



Anthropogenic VOCs Emission Inventory and Characteristics in Jiaozuo City

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ABSTRACT

To accurately understand the atmospheric VOCs emissions in Jiaozuo City and strengthen air pollution control, this study established a 2019 anthropogenic atmospheric VOCs emission inventory using a combined "top-down" and "bottom-up" methodology. The results show that the total VOCs emissions reached 22,574 tons, with solvent use sources (40.9%), industrial process sources (25.9%), and mobile sources (18.3%) constituting the major contributors. Specifically, surface coating operations, petrochemical and chemical industries, and passenger vehicles emerged as the primary contributors to solvent use sources, industrial process sources, and mobile sources respectively. Spatially, Mengzhou City and Wuzhi County demonstrated relatively higher emissions, accounting for approximately 16% and 15% of the city's total emissions respectively.

KEYWORDS

VOCs; Emission Inventory; Jiaozuo City; Emission Characteristics.

1. INTRODUCTION

With the rapid development of urbanization and industrialization, air pollution has become increasingly severe^[1]. Particulate matter (PM_{2.5}) and ozone (O₃) are now the primary pollutants affecting air quality in China. High concentrations of PM_{2.5} and O₃ significantly impact human health, ecosystems, and climate change^[2-3]. Under the dual pressures of persistent PM_{2.5} pollution and rising O₃ levels, synergistic control of these pollutants is critical^[4]. Volatile organic compounds (VOCs), as common precursors to both PM_{2.5} and O₃^[5], have become a focal point for monitoring and pollution prevention.

VOCs emissions originate from natural and anthropogenic sources. Natural sources mainly derive from terrestrial vegetation's secondary metabolic reactions, while anthropogenic sources arise from incomplete combustion and volatilization of low-boiling-point substances. In industrial cities, anthropogenic VOCs emissions far exceed natural contributions^[6]. Since natural emissions are uncontrollable, targeted mitigation of anthropogenic VOCs is more effective for alleviating PM_{2.5} and O₃ pollution.

Establishing a VOCs emission inventory enables the quantification of emissions and analysis of pollution sources, facilitating precise anthropogenic VOCs reduction^[7-8]. Previous studies have developed national and regional emission inventories, such as Wei Wei's 2005 anthropogenic VOCs inventory for China^[6], Zheng Junyu's 2006 Pearl River Delta inventory^[9], and Han Li's 2011 Sichuan Province inventory^[10]. However, as air quality management standards evolve, city-scale inventories are increasingly prioritized. Examples include studies in Xi'an^[11], Chengdu^[12], Wuhan^[13], and Suzhou^[14]. Jiaozuo City, a heavily industrialized area in Henan Province and a key city in China's

"2+26" air pollution control initiative, faces severe air quality challenges due to its industrial structure, energy consumption patterns, and geographic constraints. This study establishes a 2019 anthropogenic VOCs emission inventory for Jiaozuo, analyzing emission characteristics, spatial distribution, and sources to support pollution control strategies for Jiaozuo and similar industrial cities.

2. MATERIALS AND METHODS

2.1. Study Area

The study covers Jiaozuo City (4,072 km²), as depicted in Figure. 1, including four urban districts (Jiefang, Zhongzhan, Macun, and Shanyang), two county-level cities (Qinyang and Mengzhou), and four counties (Wuzhi, Xiuwu, Boai, and Wenxian). Based on the 《 Technical Manual for Urban Air Pollutant Emission Inventory Compilation》^[15], VOCs sources are categorized into eight classes: fossil fuel stationary combustion, industrial processes, mobile sources, solvent use, storage and transportation, biomass burning, waste treatment, and catering emissions.

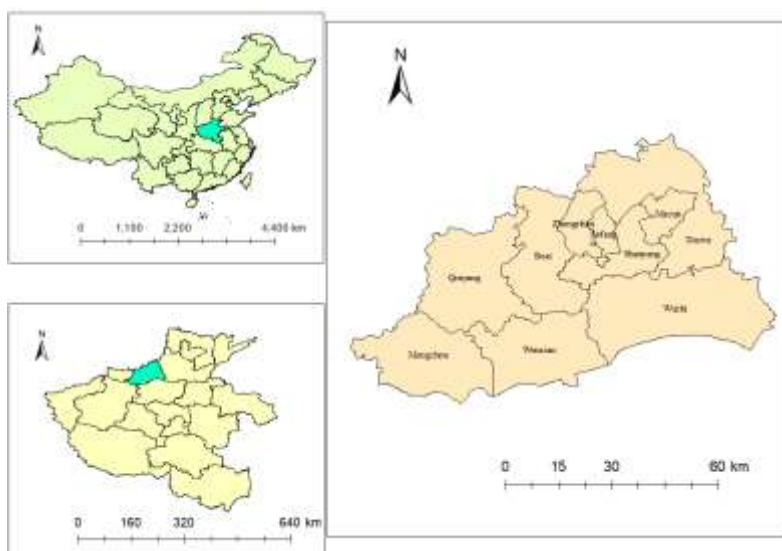


Figure 1. Location of the study domain.

2.2. Estimation Methods for Emission Inventories

The estimation methods for emission inventories primarily include the monitoring calculation method, pollution source survey method, model inversion method, and emission factor method^[6]. The "monitoring calculation method" involves obtaining real-time emissions from pollution sources through online instrument monitoring, while the "pollution source survey method" determines total emissions by directly investigating the pollutant discharge of each emission device. Although both methods offer high accuracy, they incur excessive costs and workload, and many enterprises lack online monitoring instruments to provide VOCs emission data. The "model inversion method" derives emission inventories by using observed concentrations and inverse modeling, but most VOCs species are highly reactive and influenced by atmospheric transport, migration, and dispersion. The "emission factor method" categorizes pollution sources and calculates pollutant emissions by integrating activity level data and emission factors. Consequently, the emission factor method has become the most widely adopted estimation approach globally^[16-18]. This study employs the emission factor method to estimate anthropogenic VOCs emissions in Jiaozuo City. The formula for the emission factor method is as follows:

$$E_i = A \times EF_i \times (1 - \eta) \quad (1)$$

In Equation (1): E_i : VOCs emissions from emission source i ; A : Activity level of the emission source; EF_i : Emission factor of pollution source i ; η : Removal efficiency of VOCs by pollution control measures (in this study, η is primarily derived from actual survey data).

The calculation formula for road mobile sources within the mobile source category differs from those of other emission sources. Its formula is expressed as:

$$E_i = P_i \times EF_i \times VKT \quad (2)$$

In Equation (2): E_i : VOCs emissions from vehicle type i ; P_i : Population of vehicle type i ; EF_i : Mileage-based emission factor for vehicle type i ; VKT : Annual average vehicle kilometers traveled.

2.3. Data Sources

2.3.1. Activity Level (A)

Activity level data are generally obtained through three methods: the "top-down" data survey approach [6, 19–20], the "bottom-up" survey approach [21–23], or a combination of "bottom-up" and "top-down" methods [24–26]. The "bottom-up" method is typically applied to smaller-scale urban studies, where data acquisition is challenging and labor-intensive but yields higher accuracy. Conversely, the "top-down" method is suitable for larger-scale regions (e.g., national or regional data collection), though it provides less detailed and accurate data compared to the "bottom-up" approach. Therefore, this study employs a "bottom-up" method to collect activity level data and cross-validates it with "top-down" statistical data provided by various departments in Jiaozuo City. The combined approach ensures robust activity level data for Jiaozuo City.

2.3.2. Emission Factors (EF_i)

This study adopts emission factors from the 《Technical Manual for Urban Air Pollutant Emission Inventory Compilation》 [15].

2.3.3. VOCs Removal Efficiency (η)

For enterprises equipped with VOCs pollution control technologies, removal efficiency (η) is calculated based on self-reported data. For enterprises lacking such technologies, VOCs are directly emitted, and the removal efficiency is set to 0.

3. RESULTS AND ANALYSIS

3.1. Overall Emission Characteristics

In 2019, the total anthropogenic VOCs emissions in Jiaozuo City reached 22574 t. Solvent use sources constituted the largest contributor, emitting 9225 t and accounting for 40.9% of the total VOCs emissions. This was followed by industrial process sources (5843 t, 25.9%) and mobile sources (4140 t, 18.3%). Biomass combustion sources (1749 t) and fossil fuel stationary combustion sources (1272 t) each contributed less than 10% to the total emissions. Waste treatment sources (194 t), storage and transportation sources (133 t), and other emission sources (18 t) collectively represented less than 1% of the total emissions, as detailed in Table 1 and Figure 2.

Table 1. VOCs Emission Inventory of Jiaozuo City (2019)

Primary Emission Sources	Secondary Emission Sources	VOCs Emissions (t)
Fossil fuel stationary combustion	Power and heating	443
	Industrial boilers	746
	Residential boilers	1
	Residential combustion	82
	Subtotal	1272
Industrial processes	Iron and steel	29
	Cement	10
	Brick and tile	1292
	Ceramics	20
	Lime	150
	Flat glass	69
	Other building materials	327
	Petrochemicals	61
	Plastic products	1414
	Chemicals	1000
	Footwear manufacturing	408
	Chemical fibers	10
	Pharmaceutical manufacturing	178
	Food processing	805
	Papermaking	62
	Storage tanks and loading	1
	Subtotal	5836
Mobile sources	Road mobile sources	3719
	Non-road mobile sources	421
	Subtotal	4140
Solvent use	Printing and dyeing	267
	Architectural coatings	4,483

	Industrial coating	2592
	Pesticide application	208
	Household solvents	676
	Other solvents	851
	Vehicle maintenance	125
	Dry cleaning	23
	Subtotal	9225
Storage and transportation	Oil and gas storage (gas stations)	67
	Oil and gas transportation	66
	Subtotal	133
Biomass combustion	Industrial biomass boilers	244
	Biomass stoves	524
	Open biomass burning	981
	Subtotal	1749
Waste treatment	Wastewater treatment	1
	Solid waste treatment	193
	Flue gas denitrification	0
	Subtotal	194
Other emission sources	Catering	18
	Subtotal	18
Total	Total	22574

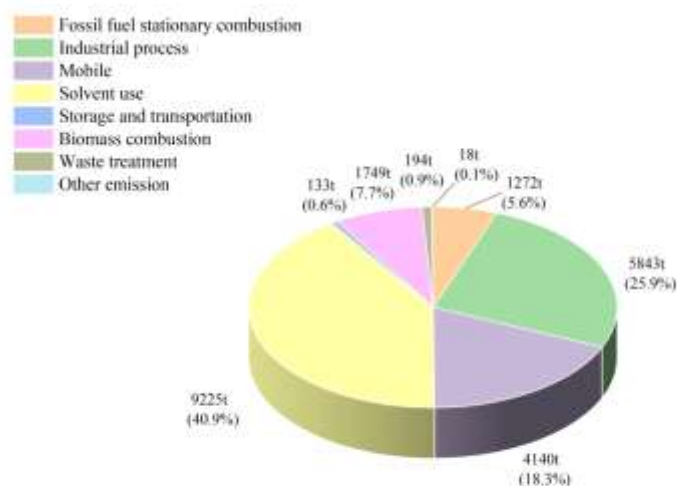
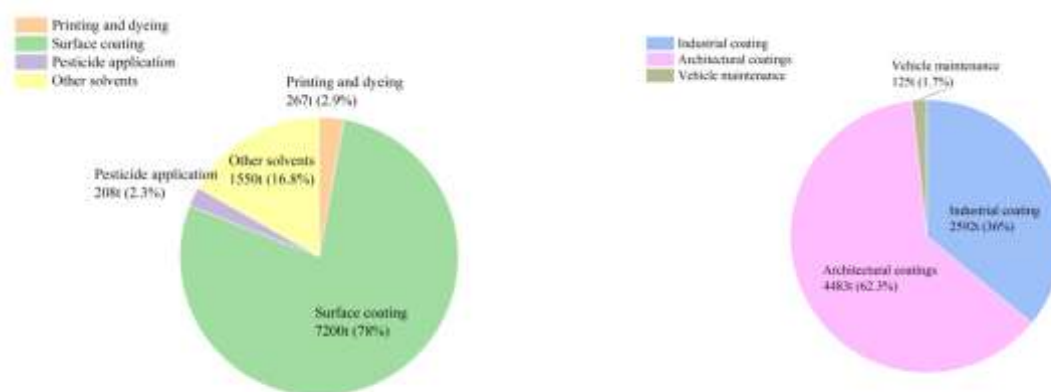


Figure 2. Contribution of Primary Emission Sources to Total VOCs Emissions

3.2. Emission Characteristics of Three Primary Emission Sources

3.2.1. Solvent Use Sources

Solvent use sources contributed the highest VOCs emissions (9225 t), with surface coating identified as the dominant subsector, accounting for 78.0% of solvent-related emissions (Figure 3(a)). In Jiaozuo City, surface coating activities are categorized into three types: architectural coatings, industrial coating, and vehicle maintenance (Figure 3(b)). Among these, architectural coatings generated 4483 t of VOCs, representing 62.3% of surface coating emissions, followed by industrial coating (2592 t, 36.0%) and vehicle maintenance (125 t, 1.7%). This highlights architectural and industrial coatings as the primary contributors to solvent-derived VOCs in Jiaozuo City.



(a) Solvent Use Sources

(b) Surface Coating

Figure 3. Contribution of Solvent Use Sources and Surface Coating Subsources to Total VOCs Emissions

3.2.2. Industrial Process Sources

Industrial process sources in Jiaozuo City contributed significantly to VOCs emissions, with the petrochemical and chemical industries (49.4%) and building materials sector (32.1%) being the

dominant contributors(Figure 4(a)). Within the petrochemical and chemical industries, the organic chemical industry alone accounted for 76.1% of emissions(Figure 4(b)).

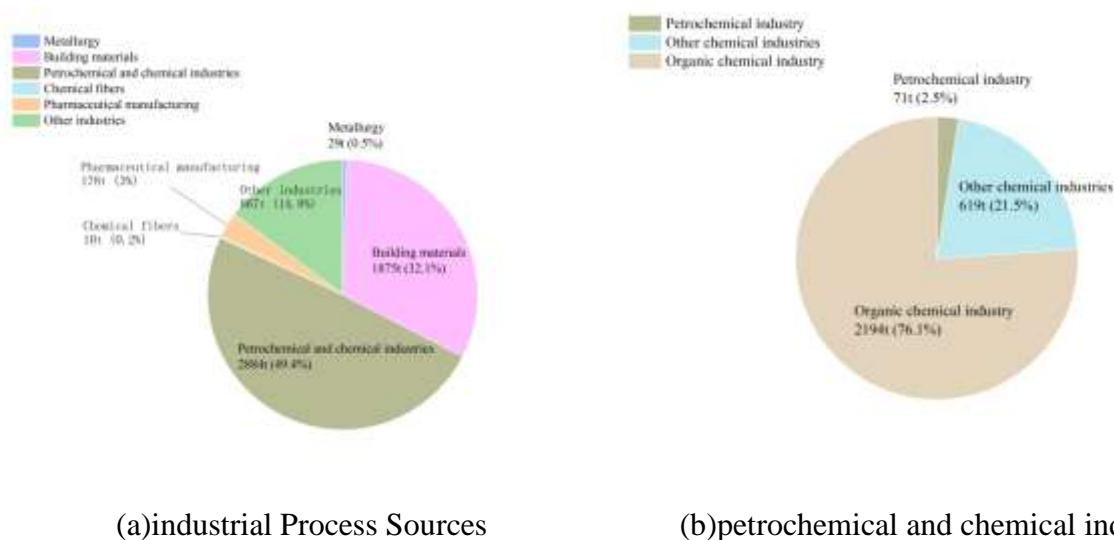


Figure 4. Contribution of Industrial Process Sources and Petrochemical/Chemical Subsources to Total VOCs Emissions

3.2.3. Mobile Sources

The majority of VOCs emissions from mobile sources originated from road mobile sources, which accounted for 3719 t (89.8% of total mobile source emissions) in Jiaozuo City (2019). Passenger vehicles (2309 t, 62.1%) and freight trucks (1253 t, 33.7%) were the primary contributors to road mobile emissions (Figure 5(a)). Notably, small passenger vehicles alone contributed 92.2% of passenger vehicle emissions (Figure 5(b)). Driven by economic growth and improved living standards, the rising ownership of small passenger vehicles has led to a continuous increase in their VOCs emissions.

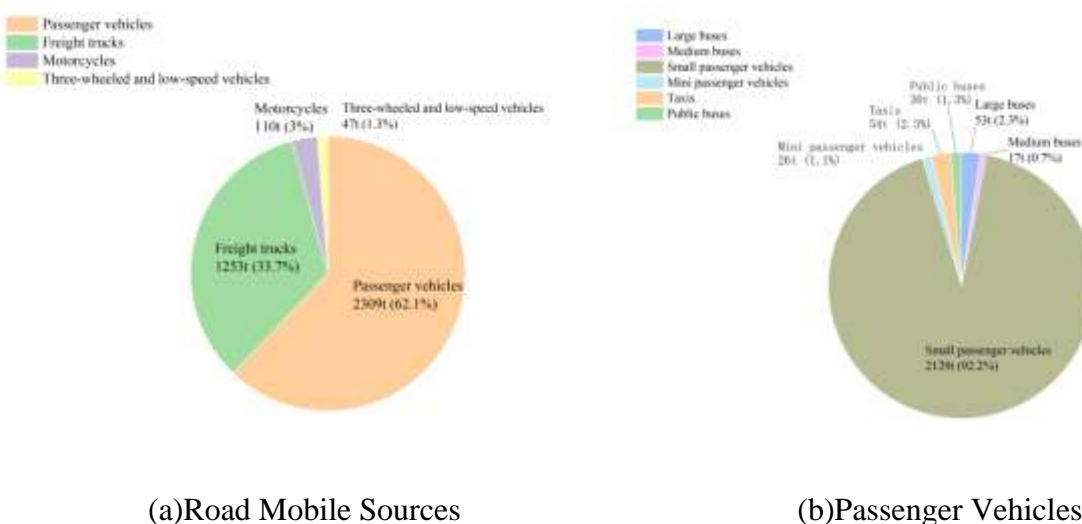


Figure 5. Contribution of Road Mobile Sources and Passenger Vehicle Subsources to Total VOCs Emissions

3.3. Spatial Distribution Characteristics

In terms of total emissions by district/county (Figure 6), Mengzhou (3,590 t) and Wuzhi (3,475 t) exhibited the highest VOCs emissions, accounting for approximately 15.9% and 15.4% of the city's total emissions, respectively. These were followed by Wenxian (2,817 t, 12.5%), Shanyang (2,673 t,

11.8%), and Qinyang (2,628 t, 11.6%), with all five regions exceeding 2,500 t in emissions. In contrast, Macun and Zhongzhan recorded significantly lower emissions, each at approximately 1,000 t.



Figure 6. Contribution of Counties and Districts to Total VOCs Emissions

3.4. Comparative Analysis with Other Studies

To objectively evaluate the VOCs emission levels in Jiaozuo City, a comparative analysis was conducted with Jinan City [27], Liaocheng City [28], and Hebi City [29]—all part of China’s "2+26" regional air pollution control cities (Table 2). Although the base years and total emission levels differ across these cities, their primary VOCs emission sources are consistent: solvent use sources, industrial process sources, and mobile sources. These three categories collectively accounted for over 80% of total emissions in all cities. Specifically, they contributed 85% in Jiaozuo City and 82% in Jinan, Liaocheng, and Hebi. This underscores the need for Jiaozuo City to prioritize mitigation efforts on these three dominant sources to achieve effective VOCs reduction.

Table 2. Comparison of VOCs Emissions (t) Across Cities in Key Source Categories

Primary Emission Sources	Jiaozuo City (2019)	Jinan City (2016)	Liaocheng City (2020)	Hebi City (2017)
Fossil fuel stationary combustion	1,272	5,815	2,134.5	539.4
Industrial process sources	5,843	38,928	6,504.9	3,052.5
Mobile sources	4,140	14,461	6,211.1	2,712.8
Solvent use sources	9,225	13,718	10,551.5	1,447.1
Storage and transportation	133	785	762.6	521.6
Biomass combustion	1,749	4,132	2,135.2	483.7
Waste treatment	194	1,527	2.5	72.6
Other sources (catering)	18	2,146	32.2	576.0
Total	22,574	81,512	28,434.5	8,829.7

3.5. Uncertainty Analysis

The uncertainties in compiling this anthropogenic VOCs emission inventory primarily arise from activity level data and emission factors. Activity level data were collected through literature reviews, departmental surveys, and statistical yearbooks, which may deviate from actual operational conditions of VOCs-emitting enterprises. Additionally, emission factors were selected based on publicly available inventory guidelines, technical manuals, and domestic literature, but lacked region-specific field measurements for key industries in Jiaozuo City, contributing to uncertainties in the refined VOCs speciation inventory. To mitigate these limitations, future efforts should prioritize enhancing activity level data quality through field verification, establishing a localized emission factor database via empirical studies on representative industries, and integrating these improvements to strengthen the scientific foundation for air quality modeling and pollution control strategies in Jiaozuo City.

4. CONCLUSIONS

(1) In 2019, the total anthropogenic VOCs emissions in Jiaozuo City reached 22574 t, with solvent use sources, industrial process sources, and mobile sources being the dominant contributors. Surface coating accounted for the largest share of solvent use emissions, while the petrochemical and chemical industries dominated industrial process emissions, and passenger vehicles contributed most significantly to mobile source emissions.

(2) Spatially, Mengzhou (15.9% of total emissions) and Wuzhi (15.4%) exhibited the highest VOCs emissions. Both regions showed substantial contributions from solvent use and industrial process sources, reflecting their industrial and urban development profiles.

(3) A comparative analysis with other cities (e.g., Jinan, Liaocheng, Hebi) revealed consistent dominance of the same three emission categories—solvent use, industrial processes, and mobile sources—collectively exceeding 80% of total emissions. Notably, Jiaozuo City's combined contribution from these sources (85%) surpassed that of peer cities (82%), underscoring the urgency of prioritizing mitigation efforts on these sectors.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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