Universities (buctrc202133), the National Natural Science Foundation of China (No. 72174125), National Natural Science Foundation of Shaanxi (2023-JC-QN-0808; QCYRCXM-2022–127), Shanghai Pujiang Program, and the National Research Program for Key Issues in Air Pollution Control (DQGG0209–07).

**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate** Ethics approval was waived; all participants gave written informed consent for participation in the study prior to sample collection.

**Consent to publish** All participants gave written informed consent for participation in the study and its publication.

**Competing interests** All other authors declare no competing interests.

## References


Bo, X. (2020). *Emission Characteristics and Environmental Impacts of Air Pollutants in China's Iron and Steel Industry*. University of Science and Technology Beijing.

Bo, X., Jia, M., Xue, X., Tang, L., Mi, Z., Wang, S., Cui, W., Chang, X., Ruan, J., & Dong, G. (2021). Effect of strengthened standards on Chinese ironmaking and steelmaking emissions. *Nature Sustainability*, *4*(9), 811–820.

CBS, (Cangzhou Bureau of Statistics) (2019). Cangzhou Statistical Bulletin of National Economic and Social Development in 2018. Accessed 27 Sep 2019.

CEEB, (Cangzhou Ecological Environment Bureau) (2019). 2018 Cangzhou Environmental Quality Bulletin. http://hb.cangzhou.gov.cn/hb/c100446/201906/3b7b30b454d24d07a8eb01adac1436f3.shtml. Accessed 3 June 2019.

Chen, X., Liu, Q., Sheng, T., Li, F., Xu, Z., Han, D., Zhang, X., Huang, X., Fu, Q., & Cheng, J. (2019). A high temporal-spatial emission inventory and updated emission factors for coal-fired power plants in Shanghai, China. *Science of the Total Environment*, *688*, 94–102.

CPG, (The Central People's Government of the People's Republic of China) (2018a). Circular of the State Council on Printing and Issuing the 3-year Action Plan for Winning the Blue Sky Defense War. https://www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm. Accessed 3 Jul 2018.

CPG, (The Central People's Government of the People's Republic of China) (2018b). Comprehensive Achievement of the Ten Measures for Air Pollution Control. https://www.gov.cn/xinwen/2018-02/01/content_5262720.htm. Accessed 1 Feb 2018.

Dong, J., Liu, Y., & Bao, H. (2021). Revalue associations of short-term exposure to air pollution with respiratory hospital admissions in Lanzhou, China after the control and treatment of current pollution. *International Journal of Hygiene and Environmental Health*, *231*, 113658.

Fan, Q. Z., Zhang, Y., Ma, W. C., Ma, H. X., Feng, J. L., Yu, Q., Yang, X., Ng, S. K. W., Fu, Q. Y., & Chen, L. M. (2016). Spatial and Seasonal Dynamics of Ship Emissions over the Yangtze River Delta and East China Sea and their potential environmental influence. *Environmental Science & Technology*, *50*(3), 1322–1329.

Fan, F. Y., Wang, H. F., & Fan, L. J. (2019). Health Damage and Economic Loss Assessment of Air Pollution in Jing-Jin-Ji Region. *Ecological Economy*, *35*(9), 157–163.

Gao, S., Li, S. B., Bo, X., Li, H. Y., Shu, M. S., Dan, M., Qu, J. B., & Lei, T. T. (2021). Source profiles and impact of VOCs based on production processes in Foundry industries. *Environmental Science*, *42*(04), 1649–1659.

Gao, Y., Zhang, L., Huang, A., Kou, W., Bo, X., Cai, B., & Qu, J. (2022). Unveiling the spatial and sectoral characteristics of a high-resolution emission inventory of CO2 and air pollutants in China. *Science of the Total Environment*, *847*, 157623.

Gong, M., Yin, S., Gu, X., Xu, Y., Jiang, N., & Zhang, R. (2017). Refined 2013-based vehicle emission inventory and its spatial and temporal characteristics in Zhengzhou, China. *Science of the Total Environment*, *599*, 1149–1159.

He, K. B. (2018). *Technical manual for compilation of urban air pollutants emission inventory*. Place Published.

Hong, C., Zhang, Q., He, K., Guan, D., Li, M., Liu, F., & Zheng, B. (2016). Variations of China's emission estimates response to uncertainties in energy statistics. *Atmospheric Chemistry and Physics Discussions*, 1–23.

Hua, K., Luo, Z. W., Jia, B., Xue, Q. Q., Li, Y. F., Xiao, Z. M., Wu, J. H., Zhang, Y. F., & Feng, Y. C. (2023). Health impacts of Air Pollution in Tianjin. *Environmental Science*, *44*(5), 2492–2501.

Huneeus, N., van der Denier, H., Castesana, P., Menares, C., Granier, C., Granier, L., Alonso, M., de Fatima Andrade, M., Dawidowski, L., Gallardo, L., Gomez, D., Klimont, Z., Janssens-Maenhout, G., Osses, M., Puliafito, S. E., Rojas, N., Ccoyllo, O. S., Tolvett, S., & Ynoue, R. Y. (2020). Evaluation of anthropogenic air pollutant emission inventories for South America at national and city scale. *Atmospheric Environment, 235*.

Jiang, P., Chen, X., Li, Q., Mo, H., & Li, L. (2020). High-resolution emission inventory of gaseous and particulate pollutants in Shandong Province, eastern China. *Journal of Cleaner Production*, *259*, 120806.

Krecl, P., Oukawa, G. Y., Charres, I., Targino, A. C., Grauer, A. F., & Silva, D. C. e. (2022). Compilation of a city-scale black carbon emission inventory: Challenges in developing countries based on a case study in Brazil. *Science of the Total Environment*, *839*, 156332.

Li, M., Liu, H., Geng, G. N., Hong, C. P., Liu, F., Song, Y., Tong, D., Zheng, B., Cui, H. Y., Man, H. Y., Zhang, Q., & He, K. B. (2017). Anthropogenic emission inventories in China: A review. *National Science Review*, *4*(6), 834–866.

Liu, F., Beirle, S., Zhang, Q., Van, D., Zheng, B., Tong, D., & He, K. (2017). NOx emission trends over Chinese cities estimated from OMI observations during 2005 to 2015. *Atmospheric Chemistry and Physics*, 1–21.

Liu, H., Wu, B., Liu, S., Shao, P., Liu, X., Zhu, C., Wang, Y., Wu, Y., Xue, Y., & Gao, J. (2018a). A regional high-resolution emission inventory of primary air pollutants in 2012 for Beijing and the surrounding five provinces of North China. *Atmospheric Environment*, *181*, 20–33.

Liu, S., Hua, S., Wang, K., Qiu, P., Liu, H., Wu, B., Shao, P., Liu, X., Wu, Y., Xue, Y., Hao, Y., & Tian, H. (2018b). Spatial-temporal variation characteristics of air pollution in Henan of China: Localized emission inventory, WRF/Chem simulations and potential source contribution analysis. *Science of the Total Environment*, *624*, 396–406.

Liu, A., Wu, Q., & Cheng, X. (2020). Using the Google Earth Engine to estimate a 10 m resolution monthly inventory of soil fugitive dust emissions in Beijing, China. *Science of the Total Environment*, *735*, 139174.

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2018). Notification on the final assessment results of the implementation of the Action Plan for the Prevention and Control of Air Pollution. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/201806/t20180601_629733.html. Accessed Accessed 17 May 2018.

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2014c). Technical Guidelines for the Preparation of Dust Source Particulate Matter Emission Inventory (on trial). https://www.mee.gov.cn/gkml/hbb/bgg/201501/t20150107_293955.htm

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2014b). Technical Guidelines for the Preparation of Atmospheric Ammonia Emission Inventory (on trial). https://www.mee.gov.cn/gkml/hbb/bgg/201408/t20140828_288364.htm

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2013). Technical regulation for ambient air quality assessment (on trial) HJ 663–2013. https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201309/t20130925_260809.shtml. Accessed.

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2016). Technical Guide for Compiling Air Pollutant Emission Inventory of Civil Coal (on trial). https://www.mee.gov.cn/gkml/hbb/bgg/201610/t20161031_366528.htm

MEE, (Ministry of Ecology and Environment of the People's Republic of China) (2014a). Technical Guidelines for the Preparation of Air Pollutant Emission Inventory from non-road Mobile sources (on trial). https://www.mee.gov.cn/gkml/hbb/bgg/201501/t20150107_293955.htm

NBSC, (National Bureau of Stastics of China). (2019). *China Statistical Yearbook 2018*. China Statistics.

Qi, Q. (2019). Study on Optimization Strategy of Road Network in Central City: A case of Cangzhou City. *Urban Roads Bridges & Flood Control*, *02*, 1–6.

Qi, J., Zheng, B., Li, M., Yu, F., Chen, C., Liu, F., Zhou, X., Yuan, J., Zhang, Q., & He, K. (2017). A high-resolution air pollutants emission inventory in 2013 for the Beijing-Tianjin-Hebei region, China. *Atmospheric Environment*, *170*, 156–168.

Qu, J., Wang, P., Bo, X., Xue, X., Dong, G., Cui, L., Kang, M., Wang, T., Tang, L., Zhu, F., & Li, S. (2020). Inventory and Distribution Characteristics of China's Thermal Power Emissions.

Sun, S., Sun, L., Liu, G., Zou, C., Wang, Y., Wu, L., & Mao, H. (2021). Developing a vehicle emission inventory with high temporal-spatial resolution in Tianjin, China. *Science of the Total Environment*, *776*, 145873.

Tang, L., Qu, J., Mi, Z., Bo, X., Chang, X., Anadon, L. D., Wang, S., Xue, X., Li, S., Wang, X., & Zhao, X. (2019). Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. *Nature Energy*, *4*(11), 929–938.

Tang, L., Ruan, J., Bo, X., Mi, Z., Wang, S., Dong, G., & Davis, S. J. (2022). Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO2 in China's cement sector. *One Earth*, *5*(8), 892–906.

Timmermans, R. M. A., van der Denier, H. A. C., Kuenen, J. J. P., Segers, A. J., Honoré, C., Perrussel, O., Builtjes, P. J. H., & Schaap, M. (2013). Quantification of the urban air pollution increment and its dependency on the use of down-scaled and bottom-up city emission inventories. *Urban Climate*, *6*, 44–62.

Under Ultra-Low econstruction *Environmental Science*, *41*(9), 7.

Wang, Y., Zhu, R., Bo, X., Dan, M., & Shu, M. (2022). Volatile organic compounds constituents of a typical integrated iron and steel plant and influence on O3 pollution. *International Journal of Environmental Science and Technology*.

WHO (2021). https://www.who.int/health-topics/air-pollution. Accessed 16 Aug 2021.

Wu, W., & Zheng, T. (2023). Establishing a dynamic two-step floating catchment area method to assess the accessibility of urban green space in Shenyang based on dynamic population data and multiple modes of transportation. *Urban Forestry & Urban Greening*, *82*, 127893.

Wu, X., Li, D., Feng, M., Liu, H., Li, H., Yang, J., Wu, P., Lei, X., Wei, M., & Bo, X. (2021). Effects of air pollutant emission on the prevalence of respiratory and circulatory system diseases in Linyi, China. *ENVIRONMENTAL GEOCHEMISTRY AND HEALTH*, *43*(11), 4475–4491.

Yang, H., Song, X., & Zhang, Q. (2020). RS&GIS based PM emission inventories of dust sources over a provincial scale: A case study of Henan province, central China. *Atmospheric Environment*, *225*, 117361.

Yao, L., Zhan, B., Xian, A., Sun, W., Li, Q., & Chen, J. (2019). Contribution of transregional transport to particle pollution and health effects in Shanghai during 2013–2017. *Science of the Total Environment*, *677*, 564–570.

Zhang, S., Ye, W., Liu, H., Wu, X., Yu, Z., Yao, Z., Fu, L., He, K., & Hao, J. (2013). Historical evaluation of vehicle emission control in Guangzhou based on a multi-year emission inventory. *Atmospheric Environment*, *76(sep.)*, 32–42.

Zhao, Y., Qiu, L. P., Xu, R. Y., Xie, F. J., Zhang, Q., Yu, Y. Y., Nielsen, C. P., Qin, H. X., Wang, H. K., Wu, X. C., Li, W. Q., & Zhang, J. (2015). Advantages of a city-scale emission inventory for urban air quality research and policy: The case of Nanjing, a typical industrial city in the Yangtze River Delta, China. *Atmospheric Chemistry and Physics*, *15*(21), 12623–12644.

Zheng, B., Huo, H., Zhang, Q., Yao, Z. L., Wang, X. T., Yang, X. F., Liu, H., & He, K. B. (2014). High-resolution mapping of vehicle emissions in China in 2008. *Atmospheric Chemistry and Physics*, *14*(18), 9787–9805.

Zhong, Z., Zheng, J., Zhu, M., Huang, Z., Zhang, Z., Jia, G., Wang, X., Bian, Y., Wang, Y., & Li, N. (2018). Recent developments of anthropogenic air pollutant emission inventories in Guangdong province, China. *Science of the Total Environment*, *627*, 1080–1092.

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