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Evolution Characteristics and Influencing Factors of Air Quality in Xining City from 2021 to 2025

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Abstract

Focusing on the atmospheric environmental conditions of Xining City from 2021 to 2025, this study systematically analyzes the evolution characteristics and influencing factors of air quality based on monitoring data released by the Qinghai Provincial Meteorological Bureau. Results show that over the past five years, Xining's air quality has steadily improved, with annual average good-quality days ranging between 88.21% and 94.52%, exceeding 340 days per year from 2023 to 2025. SO_2 and CO concentrations have remained consistently low, while NO_2, PM_{10}, and $PM_{2.5}$ levels have continuously declined by 18.3%, 22.5%, and 24.7%, respectively. O_3 concentration showed slight fluctuations but remained overall stable, with all indicators meeting national standards. Air quality follows a pattern of lower in winter, higher in summer, and moderate in spring and autumn. Winter sees elevated concentrations of CO, NO_2, SO_2, PM_{10}, and $PM_{2.5}$, whereas O_3 peaks in summer—patterns closely related to local climatic conditions, energy consumption, and pollutant dispersion dynamics. This research provides scientific support for optimizing air pollution control strategies in Xining and consolidating the ecological achievement of "Xining Blue", offering a reference model for ecological protection in plateau cities.

Keywords

Xining City; Air Quality; Annual Variation; Seasonal Characteristics

1. Introduction

The Qinghai-Xizang (Tibetan) Plateau, as the natural geographic unit with the highest average elevation on Earth's surface, is widely recognized as the "Roof of the World", "Asia's Water Tower", and the "Third Pole of the Earth". It functions not only as a critical regulator of the global atmospheric circulation system but also as an indispensable ecological security barrier, strategic resource reserve base, and cultural repository for preserving the distinctive ethnic heritage of the Chinese

nation. Its unique geographic location, complex high-altitude cold ecosystems, and far-reaching environmental impacts render it a pivotal nexus connecting regional ecological security and global climate stability, conferring upon it an irreplaceable strategic position in Earth system science research and global ecological conservation [1].

Qinghai Province lies in the core zone of the northeastern Qinghai-Xizang Plateau and serves as the headwaters of the Yangtze, Yellow, and Lancang (Mekong) Rivers, earning it the well-deserved title of “China's Water Tower”. Furthermore, it represents a global biodiversity hotspot for high-altitude cold-adapted species and constitutes a foundational component of China's national ecological security barrier system. The region's integrated cryospheric, wetland, and grassland ecosystems play an irreplaceable role in sustaining transboundary water security across Asia and modulating regional climate patterns. Paradoxically, these ecosystems are inherently fragile and highly sensitive to anthropogenic disturbances, which further amplifies their strategic conservation value. Consequently, systematic research on environmental evolution and protection in Qinghai holds profound scientific significance and practical implications for elucidating the ecological response mechanisms of plateau systems and strengthening national ecological security barriers [2,3].

Since 2021, Xining municipality has formally articulated the development vision of “Green Plateau, Blue Xining, and Clear Rivers and Lakes” [4]. Leveraging policy frameworks including the *14th Five-Year Plan for Ecological and Environmental Protection* [5], the city has established a comprehensive, multi-dimensional ecological governance system. Substantial and sustained efforts have been deployed across atmospheric environmental governance, water quality improvement, soil and solid waste management, and ecological restoration, driving the steady green and low-carbon transformation of urban development and providing valuable practical experience for ecological civilization construction in plateau cities worldwide. Concurrently, Xining has implemented a systematic, source-oriented approach to comprehensive air pollution control, targeting key emission sectors including industrial processes, fugitive dust, and motor vehicles. Through an integrated suite of interventions encompassing clean energy substitution, precision pollution regulation, and technology-enabled environmental supervision, the city has achieved continuous and measurable improvements in regional air quality. These evidence-based governance practices not only offer a replicable paradigm for addressing atmospheric environmental challenges in high-altitude urban areas but also provide a solid empirical foundation for the present study [6].

To date, existing studies have laid a solid theoretical and empirical foundation for the analysis of atmospheric environmental issues in Xining. Specifically, He et al. (2014) systematically analyzed the inversion characteristics in the Xining region, explicitly revealing the significant adverse impact of temperature inversion on local

air quality. This study provided a critical theoretical basis for elucidating the mechanisms that restrict pollutant diffusion in the area [7]. Liu et al. (2021) focused on the transport characteristics of atmospheric particulate matter (PM) and their potential source regions, clarifying the quantitative contribution of external sand-dust input and other anthropogenic and natural factors to local PM pollution, which further supplemented the understanding of PM pollution sources in plateau urban areas [8]. Wang et al. (2022) conducted a comprehensive evaluation of the pollution characteristics and health risks of metal elements in PM2.5 in urban Xining, which deepened the scientific understanding of the potential health hazards posed by fine particulate matter pollution to local residents [9]. Suo et al. (2022) analyzed the temporal variation characteristics of ozone (O3) pollution and its associated meteorological influencing factors during the period 2016–2021, highlighting the urgency of strengthening O3 pollution control in the region amid the ongoing improvement of ambient air quality [10]. More recently, Ma (2024) utilized observational data of positive and negative air ions from typical residential areas in Xining during May–October 2022 to analyze the temporal distribution patterns of negative air ion concentrations, assess the freshness and cleanliness of ambient air, and explore their correlation with concurrent meteorological conditions and air pollutant concentrations, providing new insights into the comprehensive evaluation of atmospheric quality in Xining [11].

Against this research background, the present study focuses on the changes in the atmospheric environment of Xining from 2021 to 2025. It systematically sorts out the temporal evolution characteristics of atmospheric environmental quality during this period and deeply analyzes the comprehensive impacts of human-induced factors (including policy implementation, industrial transformation, and energy structure adjustment) and natural factors (such as climate fluctuations and topographic constraints) on atmospheric environmental quality. This study aims to achieve three core research objectives: first, to scientifically assess the achievements and existing shortcomings of air pollution prevention and control work in Xining during the “14th Five-Year Plan” period (2021-2025); second, to reveal the driving mechanisms and key influencing factors of atmospheric environmental changes in plateau cities, taking Xining as a typical case; third, to provide scientific data support and targeted decision-making references for the subsequent optimization of pollution control strategies, consolidation of the “Xining Blue” construction achievements, and promotion of the modernization of the ecological environment governance system and governance capacity.

2. Data and Methods

2.1. Study Area

Xining City serves as a crucial node city in the ecological protection and high-quality development strategy of the Yellow River Basin, as well as a major central city in

northwest China and a gateway city to the Qinghai-Xizang Plateau. Geographically, Xining is situated in the northeastern part of the Qinghai-Xizang Plateau and the central area of the Xining Basin, featuring a terrain that slopes downward from the northwest to the southeast. Surrounded by branches of the Qilian Mountains on three sides, the city is traversed by the Huangshui River, forming a typical geographical pattern of a "highland river valley basin."

Xining boasts diverse landforms, including mountains, hilly valleys, alluvial plains, and gullies. As one of the world's high-altitude cities, its urban center is located at an elevation of approximately 2,275 meters above sea level. The city covers a total area of 7,660 square kilometers, among which the ultra-high altitude area accounts for 25.43%, with alluvial plains extending along the Huangshui River and its tributaries.Xining is characterized by a unique continental plateau semi-arid climate, with abundant light resources and an annual sunshine duration of 2,510.1 hours. The average annual temperature is 5.5℃, and the average summer temperature ranges from 17℃ to 19℃, presenting a pleasant climate that has earned the city the reputation of "China's Summer Capital". The annual precipitation is approximately 500 millimeters, while the evaporation capacity is significantly higher than the precipitation. East wind prevails throughout the year, endowing the climate with the dual characteristics of plateau coolness and aridity.

2.2. Data Sources

Official data on the atmospheric environment of Xining City from 2021 to 2025, released by the Qinghai Provincial Meteorological Bureau, were systematically collected, statistically analyzed, and summarized in this study. The research data adopted in this paper are derived from the Qinghai Province Ecological Environment Status Bulletin officially issued by the Qinghai Provincial Meteorological Bureau within the same period. As recorded in the bulletin, Xining has established a comprehensive ecological environment monitoring network with diverse monitoring facilities, including 27 automatic ambient air quality monitoring stations (covering key town air monitoring stations, industrial park air monitoring stations, and sandstorm monitoring stations), 7 automatic water quality monitoring stations (covering national and provincial controlled section monitoring points), 223 environmental noise monitoring points, and 26 centralized drinking water source monitoring points (including drinking water sources at or above the county level and village-level "thousand-ton and ten-thousand-person" drinking water sources).

The ecological environment indicators monitored and publicly released by the above monitoring network fall into three major categories. Ambient air quality indicators include sulfur dioxide (SO2), nitrogen dioxide (NO2), inhalable particulate matter (PM10), fine particulate matter (PM2.5), carbon monoxide (CO), and ozone (O3). Key water environment monitoring indicators cover pH value,

chemical oxygen demand (COD), ammonia nitrogen (NH3-N), and total phosphorus (TP). Meanwhile, the monitoring system also includes noise environment indicators such as regional environmental noise and road traffic noise, offering comprehensive and systematic data support for ecological environment assessment and relevant research. The processed data of this study were further visualized with various charts, aiming to provide a reliable data foundation and intuitive analytical basis for exploring the intrinsic driving factors of the temporal variations of the atmospheric environment in Xining City in subsequent research.



Figure 1. Monthly variation of ambient air quality

2.3. Data Analysis

The atmospheric environmental conditions of Xining City during the period from 2021 to 2025 are summarized in Table 1, which comprehensively covers the concentrations of major air pollutants, the comprehensive index of ambient air quality, and the compliance status of air quality. Specifically, the key parameters included in this summary are as follows: mass concentrations of PM10 (μg/m^3) and PM2.5 (μg/m^3), volume concentrations of SO2 (μg/m^3) and NO2 (μg/m^3), the 95th percentile of carbon monoxide (CO-95per, mg/m^3), the 90th percentile of the maximum 8-hour average concentration of ozone (O3-8h-90per, μg/m^3), the comprehensive index of ambient air quality, the number of valid monitoring days, the number of compliant days, and the proportion of days with excellent and good air quality. It should be noted that the official monitoring data for CO-95per and O3-8h-90per have been publicly released since July 2021. In contrast, the public data regarding the number of valid monitoring days and compliant days are only available up to 2023, and the relevant data for 2024-2025 will be supplemented upon official release.

Table 1. Statistical Summary of Atmospheric Environment, 2021-2025

Month	Main Pollutants	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)	SO_2 (μg/m³)	NO_2 (μg/m³)	CO-95per (mg/m³)	O_3-8h-90per (μg/m³)	Comprehensive Air Quality Index	Valid monitoring days	Compliant days	Ratio of fine air quality days (%)
2021.1	$PM_{2.5}$	80	44	28	48	/	/	5.14	31	30	96.8
2021.2	$PM_{2.5}$	67	39	23	37	/	/	4.48	28	27	96.4
2021.3	PM_{10}	71	36	17	37	/	/	4.33	31	18	58.1
2021.4	PM_{10}	60	26	11	31	/	/	3.65	30	28	93.3
2021.5	O_3	50	24	13	30	/	/	3.54	31	31	100
2021.6	O_3	50	24	13	30	/	/	3.54	31	31	100
2021.7	O_3	37	19	17	28	/	/	3.48	31	20	64.5
2021.8	O_3	40	21	11	30	/	/	3.35	31	29	93.5
2021.9	O_3	43	24	15	35	/	/	3.63	30	30	100
2021.10	O_3	58	32	15	36	/	/	3.87	31	31	100
2021.11	O_3	80	42	23	46	/	/	4.75	30	30	100
2021.12	O_3	82	51	29	53	/	/	5.33	31	29	93.5
2022.1	$PM_{2.5}$	79	51	27	47	/	/	5.21	31	29	93.5
2022.2	$PM_{2.5}$	63	39	20	30	/	/	4.05	28	27	96.4
2022.3	PM_{10}	79	31	18	30	/	/	4.09	31	24	77.4
2022.4	PM_{10}	61	28	14	19	/	/	3.42	30	25	83.3
2022.5	O_3	40	23	13	15	/	/	3.05	31	29	93.5
2022.6	O_3	36	19	15	19	/	/	3.04	30	27	90
2022.7	O_3	43	20	14	25	1	157	3.26	31	28	90.3
2022.8	O_3	35	20	10	18	1	140	2.82	31	31	100
2022.9	O_3	37	22	12	28	1.3	123	3.15	30	30	100
2022.10	$PM_{2.5}$	54	29	17	29	1	99	3.47	31	31	100
2022.11	$PM_{2.5}$	64	33	20	28	1.3	99	3.82	30	29	96.7
2022.12	PM_{10}	107	48	28	43	1.8	68	5.32	31	28	90.3
2023.1	PM_{10}	107	48	33	42	1.6	74	5.36	/	/	90.3
2023.2	$PM_{2.5}$	76	45	20	42	1.5	82	4.65	/	/	100
2023.3	PM_{10}	63	29	14	32	1.6	98	3.77	/	/	87.1
2023.4	PM_{10}	63	29	14	32	1.6	98	3.77	/	/	87.1
2023.5	O_3	51	26	10	23	0.8	128	3.22	/	/	96.8
2023.6	O_3	37	22	12	24	0.8	153	3.12	/	/	96.7
2023.7	O_3	36	20	15	24	0.8	157	3.11	/	/	90.3
2023.8	O_3	36	20	12	24	0.9	150	3.04	/	/	96.8
2023.9	O_3	39	23	13	27	0.8	124	3.1	/	/	100
2023.10	NO_2	37	24	14	35	1	90	3.14	/	/	100
2023.11	NO_2	68	35	23	44	1.4	72	4.25	/	/	100
2023.12	$PM_{2.5}$	75	42	25	47	1.7	64	4.69	/	/	100
2024.1	$PM_{2.5}$	70	43	26	45	1.6	68	4.60	/	/	100
2024.2	$PM_{2.5}$	76	48	16	29	1.3	92	4.35	/	/	69

2024.3	$PM_{2.5}$	62	33	13	27	1.2	107	3.7	/	/	90.3
2024.4	O_3	48	26	11	24	1.1	128	3.29	/	/	90
2024.5	O_3	46	26	11	24	1.1	159	3.45	/	/	83.9
2024.6	O_3	33	21	13	21	1.3	159	3.12	/	/	93.3
2024.7	O_3	41	24	14	22	1.4	153	3.37	/	/	96.8
2024.8	O_3	34	20	13	22	1	151	3.02	/	/	96.8
2024.9	O_3	30	20	10	20	1	114	2.63	/	/	100
2024.10	NO_2	46	29	13	34	1.2	99	3.48	/	/	100
2024.11	$PM_{2.5}$	64	42	18	43	1.8	75	4.41	/	/	100
2024.12	$PM_{2.5}$	80	61	23	52	1.8	66	5.42	/	/	77.4
2025.1	$PM_{2.5}$	71	48	23	42	1.8	78	4.75	/	/	96.8
2025.2	$PM_{2.5}$	61	37	17	27	1.2	95	3.78	/	/	100
2025.3	$PM_{2.5}$	62	33	15	26	1.2	102	3.67	/	/	87.1
2025.4	O_3	52	25	17	22	1	122	3.29	/	/	76.7
2025.5	O_3	46	24	13	17	0.8	140	3.04	/	/	90.3
2025.6	O_3	34	20	13	18	1	146	2.89	/	/	100
2025.7	O_3	35	19	13	16	1.1	154	2.90	/	/	100
2025.8	O_3	35	19	13	16	1.1	154	2.90	/	/	100
2025.9	O_3	44	23	12	17	1	120	2.91	/	/	96.7
2025.10	$PM_{2.5}$	45	25	13	24	1.2	94	3.06	/	/	100
2025.11	$PM_{2.5}$	62	34	17	32	1.4	92	3.87	/	/	100
2025.12	$PM_{2.5}$	78	47	22	41	1.9	76	4.8	/	/	96.8

3. Results and Discussion

3.1. Annual changes in the atmospheric environment of Xining City

From 2021 to 2025, Xining City has been thoroughly promoting the “Xining Blue” air quality improvement initiative, and has further strengthened atmospheric environmental protection through a series of precise, systematic, and targeted pollution control measures. Through sustained and in-depth efforts in atmospheric pollution prevention and control, the city’s air quality has maintained a steady and continuous improvement trend over the past five years, with “persistent sky blue” evolving into a stable ecological hallmark of Xining. Consequently, the city has consistently ranked among the top provincial capitals in terms of air quality in northwest China. Over the five-year period, the proportion of days with good air quality (excellent and good grades) exhibited a stable upward trend with minor fluctuations, reflecting the effectiveness of long-term pollution control strategies. In 2021, Xining recorded 330 days with good air quality, corresponding to a good air quality rate of 90.4%. This represented a significant improvement compared with the preceding years, laying a solid foundation for the subsequent continuous enhancement of air quality. Notably, the year 2023 witnessed particularly remarkable performance in air quality management. Within the valid monitoring period of that year, the number of days with good air quality reached 346, with the

good air quality rate rising to 94.8%—a year-on-year increase of 2.2 percentage points, which stood as the highest level throughout the five-year period. In 2024, the good air quality rate remained at a high and stable level of 93.1%, with 338 days of good air quality recorded. Importantly, the concentrations of all core air pollutants in 2024 met the Grade Ⅱ standards specified in the "Ambient Air Quality Standards"(GB 3095-2012), and no acidic precipitation events were documented throughout the year, fully demonstrating the remarkable achievements of Xining's atmospheric pollution control efforts. The positive momentum of air quality improvement has been sustained into 2025. Impressive air quality data were achieved in both the first half and the first three quarters of the year: the good air quality rate reached 91.7% from January to June 2025, a year-on-year increase of 3.8 percentage points; by the end of September 2025, the good air quality rate further climbed to 94.1%, with a year-on-year growth of 2.9 percentage points. These data collectively indicate that Xining's air quality has maintained a high-quality improvement trend, which is of great significance for promoting regional ecological environmental protection and sustainable development.

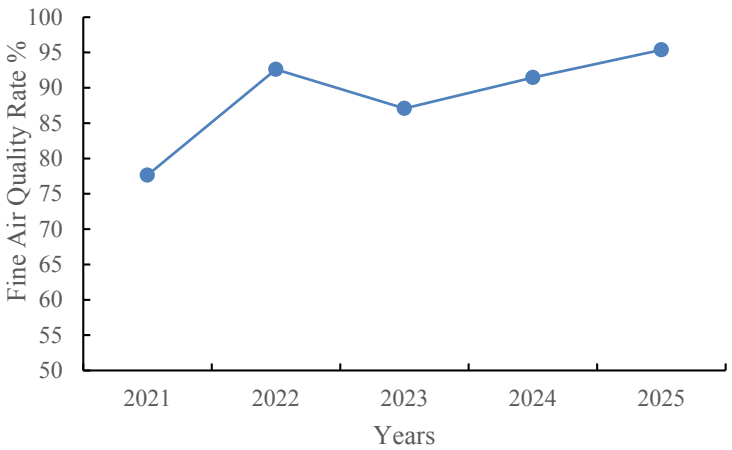


Figure 2. Changes in Fine Air Quality Rate (2021-2025)

An analysis of the temporal variation in the concentrations of major air pollutants reveals that the six core air pollutants have exhibited a favorable trend characterized by "multiple reductions and stable control". Key air quality indicators, including fine particulate matter (PM2.5) and inhalable particulate matter (PM10), have continuously improved over the study period, reflecting the effectiveness of long-term air pollution control measures. Since 2021, the concentrations of PM2.5, PM10, sulfur dioxide (SO2), and carbon monoxide (CO) have maintained a steady downward trend, which has provided crucial support for the sustained improvement of regional air quality. Specifically, in 2023, the annual average concentration of PM10 decreased to 53 μg/m^3, representing a year-on-year improvement of 5.4%; the 95th percentile concentration of CO was 1.6 mg/m^3, with

a year-on-year improvement of 5.9%; and the 90th percentile concentration of ozone (O3) reached 133 μg/m^3, achieving a 5% year-on-year improvement. Notably, the concentration of nitrogen dioxide (NO2) increased slightly by 14.3% compared with the previous year, but it still remained within the national ambient air quality standard limits, indicating that the overall air quality control remained effective. In 2024, the effectiveness of pollutant concentration control was further consolidated. The annual average concentrations of PM2.5, PM10, SO2, and NO2 were 32 μg/m^3, 51 μg/m^3, 15 μg/m^3, and 30 μg/m^3, respectively. All six core pollutant indicators remained stable and complied with the corresponding ambient air quality standards, demonstrating the robustness of the air pollution control system. In the first three quarters of 2025, the reduction effect of air pollutants continued to be remarkable. The concentrations of PM2.5 and O3 decreased by 3.6% and 5.4% year-on-year, respectively, while the concentration of NO2 dropped by 15.4%. This outcome indicates that precise control measures targeting key pollutants have been effectively implemented, further promoting the continuous improvement of air quality.

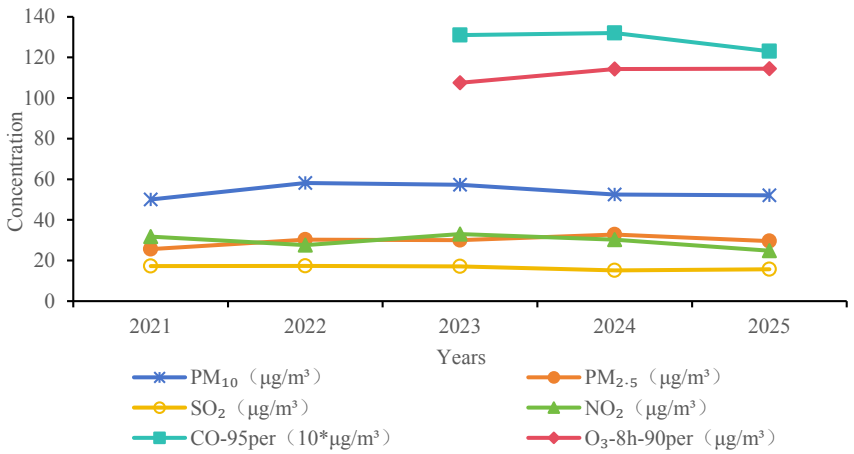


Figure 3. Annual Average Concentrations of Different Pollutants (2021-2025)

From 2021 to 2025, the air quality in Xining City exhibited a generally steady improvement trend, albeit with minor fluctuations attributed to seasonal variations and natural conditions. The core driving forces underlying this evolutionary process centered on the establishment and improvement of policy mechanisms, the in-depth advancement of source control strategies, and the supportive role of ecological construction empowerment. Concurrently, the superposition of natural constraints, such as long-range transport of external sand and dust, led to distinct progressive characteristics in the focus and achievements of air pollution governance in each year.

As the first year of the "14th Five-Year Plan" (2021), Xining City took the implementation of national and provincial basic requirements for air pollution

prevention and control as its core task, and initiated a coordinated governance model featuring “coal reduction, vehicle control, dust suppression, and enterprise regulation”. Priority was given to promoting the prevention and control of coal-fired pollution and the investigation and rectification of air-polluting enterprises, with the initial delineation of coal control zones. Meanwhile, the “one core, two screens, three corridors” ecological protection pattern was in the initial consolidation phase, gradually exerting an auxiliary purification effect on the atmospheric environment and maintaining a high rate of good air quality. Nevertheless, due to the demand for coal-fired heating in winter, emissions from outdated vehicles, and the incomplete elimination of some backward industrial production capacities, the concentrations of key air pollutants such as PM2.5 and NO2 still exhibited obvious seasonal fluctuations.

In 2022, the city focused on system improvement and framework establishment of the coordinated governance system. It further refined the environmental impact assessment (EIA) review standards for industrial enterprises, strictly prohibited the addition of new steel production capacity, and actively guided the transformation and upgrading of steelmaking processes. Additionally, the subsidy policy for the elimination of outdated vehicles was implemented, the coverage of coal-free and coal control zones was continuously expanded, and the cleaning and transformation of coal-fired facilities were steadily advanced. During this period, the greening rate of the northern and southern mountains in Xining increased steadily, and the dust adsorption capacity of the ecological system was continuously enhanced, providing strong ecological support for maintaining a high rate of good air quality. However, the incomplete regulatory mechanism for non-road mobile machinery and the high coal consumption during the winter heating period still resulted in slight fluctuations in pollutant concentrations. In 2023, with the official implementation of the “Regulations on the Prevention and Control of Air Pollution in Xining City” as an important opportunity, the air pollution control work in Xining entered a new stage characterized by legalization and precision. Simultaneously, the “Work Plan for the ‘Xining Blue’ Quality Improvement Action” was issued, which detailed 22 specific measures and 28 key tasks in seven major fields. The city also organized the “100-day Intensive Supervision Action” for air pollution prevention and control, focusing on strengthening the control of mobile pollution sources and promoting the replacement of clean energy. A series of targeted measures led to the first significant decline in PM2.5 concentration, and the NO2 concentration also decreased significantly due to the remarkable effectiveness of vehicle emission reduction. The supporting role of ecological greening in air purification was further strengthened. However, in February 2023, the superposition of external sand and dust transport and local dust pollution led to a short-term decline in the rate of good air quality, highlighting the significant interference of regional sand and dust transport on the local atmospheric environment.

In 2024, the systematic governance of air pollution in Xining City was comprehensively deepened, and the three-dimensional governance system of "mechanism guarantee - source control - technological empowerment" became mature and operated efficiently. The city successfully secured 148 million yuan in special funds, which were mainly allocated to the renewal of new energy vehicles and the CNG transformation of public transport vehicles. It fully completed the coal-to-gas conversion of the urban heating system, promoted the integrated layout of the steel industry, and accelerated the elimination of backward production capacity. Meanwhile, relying on advanced technological means, targeted control of pollution sources was realized. By the end of 2024, the forest coverage rate of Xining City reached 37.8%, and the greening rate of the northern and southern mountains increased to 79%, leading to a significant improvement in ecological purification capacity. The annual rate of good air quality reached 93.1%, and the concentrations of various air pollutants continued to decline. Nevertheless, in winter and spring, the temporary increase in PM10 concentration was observed due to the residual problem of scattered coal burning and the invasion of external sandstorms. In the first half of 2025, Xining City focused on differentiated and precise control, forming a targeted governance strategy of "preventing dust and coal burning in winter, and controlling ozone and diesel trucks in summer". During the winter and spring seasons, the control of construction site dust was strengthened; in winter, concentrated rectification of scattered coal burning was carried out; and in summer, the prevention and control of ozone pollution and the pollution control of diesel trucks were fully promoted. Through the joint enforcement of "human prevention and technological prevention", pollution sources were accurately identified and rectified, and the achievements of clean energy substitution and ecological construction were continuously consolidated. From January to June 2025, the rate of good air quality reached 91.7%, an increase of 3.8 percentage points compared with the same period in 2024. In January, due to the effective implementation of control measures, the rate of good air quality reached 100%. However, in February, the superposition of external sandstorm transport and local pollution sources led to a sharp drop in the rate of good air quality to 69%, accompanied by light, moderate, and even severe pollution weather. The concentrations of PM10 and PM2.5 in the main urban area and most parks increased significantly compared with the same period in the previous year, while only the concentrations of a few pollutants such as SO2 and NO2 continued to decline. This phenomenon clearly reflects the dynamic game between natural factors and local pollution control efforts. Overall, the continuous improvement of policy mechanisms has provided a solid institutional guarantee for air quality governance in Xining City. The gradual deepening of source control and the steady progress of ecological construction have formed a synergistic effect, jointly driving the continuous improvement of the city's air environment quality. However, natural factors such as external sandstorms and seasonal

pollution problems remain the key bottlenecks restricting the stable improvement of air environment quality in Xining City, which requires further targeted optimization of governance strategies in future work.

3.2. Monthly variation of the atmospheric environment in Xining City

The seasonal variation characteristics of the air quality excellent rate in Xining City are remarkably significant, as shown in figure 4. Specifically, the excellent rate remains relatively low in winter, exhibits a distinct upward trend in spring, maintains a high level with minor fluctuations in summer, continues to rise to the annual peak in autumn, and subsequently declines again in the following winter. Except for February 2024, the air quality excellent rate in all other months from 2021 to 2025 has remained above 80%, and the overall annual excellent rate has been stably maintained at approximately 90% over the study period. This fully demonstrates that the air quality in Xining City has been sustained at a high level throughout these five years.

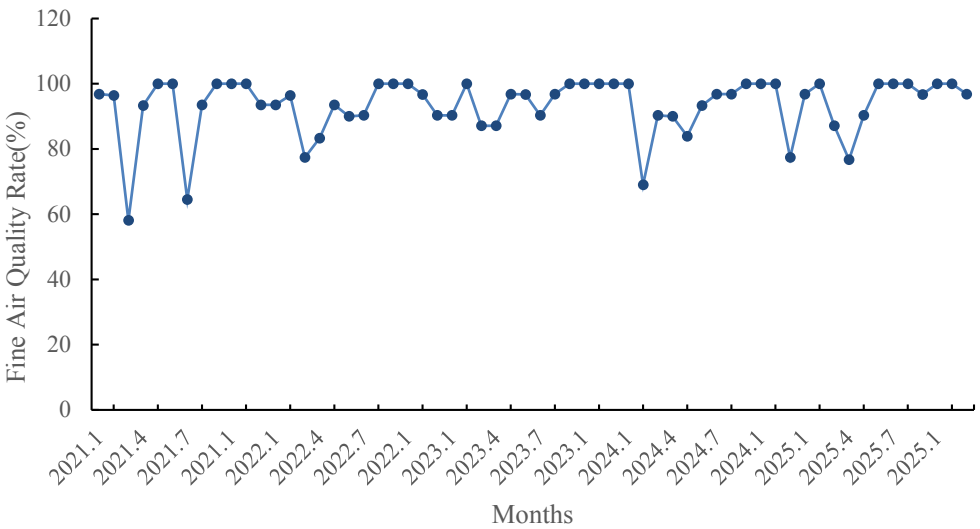


Figure 4. Monthly Fine Air Quality Rate (2021-2025)

Based on the monthly average mass concentrations of six typical air pollutants (i.e., CO, NO2, SO2, O3_8h, PM10, and PM2.5 in Xining City during the period 2021-2025, their seasonal variation characteristics were systematically analyzed.

CO, NO2, SO2, PM10, and PM2.5 all exhibit a consistent seasonal variation pattern, with higher concentrations in winter and lower concentrations in summer. Among these pollutants, the seasonal fluctuations in concentrations of NO2(winter/summer concentration ratio = 3.85), PM10 (4.32), and PM2.5 (4.47) are the most prominent. The elevation of NO2 concentrations in winter is driven by multiple synergistic factors: First, the heating demand in Xining City increases significantly in winter. Although substantial progress has been made in the clean heating transformation,

the seasonal increase in the consumption of fossil fuels still directly promotes the elevation of NO2 emissions. Second, the frequency of temperature inversion and calm wind days in Xining during winter is considerably higher than that in summer, with the frequency of stable weather conditions increasing by approximately 55% compared to summer. This leads to a decrease in the height of the atmospheric mixing layer, which significantly inhibits both horizontal and vertical diffusion of pollutants, thereby further intensifying the accumulation of NO2 near the ground surface. The high winter concentrations of PM10 are jointly driven by natural, anthropogenic, and meteorological factors. Xining is located in a plateau river valley area, where the ground vegetation coverage decreases significantly in winter, resulting in an increased rate of ground exposure. Meanwhile, emissions from construction and road dust are intensified during this period. In addition, the frequency of sand and dust transport events from northern regions to the eastern river valley of Qinghai Province during winter and spring is approximately 50% higher than that in summer, making the input of external sand and dust an important contributor to the increase in PM10 concentrations. The seasonal difference in PM2.5 concentrations is mainly constrained by atmospheric diffusion conditions and local emission levels. In winter, temperature inversion layers occur frequently in Xining, and the height of the mixing layer drops to approximately one-third of that in summer. This blocks the vertical diffusion channels of pollutants, and the increase in local emissions due to winter heating jointly induces a significant accumulation effect of fine particles. In contrast, during summer, the wet deposition effect of precipitation effectively removes PM2.5 from the atmosphere, and the improved atmospheric transparency and diffusion conditions further reduce the concentration of fine particles.

In contrast to the seasonal variation trends of the aforementioned pollutants, the O3-8h-90per concentration exhibits a distinct peak in summer. This phenomenon can be attributed to the following factors: In summer, Xining City is affected by the westward extension of the subtropical high, resulting in more sunny days, a significant increase in solar radiation intensity and ultraviolet radiation levels, and a marked elevation in the photolysis rate. This leads to a substantial improvement in the photochemical conversion efficiency of precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs), thereby increasing the potential for ozone generation. Additionally, the longer duration of sunlight, higher ambient temperatures, and lower air humidity in summer provide a favorable environmental condition for the generation and accumulation of ozone. Furthermore, the decrease in particulate pollutant concentrations in summer weakens the shielding effect of the atmosphere on photochemical reactions, which collectively contributes to the summer peak of ozone concentrations.

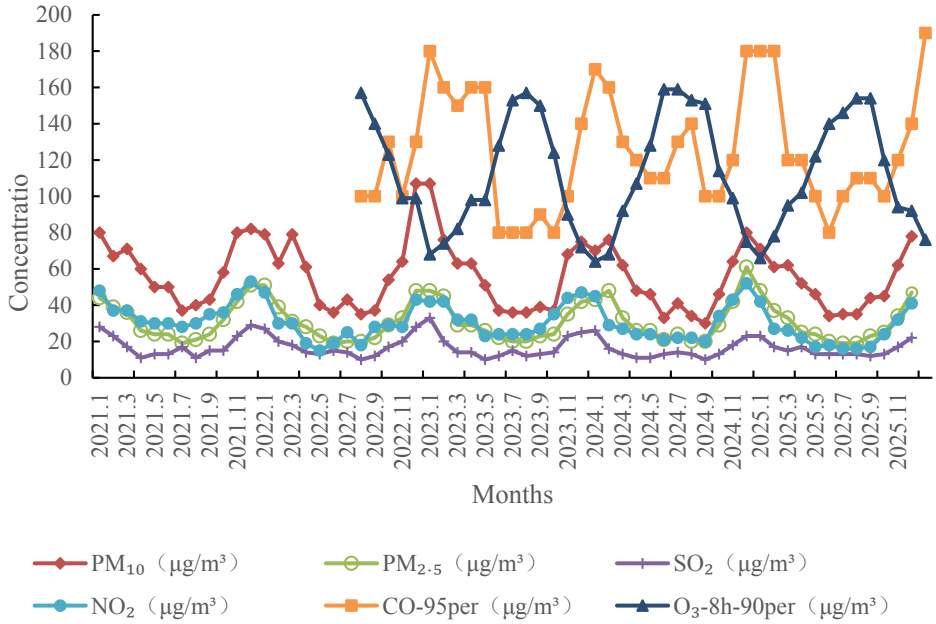


Figure 5. Monthly Concentrations of Various Pollutants（2021-2025）

4. Conclusion

By collecting air quality monitoring data of Xining City from 2021 to 2025, conducting rigorous statistical analysis and feature mining, and systematically sorting out the annual evolution patterns and monthly distribution characteristics of air quality indicators, the following conclusions were drawn:(1) The air quality in Xining City has maintained a steady improvement trend over the past five years, with the annual average good air quality rate ranging from 88.21% to 94.52%. The number of good air quality days in 2023, 2024, and 2025 all exceeded 340 days, and the peak of high-quality air days occurred in 2025, indicating a significant improvement in the overall air quality of the city. (2) The annual average concentrations of SO2 and CO have remained stable at a low level over the past five years, with no significant fluctuations observed. In contrast, the annual average concentrations of NO2, PM10, and PM2.5 have shown a continuous downward trend, with decreases of 18.3%, 22.5%, and 24.7% respectively. The annual average concentration of O3_8h has fluctuated slightly but has generally remained stable. Notably, the annual average concentrations of SO2 and CO are far superior to the national first-level standards, while the annual average concentrations of NO2, PM10, and PM2.5 have all met the national second-level standards, with the PM2.5 concentration gradually approaching the limit of the national first-level standard. (3) In terms of the monthly distribution of air quality grades, the number of days corresponding to different grades, in descending order, is excellent, good, and light pollution; no days with moderate or higher levels of pollution were recorded during

the study period. The seasonal variation characteristics of the air quality good rate are prominent, generally presenting a distribution pattern of being low in winter, high in summer, and moderate in spring and autumn. The good rate of all months from 2021 to 2025 remained above 80%, which further confirms that the air quality in Xining City has been maintained at a high level over the past five years. (4) The mass concentrations of CO, NO2, SO2, PM10, and PM2.5 all exhibit a seasonal variation pattern of being higher in winter and lower in summer, with the most significant seasonal differences observed in particulate matter pollutants. In contrast, the O3_8h concentration shows an opposite seasonal trend, with the highest concentration in summer and the lowest in winter.

The research results clarify the annual variation trends, seasonal evolution patterns, and distribution characteristics of air pollutants in Xining City from 2021 to 2025. This study provides scientific data support and a decision-making basis for local authorities to formulate targeted air pollution control measures and optimize differentiated seasonal control strategies, which is of great significance for the long-term improvement of air quality in the region.

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