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Analysis and Prediction of Air Quality in Changsha City

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Abstract:

Air quality is a critical factor affecting public health and the ecological environment, and it is significant for the sustainable development of cities. This study analyzes air quality data in Changsha from 2013 to 2023, revealing trends and seasonal characteristics while exploring the correlations among pollutants. The results indicate a significant overall improvement in air quality in Changsha, with the annual average Air Quality Index (AQI) decreasing from 120 in 2013 to 80 in 2022. Concentrations of PM2.5 and PM10 have markedly declined, while O3 concentrations show an increasing trend. Seasonal analysis shows that winter has the poorest air quality and summer has the best. Correlation analysis reveals a high positive correlation between PM2.5 and AQI. The study suggests strengthening the comprehensive management of PM2.5, establishing a synergistic control mechanism for O3 pollution through VOCs and NOx, implementing seasonal differentiated management strategies, deepening regional joint prevention and control, enhancing traffic source pollution control, improving early warning capabilities, promoting public participation, and strengthening policy support and economic incentives. These measures will contribute to further improving air quality in Changsha and promoting the city's sustainable development.

Keywords: Changsha City; Air Quality; PM2.5; Time Series Analysis; Seasonal Variation

1. Introduction

In recent years, air quality issues have increasingly attracted social attention alongside the rapid economic development in China. As the capital city of Hunan Province, Changsha's air quality not only impacts on the health of residents but also serves as an important indicator of urban sustainable development.

Currently, research on air quality in Changsha is gradually increasing. Xiong analyzed the transmission pathways and potential source areas of PM2.5 in Changsha, revealing the spatiotemporal distribution characteristics of PM2.5 in the region, and pointed out that winter is a high incidence period for PM2.5 pollution, predominantly from local emissions [1]. Liao evaluated statistical methods for predicting major air pollutants, assessing the application of time series analysis and regression models in air quality

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prediction, and providing a reliable statistical foundation for subsequent research [2]. Devasekhar combined machine learning techniques with traditional statistical methods, verifying the applicability of Support Vector Machine (SVM) and Random Forest (RF) algorithms in air pollution prediction, indicating the potential of machine learning to enhance prediction accuracy, especially in complex pollution environments [3]. Berkani developed a data-driven urban air pollution prediction model based on the MoreAir case study and applied it in multiple cities [4]. This model can predict changes in pollutant concentrations based on meteorological data, providing a technical reference for air quality management in Changsha [4]. Zheng conducted a comprehensive evaluation of air quality in Changsha from 2018 to 2022 based on a combined weighting method, showing that PM2.5 and O_3 are the main pollutants and recommending differentiated management measures for different seasons [5].

Although these studies provide valuable insights into air quality issues in Changsha, the impact of rapid urbanization on air quality in China requires further exploration. For instance, in Beijing, the urbanization rate increased from 84.9% to 86.5% from 2008 to 2017, while the annual average concentration of PM2.5 decreased from 90μg/m³ to 58μg/m³ during the same period, indicating a potentially positive impact of urbanization on air quality [6]. As an important city in central China, Changsha is located in the Xiangjiang River basin, where the basin topography imposes certain restrictions on pollutant diffusion, while also facing dual pressures of economic development and environmental protection. In 2021, Changsha's GDP reached 1.21435 trillion yuan, with an urbanization rate of 82.02%, further highlighting the importance of air quality management in its sustainable development [7].

This study aims to analyze air quality data in Changsha from 2013 to 2023, exploring long-term trends, seasonal characteristics of pollutant concentrations, and correlations among pollutants. Additionally, the potential impact of urbanization on air quality in Changsha will be examined. Through a systematic analysis of these aspects, this study will provide scientific evidence for formulating targeted air quality improvement strategies in Changsha and contribute new insights into the challenges and opportunities of air quality management in the context of rapid urbanization.

2. Research Methods

2.1 Data Sources

The data used in this study was sourced from the Changsha Environmental Monitoring Department, covering daily air quality data from December 2013 to February 2023. The dataset includes the following indicators: date, Air Quality Index (AQI), air quality level, PM2.5 concentration, PM10 concentration, SO2 concentration, CO concentration, NO2 concentration, and O3_8h (8-hour average ozone concentration).

2.2 Data Preprocessing

Before analysis, comprehensive preprocessing was conducted to ensure the reliability and comparability of the data. First, missing values were addressed: for a small number of randomly missing entries, linear interpolation was used for imputation. For continuous missing data exceeding three days, the mean of historical data during the same period was used as a replacement. Next, outlier detection was performed using the 3σ principle to identify potential outliers. Identified outliers were verified against meteorological data and pollution event records; confirmed true outliers were retained, while others were replaced with the median of the surrounding three days. Subsequently, data standardization was performed using the Z-score normalization method to transform pollutant concentration data into a standard normal distribution, eliminating dimensional influences among different pollutants. Finally, data alignment was executed to ensure consistent timestamps across all pollutant data, facilitating subsequent time series and correlation analyses.

2.3 Analysis Methods

2.3.1 Data Summary and Statistics

To comprehensively analyze the long-term changes in air quality in Changsha, the annual average concentrations of each pollutant were first calculated. The calculation formula is as follows:

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \quad (1)$$

Note: C represents the annual average concentration, N denotes the number of valid measurement days in a year (usually 365 days, 366 days in a leap year), C_i indicates the daily average concentration on the i-th day.

This method ensures the accuracy and representativeness of the annual data. The concentration units for all particulate matter (PM2.5, PM10) and gaseous pollutants (SO2, NO2, O3_8h) are expressed in μg/m³, while CO concentration is measured in mg/m³ [8].

2.3.2 Time Series Analysis

a) Moving Average Method: To smooth short-term fluctuations and highlight long-term trends, a Simple Moving Average (SMA) method was employed. For annual data, a

3-year moving average was used, with the following calculation formula:

$$SMA_t = \frac{x_t + x_{t-1} + x_{t-2}}{3} \quad (2)$$

Where x_t represents the observation value for the year t.

b) Seasonal Analysis: To study the seasonal variation in air quality, the average pollutant concentration for each season was calculated. The formula for calculating seasonal averages is as follows:

$$S_i = \frac{\sum x_{ij}}{n} \quad (3)$$

Where S_i is the average for the i-th season, x_{ij} is the observation value for the j-th year in the i-th season, and n is the number of years [9].

c) Mann-Kendall Trend Test: To test whether there is a significant increasing or decreasing trend in the indicators, the Mann-Kendall trend test was employed. The test statistic S is calculated using the following formula:

$$S = \sum_{i<j} sign(x_j - x_i) \quad (4)$$

Where $sign(\ )$ is the sign function. The standardized statistic Z is used to determine the significance of the trend.

2.3.3 Correlation Analysis

To investigate the relationships between different pollutants, the Pearson correlation coefficient was used. This coefficient measures the degree of linear correlation between two variables, calculated as follows:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum}} \quad (5)$$

Where $\bar{x}$ and $\bar{y}$ are the means of x and y, respectively. These methods collectively form the framework for analyzing air quality data in Changsha, enabling a comprehensive and systematic study of long-term trends, seasonal characteristics, and the interrelationships among pollutants [10].

3. Discussion and Analysis

3.1 Overall Trend of Air Quality

Using the moving average method and the Mann-Kendall trend test, it was found that the overall air quality in Changsha is showing an improvement trend. As shown in Figure 1, the annual average AQI decreased from approximately 175 in 2013 to around 100 in 2022, representing a decrease of 42.86%. The results of the Mann-Kendall trend test indicate that this declining trend is statistically significant ($p = 0.043$, $p < 0.05$).

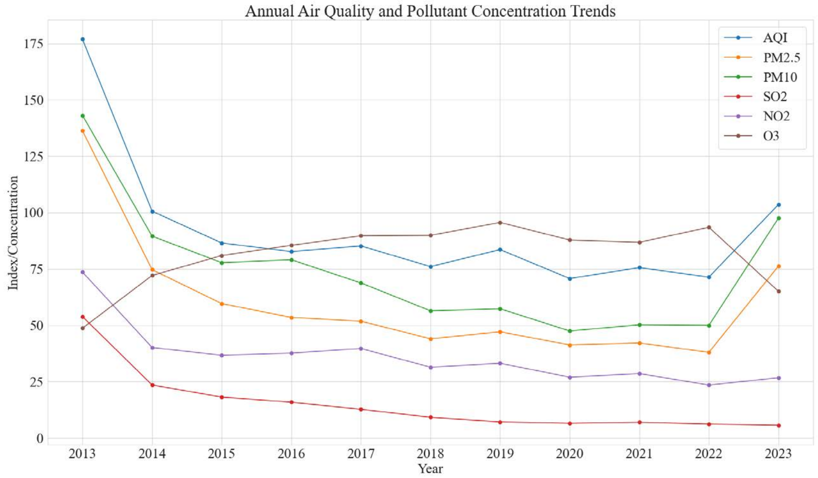

Fig. 1 Annual average concentration trends of major air pollutants in Changsha city (2013-2022) (Photo/Picture credit: Original).

From Fig. 1, it is evident that the AQI and the annual average concentrations of major air pollutants in Changsha show a significant improvement trend from 2013 to 2023. The AQI was very high in 2013, exceeding 175, but it rapidly decreased between 2013 and 2015, stabilizing thereafter, indicating a substantial enhancement in air quality. The concentrations of PM2.5 and PM10 were also high in 2013 but gradually declined, with the most significant decrease occurring from 2013 to 2015. In subsequent years, these concentrations remained relatively stable, demonstrating effective control over particulate pollution. The decline of SO2 was particularly notable, plummeting from nearly 50 in 2013 to close to zero in 2023, showcasing the significant success of sulfur dioxide management. Although NO2 also exhibited a downward trend during this period, the changes were more gradual, with

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concentrations stabilizing after 2017. In contrast to other pollutants, O3 showed minimal change, with overall fluctuations being small, highlighting the complexity of ozone management, which may require more detailed regulatory measures. Overall, Changsha has significantly improved its air quality over the past decade through a series of air quality control measures, particularly in managing particulate matter and sulfur dioxide, but challenges remain in controlling NO2 and O3.

3.2 Seasonal Variation

Through seasonal decomposition, a distinct seasonal pattern in air quality was observed. Fig. 2 illustrates the average concentration trends of major air pollutants across different seasons.

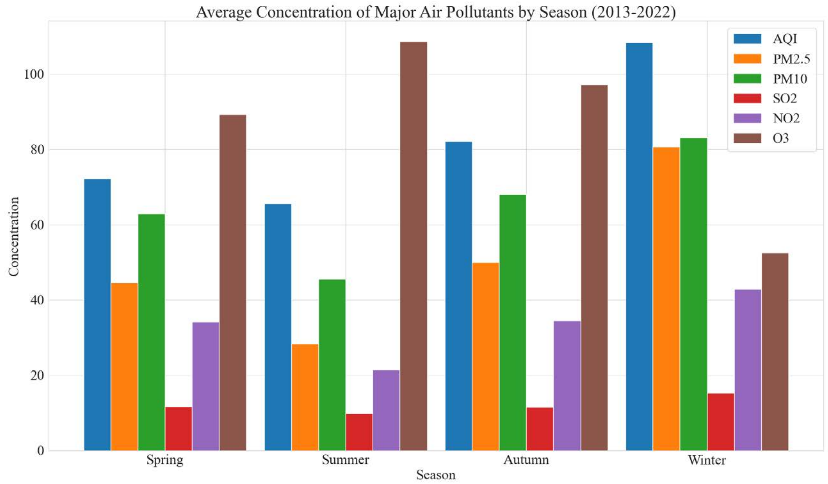

Fig. 2 Average concentration of major air pollutants in Changsha city by season (2013-2022) (Photo/Picture credit: Original).

As shown in Fig. 2, the average concentrations of major air pollutants in Changsha from 2013 to 2022 exhibit significant seasonal differences. The AQI values are higher in winter and autumn, particularly nearing 100 in winter, indicating poorer air quality, while spring and summer show lower AQI values, suggesting relatively better air quality. The concentrations of PM2.5 and PM10 are higher in autumn and winter, especially in winter, where particulate pollution is most severe, likely related to winter heating and poor air circulation. The concentrations of SO2 are nearly zero in spring and autumn, indicating effective pollution control; although there is an increase in winter, it remains at a low level. NO2 concentrations are highest in winter, followed by autumn, possibly associated with traffic and heating emissions, while summer shows the lowest concentrations. The trend for O3 differs from that of other pollutants, peaking in summer, exceeding 100, likely due to high temperatures and strong sunlight promoting O3 formation, while O3 concentrations are relatively low in winter and autumn. Overall, winter experiences more severe air pollution, while summer, despite lower levels of particulate matter and NO2, shows elevated O3 concentrations.

3.3 Correlation Among Pollutants

Using Pearson correlation coefficients and Spearman rank correlation coefficients, relationships between pollutants were analyzed, as shown in Fig. 3.

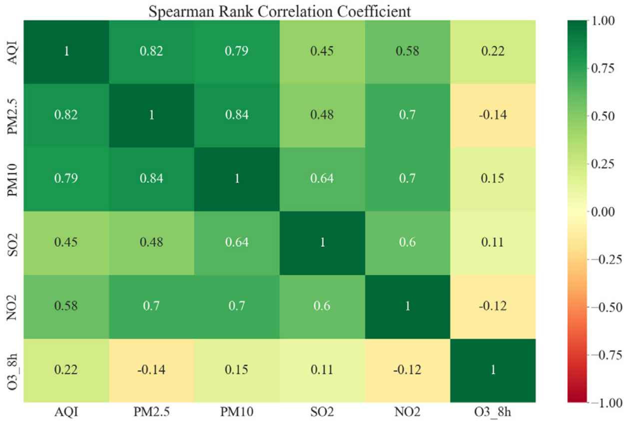

Fig. 3 Correlation coefficient matrix of major air pollutants in Changsha City (2013-2022) (Photo/Picture credit: Original).

From Fig. 3, the Spearman rank correlation coefficient matrix reveals the correlations among major air pollutants. AQI shows a very strong positive correlation with PM2.5 and PM10, with coefficients of 0.82 and 0.79 respectively, indicating that particulate pollution is a major factor affecting air quality. The correlation between PM2.5 and PM10 is also very high, reaching 0.84, suggesting that these two types of particulate pollution often occur simultaneously. The correlation between SO2 and PM10 is 0.64, indicating a certain association between SO2 and particulate pollution. NO2 has strong correlations with PM2.5 and PM10, both around 0.7, signifying a clear association between NO2 and particulate pollution. Conversely, O3 shows generally low correlations with other pollutants, even displaying a negative correlation with PM2.5 and NO2, indicating that the formation mechanism of O3 differs from that of other pollutants, potentially influenced by photochemical reactions and other factors. Overall, the correlations between particulate matter (PM2.5 and PM10) and air quality, as well as other pollutants, are most significant, while O3 shows weaker associations with other pollutants, suggesting the complexity of O3 management.

3.4 Stability Analysis of Trends

The statistical significance of the changing trends in pollutant concentrations was further confirmed through the Mann-Kendall trend test, the results of which are shown in Fig 1.

Based on the Mann-Kendall trend test results, it can be concluded that the Air Quality Index (AQI) in Changsha showed a significant decreasing trend from 2013 to 2022. The test results indicate a Z value of -2.024, confirming a clear downward trend, with a Tau value of -0.491, suggesting a moderate negative correlation of AQI over time, meaning that as the years progress, the AQI gradually decreases. The S value is -27, indicating that during the analysis period, the count of decreasing instances significantly exceeds that of increasing instances. The p-value of the test is 0.043, with a significance level of 0.05, thus concluding that this trend is statistically significant. This suggests that the decline in AQI is not coincidental and meets the criteria for a significant decrease. Notably, the slope is -3.15, indicating that the AQI decreases by approximately 3.15 units each year. This test allows us to infer that the air quality in Changsha has significantly improved during this period, with the annual average AQI decreasing from around 175 in 2013 to approximately 100 in 2022, representing a reduction of about 42.86%, demonstrating the effectiveness of air pollution control measures. However, despite the significant downward trend, more effective policies will be necessary in the future to maintain this improvement.

4. Recommendations

4.1 Strengthen Comprehensive Management of PM2.5 and PM10

Although PM2.5 and PM10 pollution has been controlled in recent years, particulate pollution remains severe in autumn and winter in Changsha, particularly highlighted by PM2.5 and water-soluble organic carbon pollution in winter. Wang's research indicates that the characteristics of PM2.5 pollution in autumn and winter in Changsha are closely related to regional transmission and local emissions [8]. Therefore, Changsha should further strengthen control over industrial emissions and dust from construction, implementing stricter dust control measures while promoting clean energy to reduce coal emissions during the heating season [9].

4.2 Enhance Synergistic Control of VOCs and NOx for O3 Pollution

The management of ozone pollution is challenging, and recent years have seen an upward trend in O3 concentrations. A study analyzing a heavy pollution event in Changsha found that O3 pollution is primarily influenced by VOCs and NOx emissions [10]. Hence, it is recommended that Changsha adopt synergistic control measures, comprehensively monitoring VOCs and NOx emissions, especially in the transportation and industrial sectors, implementing dual controls to reduce precursor emissions of ozone. Additionally, promoting industrial materials with low VOC content and clean fuels will effectively suppress ozone formation.

4.3 Implement Seasonal Differentiated Management Strategies

Seasonal analysis indicates that pollution is particularly severe in winter and spring in Changsha, with significant particulate pollution in autumn and winter and spring dust also impacting air quality [8, 9]. Therefore, it is suggested that Changsha adopt seasonal differentiated management strategies. In winter, promoting clean heating technologies should be prioritized to reduce pollution from coal heating; in spring, enhancing dust control on roads is necessary to decrease suspended particulate concentrations in the air. Moreover, summer should focus on controlling ozone pollution through measures to reduce VOC emissions, thereby lowering the risk of ozone formation.

4.4 Deepen Regional Joint Prevention and Control

Air pollution is regionally transmissible, making it challenging for individual city management measures to achieve significant results. Li pointed out that regional joint prevention and control in the Beijing-Tianjin-Hebei area has effectively improved air quality but faces challenges related to industrial structural adjustments and regional coordination [11]. Changsha can draw on this experience to strengthen joint prevention and control with

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neighboring cities, facilitating information sharing and collaboratively developing regional pollution prevention and control plans to promote overall regional environmental improvement [12].

5. Conclusion

Through a systematic analysis of air quality data in Changsha from 2013 to 2023, this study reveals long-term trends, seasonal characteristics, and the interrelationships among major pollutants in the city. The results indicate a significant overall improvement in air quality in Changsha over the past decade, with the annual average AQI decreasing from approximately 175 in 2013 to around 100 in 2022, representing a decline of 42.86%. The concentrations of PM2.5 and PM10 have significantly decreased, demonstrating the effectiveness of particulate pollution control measures, while O3 concentrations show an upward trend, reflecting the complexity of ozone pollution management. Additionally, seasonal analysis highlights that winter has the worst air quality, while summer is the best, emphasizing the importance of seasonal differences in air quality management.

In summary, Changsha has achieved remarkable results in air quality control measures over the past decade, but challenges remain regarding O3 and particulate pollution. Moving forward, it is crucial to enhance pollution source control, optimize seasonal management strategies, promote regional collaborative governance, and continue improving air quality management to achieve sustained improvement in air quality and support the sustainable development of the city.

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