

*Original Research*

# Spatiotemporal Distribution Characteristics of PM<sub>2.5</sub> Pollution and the Influential Meteorological Factors in the Henan Province, China, 2021

Xinzhan Liu<sup>1,2</sup>, Ling Yang<sup>1,2\*</sup>

<sup>1</sup>College of Geography and Environmental Science, Henan University, Kaifeng, 475004, China

<sup>2</sup>Key Laboratory of Geospatial Technology for Middle and Lower Yellow River Regions, Henan University, Ministry of Education, Kaifeng, 475004, China

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## Abstract

This paper presents an analysis of the temporal and spatial variation of PM<sub>2.5</sub> pollution in Henan Province in 2021, based on monitoring and meteorological data. The findings indicate that areas with high concentrations of PM<sub>2.5</sub> are primarily distributed in the central and northern parts of Henan Province, while areas with low values are primarily distributed in the southeast part of Henan Province. In winter, PM<sub>2.5</sub> concentrations are high in the southwest and east-central parts, and lower in the southeast and northwest. The seasonal variation of PM<sub>2.5</sub> concentration is low in summer and high in spring and winter. The monthly average of PM<sub>2.5</sub> concentration exhibits a U-shaped pattern, with low values in the summer and higher values in the winter. The difference between weekday and weekend PM<sub>2.5</sub> concentrations is minor, and the daily average presents a pulse-type fluctuation. Peak PM<sub>2.5</sub> concentrations occur in the morning in all seasons, while in winter the peak time is significantly postponed compared to other seasons. The most polluted cities distributed in northeastern Henan Province form a high-high agglomeration, and the cities located in northwestern Henan Province form a low-low agglomeration.

**Keywords:** correlation analysis, Henan province, meteorological factors, PM<sub>2.5</sub>, spatiotemporal variations

## Introduction

In recent times, owing to the rapid progress of the economy and the expansion of urban areas, air pollution has emerged as a widespread concern globally

[1]. Fine particulate matter, referred to as lung-borne particulate matter, with a diameter of 2.5 micrometers or less (PM<sub>2.5</sub>) is a significant contributor to air pollution [2]. PM<sub>2.5</sub> exhibits a minute particle size, spreads over a wide area, is actively disseminated, and has a considerable impact on neighboring regions, with a long residence period. High concentrations of PM<sub>2.5</sub> can lead to hazy weather, which poses a significant

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\*e-mail: yangling2009@henu.edu.cn

threat to health, causing respiratory illnesses [3-4], and reduces visibility, increasing the risks associated with traffic safety [5].  $PM_{2.5}$  primarily originates from sources such as road traffic emissions [6], industrial activities, fossil fuel combustion, biomass combustion, and secondary aerosols [7]. The concentration of  $PM_{2.5}$  is subject to changes in meteorological factors [8]. When wind speeds are high, they facilitate the dispersion of pollutants, thereby reducing the likelihood of accumulation and causing a decrease in  $PM_{2.5}$  concentrations [9]. Higher atmospheric pressure leads to a stable atmospheric structure, which is unfavorable for the dilution and diffusion of pollutants [10]. Therefore, exploring the spatiotemporal variations of  $PM_{2.5}$  concentrations and analyzing the correlation between  $PM_{2.5}$  concentrations and meteorological factors is essential for the prevention and control of air pollution. Mehmet et al. found a higher spatial distribution of air pollution in the northwest and southeast by collecting soil samples from the surface layer of Ankara, the capital and second-largest city of Turkey [11].

In recent decades, China has experienced rapid industrialization and urbanization, leading to a significant environmental issue of air pollution, particularly in relation to high-concentration  $PM_{2.5}$  [12]. To address this problem, the Chinese government has implemented various policies aimed at improving air quality. Concurrently, scientists have conducted extensive research on the distribution and source of  $PM_{2.5}$  pollution. Zhao et al. examined the annual and daily fluctuations of  $PM_{2.5}$  concentration in China between 2014 and 2015 and found that severe air pollution tends to occur during winter, with high concentrations in the north and low concentrations in the south [13]. Similarly, Lin et al. utilized a Geographically Weighted Regression (GWR) model to investigate the geographic pattern of  $PM_{2.5}$  concentration in China from 2001 to 2010, revealing that the areas with high  $PM_{2.5}$  concentration were densely populated and urban expansion was rapid [14]. Furthermore, Lin et al. discovered that high hourly  $PM_{2.5}$  concentrations were associated with increased mortality in the Pearl River Delta Region (PRD) [15]. Hu et al. studied the variance of  $PM_{2.5}$  concentrations in the North China Plain and Yangtze River Delta and found no significant difference between  $PM_{2.5}$  concentrations on weekdays and weekends [9]. Xue et al. collected  $PM_{2.5}$  samples in Hefei, China, between October 2016 and January 2017, concluding that  $PM_{2.5}$  mainly originated from coal combustion and industrial emissions [16]. Ren et al. reported that  $PM_{2.5}$  concentrations in Beijing during the non-heating season were mainly due to biomass burning and dust [17]. Most research in this area has been focused on economically developed regions of China, such as Beijing-Tianjin-Hebei [18-19], the Yangtze River Delta [20-21], and the Pearl River Delta region [22-23],

with limited investigations on the concentration of  $PM_{2.5}$  in Henan Province.

Henan Province is a region that has been plagued by a severe  $PM_{2.5}$  pollution problem, which is one of the most pressing environmental issues in China. The impact of this problem has been highlighted by the fact that, from 2001 to 2017, Henan had the highest number of premature deaths caused by  $PM_{2.5}$  when compared to all other provinces in the country [24]. Moreover, the health loss values in the cities of Henan have increased significantly during the period of 2015-2017 [25], largely due to the higher  $PM_{2.5}$  exposure risk. This health concern is further exacerbated by the high use of coal by rural residents in Henan Province, which leads to high anthropogenic emissions and contributes to the concentration of  $PM_{2.5}$  [26], resulting in serious air pollution. The average  $PM_{2.5}$  concentrations in Henan Province remained high from 2015-2018, with a large portion of the total area of Henan Province being affected by severe air pollution [27]. Despite various studies on  $PM_{2.5}$  in Henan Province, most have focused on a certain city [28-29] or several cities [30] to investigate the temporal and spatial distribution of  $PM_{2.5}$  concentration. However, there is still a dearth of research on the concentration of  $PM_{2.5}$  throughout the entirety of Henan Province.

Air pollution has a significant impact on human health [31],  $PM_{2.5}$  concentrations are closely related to topographic structure, weather conditions, and human activities, so it is important to study temporal and regional variations in  $PM_{2.5}$  concentrations [32]. There are relatively few studies on  $PM_{2.5}$  concentrations in Henan Province in 2021, and relatively few studies analyzing the correlation between  $PM_{2.5}$  concentrations and meteorological factors. Because of the important impact of air pollution on human health, it is crucial to monitor regional and cyclical changes in  $PM_{2.5}$  concentrations, especially in Henan Province, which has a high population density. This study aims to determine the regional and cyclical variation of  $PM_{2.5}$  concentrations in Henan Province in 2021. In order to enhance comprehension of the temporal and spatial attributes of air pollution in Henan Province, and to investigate the relationship between  $PM_{2.5}$  concentration and meteorological factors, the present study has analyzed  $PM_{2.5}$  concentration data from 17 prefecture-level cities in Henan Province during the year 2021. The research has successfully identified the spatial-temporal variation and spatial clustering pattern of  $PM_{2.5}$  concentration in Henan Province. Furthermore, the study has examined the correlation between  $PM_{2.5}$  concentration and meteorological factors, by integrating meteorological data and  $PM_{2.5}$  concentration data from the year 2021. The findings of this research furnish valuable theoretical support for the effective and scientific control of air pollution in Henan Province.

## Mater and Methods

### Study Area

Henan Province, situated at (31°23'–36°22'N, 110°21'–116°39'E) in central China, boasts a land area of 167,000 Km<sup>2</sup>, of which 75,000 Km<sup>2</sup> is arable. It holds a significant position as a key grain production region in China, contributing one-fifth of the country's total wheat production. The province experiences a typical temperate monsoon climate, characterized by hot and rainy summers and cold winters, with significant seasonal variations. The topography of Henan Province features high terrain in the northwest and low terrain in the east, with plains in the central-eastern region and basin topography in the southwest. Henan Province ranks among the largest energy-consuming provinces in China, with coal energy being its primary source. The heating season spans from November to March.

### Data Sources

China's ecological and environmental monitoring agency has established an air-quality monitoring system that comprehensively covers the majority of the country and has subsequently published monitoring data on its official website. The PM<sub>2.5</sub> concentration data utilized in this paper were procured from the National Urban Air Quality Real-Time Publishing Platform (<https://www.air.cnemc.cn:18007>). This dataset includes hourly monitoring values of PM<sub>2.5</sub> from 17 prefecture-level cities, resulting in a total of approximately 840,960 data

Table1. PM<sub>2.5</sub> concentration classification.

Air quality	PM <sub>2.5</sub> /ug /M <sup>3</sup>
Good	0-35
Excellent	35-75
Mild Pollution	75-115
Moderate Pollution	115-150
Heavy Pollution	150-250
Severe Pollution	250-500

points collected between January 1, 2021, and December 31, 2021. Following the removal of invalid data, 805,222 valid data points were retained. Fig. 1 depicts the distribution of 96 ground monitoring stations situated in Henan Province. The meteorological data, including wind speed, dew point temperature, air pressure, relative humidity, and other relevant parameters, were obtained from the World Weather Network website (<https://www.rp5.ru>). The entirety of Henan Province comprises a total of 14 meteorological stations, which collectively yield 442,456 data points for the entire year.

## Methods

### Inverse Distance-Weighted Interpolation

Inverse distance weighting [33] is based on the first law of geography, which state that the closer two items

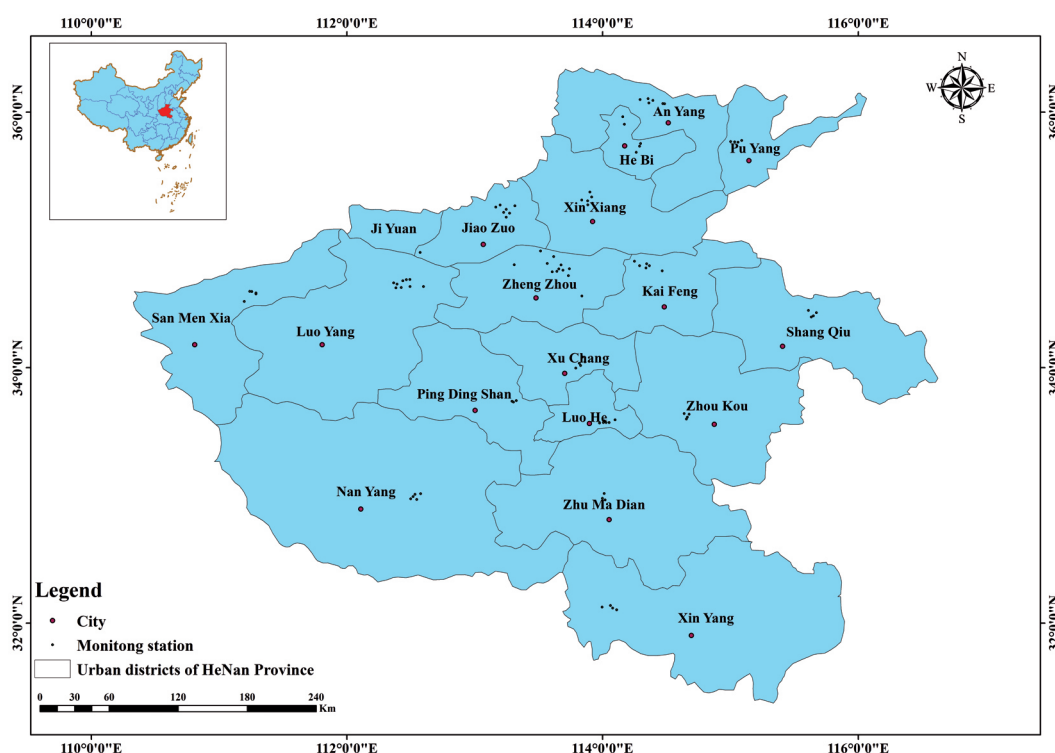


Fig. 1. Study area and spatial distribution of the 96 monitoring stations in Henan Province.

are, the more similar their qualities are. The method determines the value of an unknown point by using a weighted average of the values of adjacent known sample points, with the distance between the unknown point and the known sample point is serving as the weighted. The closer the sample point is to the unknown point, the greater the weight assigned in the calculation process. The formula for calculating is as follows:

$$Z_{(S_0)} = \sum_{i=1}^N \lambda_i Z_{(S_i)} \quad (1)$$

$Z_{(S_0)}$  is the predicted value at  $S_0$ ;  $N$  is the number of known sample points around the unknown point to be used in the calculation;  $\lambda_i$  is the weight of each known sample point to the unknown sample point in the calculation, the weight decreases with the distance between the known sample point and the unknown point.

#### Pearson's Correlation Analysis

The Pearson correlation [34] coefficient is used to describe the linear correlation between two sets of  $X$  and  $Y$  data, taking values between  $[-1,1]$ , and is calculated as follows:

$$P_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{\frac{n \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{\sqrt{n \sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2} \sqrt{n \sum_{i=1}^n y_i^2 - (\sum_{i=1}^n y_i)^2}}}{\quad} \quad (2)$$

$cov(X,Y)$  is the covariance of  $X$  and  $Y$ ;  $\sigma_X$ ,  $\sigma_Y$  are the standard deviations of  $X$  and  $Y$ ,  $P_{X,Y}$  respectively. The scope of  $P_{X,Y}$  is  $[-1,1]$ , greater than 0 means positive correlation, less than 0 means negative correlation, the closer to 1, the stronger the positive correlation between the two variables, and closer to -1, the stronger the negative correlation between the two variables.

#### Global and Local Autocorrelation Analysis

The spatial distribution of air pollution involves complex spatiotemporal and geospatial processes. It has been shown that air pollution exhibits a certain degree of spatial autocorrelation in geographic space [35]. In this study, the global Moran's  $I$  [36] was used to analyze the global autocorrelation of  $PM_{2.5}$  concentrations in Henan Province, The global Moran's  $I$  is expressed as:

$$I_{Global} = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}} \quad (3)$$

$I_{Global}$  is the global Moran's  $I$  value, which ranges from  $[-1,1]$ , with values greater than 0 indicating positive correlation, less than 0 indicating negative correlations, and equal to 0 means no correlations; where  $n$  represents

the number of cities,  $n = 1, 2, \dots, 17$ ;  $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ ,  $\bar{x}$  is

the mean of the sample data;  $S^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$ ,  $S^2$

denotes the variance of the samples;  $x_i, x_j$  is the observed  $PM_{2.5}$  of spatial location  $i, j$ .  $W_{ij}$  is the spatial weight matrix (This study uses the adjacency matrix).

The  $Z$  values are used to test the significance of spatial autocorrelation and are calculated as follows:

$$Z = \frac{I - E(I)}{\sqrt{Var(I)}} \quad (4)$$

where  $Var(I)$  and  $E(I)$  are the variance and expected of the Moran's  $I$ , respectively.

$I_{Local}$  was used to analyze the spatial agglomeration characteristics of cities in the region [37], and is calculated as follows:

$$I_{Local} = \frac{x_i - \bar{x}}{S^2} \sum_{j=1, j \neq i}^n W_{ij} (x_j - \bar{x}) \quad (5)$$

The scope of  $I_{Local}$  is  $[-1,1]$ , greater than 0 means positive correlation, less than 0 means negative correlation, and equal to 0 means no correlation.  $x_i$ ,  $S^2$ ,  $\bar{x}$ ,  $W_{ij}$  are the same as above. Based on the calculated  $I_{Local}$ , the spatial association modes can be classified into four types: High-High clustering type (hereinafter HH), Low-Low clustering type (hereinafter LL), Low-High clustering type (hereinafter LH), High-Low clustering type (hereinafter HL). In this study, the H-H (LL) type indicates that cities with high (low)  $PM_{2.5}$  concentrations are surrounded by cities with high (low)  $PM_{2.5}$  concentrations. The L-H (HL) type indicates that cities with low (high)  $PM_{2.5}$  concentrations are surrounded by cities with high (low)  $PM_{2.5}$  concentrations.  $I_{Local}$  that did fails the significance test is classified as not significant.

## Results and Discussion

### Temporal Variation in $PM_{2.5}$ Henan Province

#### Seasonal Variation

The present study depicts the seasonal average concentration of  $PM_{2.5}$  in Henan Province in the year 2021, along with the varying levels of air quality in different seasons, as demonstrated in Fig. 2. The study reveals that during the spring, summer,

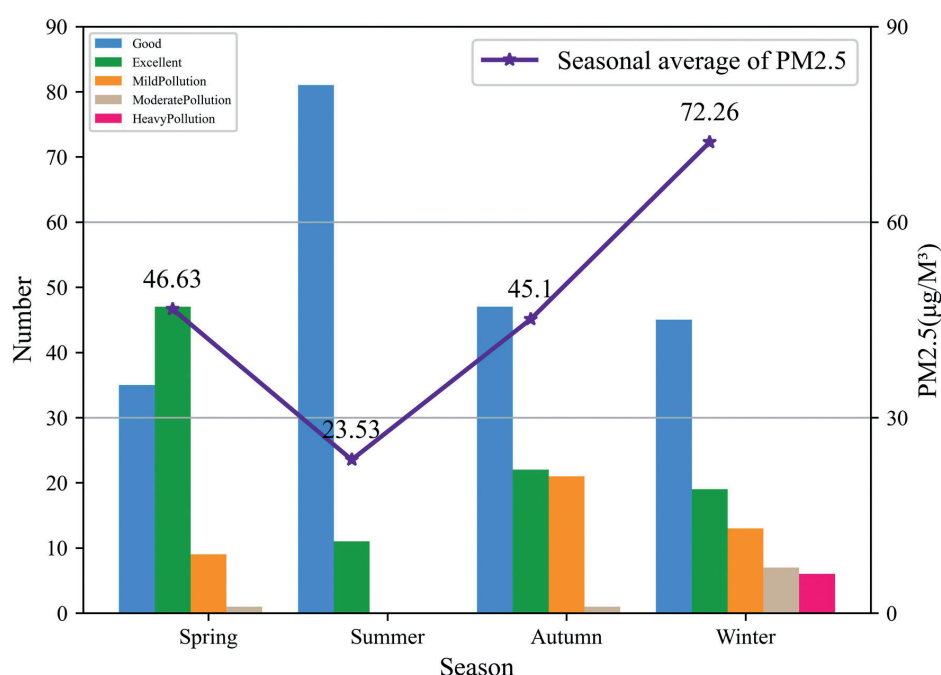


Fig. 2. Seasonal average  $PM_{2.5}$  concentrations in Henan Province during 2021.

autumn, and winter seasons, the respective seasonal averages of  $PM_{2.5}$  concentrations were 46.63, 23.53, 45.1, and 72.26  $\mu\text{g}/\text{m}^3$ . Furthermore, the difference between the highest and lowest  $PM_{2.5}$  concentrations during the same seasons in 2021 were 132.23, 35.02, 112.93, and 203.49  $\mu\text{g}/\text{m}^3$ , respectively. It has been observed that Heavy Pollution is exclusively prevalent in winter, while Moderate Pollution is predominantly observed in winter, with relatively lower frequency in spring and fall. Mild Pollution has been observed to occur more frequently in fall, followed by winter, and least commonly in spring. Conversely, Excellent Weather is most frequently observed in spring, with a close proximity in autumn and winter; Good Weather is most commonly observed in summer, with the least frequency in spring and a closer proximity in autumn and winter. Overall, the air quality is found to be the highest in summer, followed by autumn, and the poorest in spring and winter.

#### Monthly Variation

The present study depicts the distribution of monthly  $PM_{2.5}$  concentration data within the Henan Province for the year 2021, as presented in Fig. 3. The findings reveal that the monthly average concentrations of  $PM_{2.5}$  exhibit a U-shaped trend, with the highest value observed in January and the lowest value in July. Notably, the average concentrations of  $PM_{2.5}$  demonstrate a progressive decline from January to July, with the monthly average values between July and August being comparatively lower and less volatile. Furthermore, from September to November, there is a clear and significant upward trend in the monthly average concentrations of  $PM_{2.5}$ .

The  $PM_{2.5}$  levels exhibited minor fluctuations between the months of May and June, but demonstrated the greatest variability from September to October. This trend can be attributed primarily to the depletion of vegetation cover following crop harvesting, which renders cultivated land susceptible to wind erosion and subsequent  $PM_{2.5}$  pollution. This issue is further exacerbated by the burning of straw, which serves to exacerbate the levels of  $PM_{2.5}$  concentration [38]. Notably, the primary grain crops cultivated in Henan Province include wheat, rice, and maize, with the wheat harvest season occurring between late May and early June, and the rice and corn harvest period extending from late September to early October. Significantly, suspended particulate matter generated during the grain harvesting process represents a crucial source of  $PM_{2.5}$  pollution [39]. Consequently, while  $PM_{2.5}$  concentrations did not exhibit a significant decline between the months of May and June, they did demonstrate a marked increase between September and October.

#### Intra-Week Variation

Fig. 4 illustrates the variations in  $PM_{2.5}$  concentration across different seasons and weeks in Henan Province for the year 2021. The concentration of  $PM_{2.5}$  during spring and winter exhibited a pattern of initial decline, followed by an increase and subsequent decrease. Similarly, the concentration during summer and autumn showed an initial increase, followed by a decrease. Winter recorded the highest fluctuations, followed by spring and fall, while summer saw the least fluctuations. Interestingly, the weekend effect was found to be insignificant across all four seasons and even showed



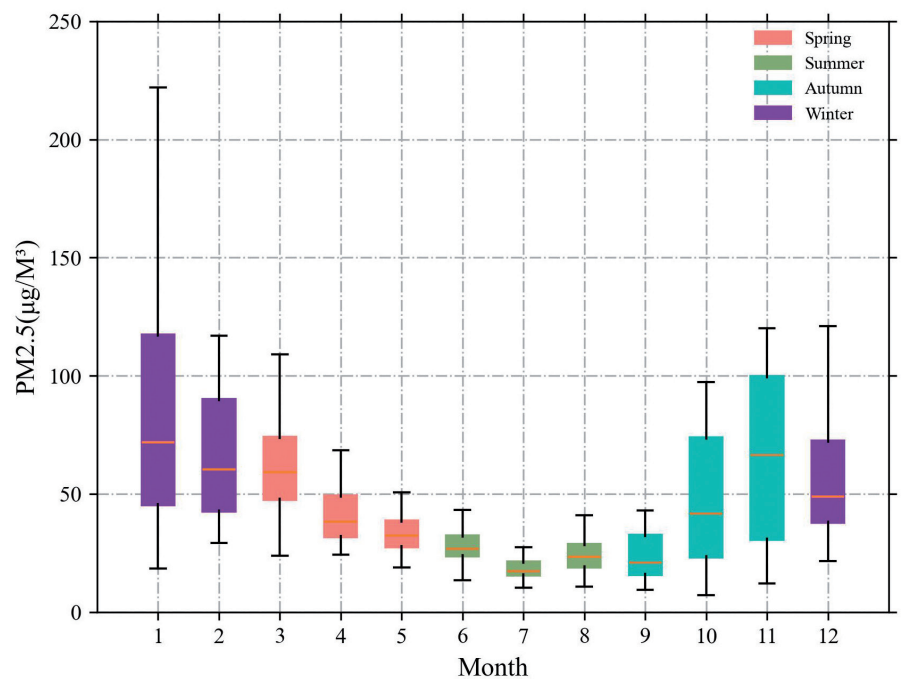


Fig. 3. Monthly  $PM_{2.5}$  concentration data distribution in Henan Province in 2021.

a clear “anti-weekend effect”. This effect suggests that reduced human activity during weekends does not necessarily lead to a reduction in emissions, contrary to the popular belief that weekends are times of rest [40].

*Daily Variation*

The present study depicts the diurnal variations in  $PM_{2.5}$  concentrations in the Henan Province during

different seasons in the year 2021, as demonstrated in Fig. 5. It is noteworthy that the peak  $PM_{2.5}$  concentrations manifest in the morning during all seasons, with the highest concentrations occurring between 6:00-9:00 in spring, autumn, and summer, and between 7:00-10:00 in winter. This phenomenon can be attributed to the escalation of  $PM_{2.5}$  concentrations in the morning due to the elevated traffic, while in winter, the delayed dawn and consequent travel delays

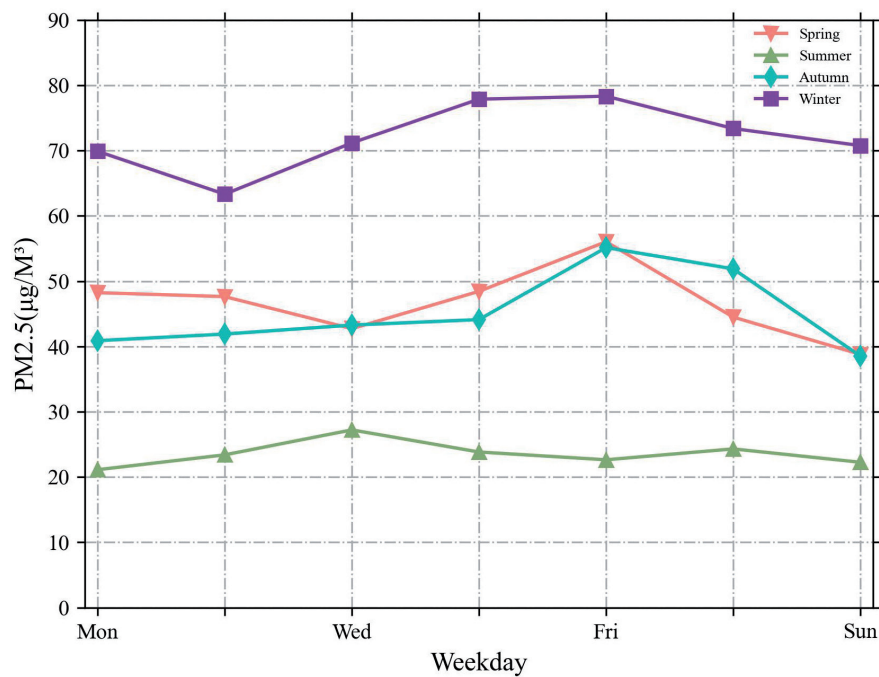


Fig. 4. Change in  $PM_{2.5}$  concentration per day of the week in different seasons in Henan Province in 2021.

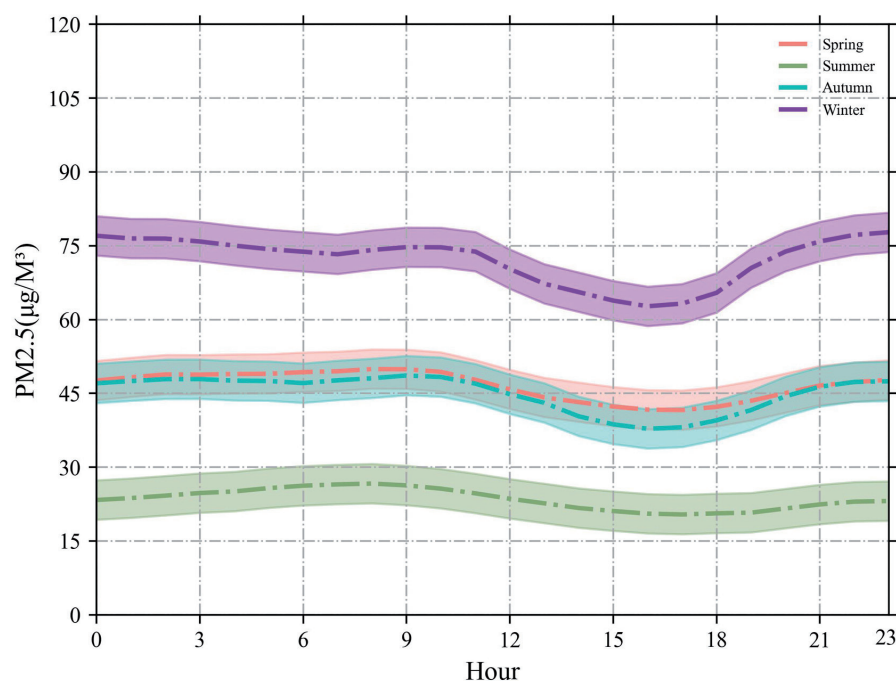


Fig. 5. Change in  $PM_{2.5}$  concentrations over 24 hours in different seasons in Henan Province in 2021.

contribute to the later manifestation of peak  $PM_{2.5}$  concentrations. Furthermore, the trough of  $PM_{2.5}$  concentration is generally observed around 15:00, owing to the intensified vertical convection of the air and the augmented diffusion rate of atmospheric pollutants caused by the rise in temperature. As such, the concentrations tend to decrease during this time.

In both spring and autumn, the  $PM_{2.5}$  concentration experiences a similar pattern, characterized by an initial increase, followed by a decrease, and then another increase. This can be attributed to the large temperature differential between day and night during these seasons, which leads to a stable atmospheric structure that impedes the dilution and diffusion of pollutants, resulting in higher  $PM_{2.5}$  concentrations [41]. Conversely, during summer, the  $PM_{2.5}$  concentration changes less, gradually increasing before dropping after 8:00, and rising again slowly after 18:00. The natural environment in summer is conducive to the diffusion of  $PM_{2.5}$ , and the variation in  $PM_{2.5}$  concentration throughout the day is primarily influenced by human activities. Notably, traffic peaks occur at 8:00 and 18:00, during which motor vehicle exhaust emissions are elevated, leading to a higher concentration of  $PM_{2.5}$ .

#### Hourly Variation

The figure presented in Fig. 6 depicts the diurnal changes in  $PM_{2.5}$  levels across various seasons, on a daily basis, in Henan Province in 2021. The graphical representation shows that the concentration of  $PM_{2.5}$  displays a wave-like pattern, with more complex fluctuations observed on Thursday and Friday,

characterized by multiple peaks during the day. Notably, a peak in  $PM_{2.5}$  levels is observed at 00:00, primarily attributed to the low temperature and shallow planetary boundary layer height. The stable atmospheric structure, as evidenced by previous studies [42], poses a challenge to the dispersion and dilution of pollution.

Fig. 7 illustrates the hourly fluctuations in  $PM_{2.5}$  concentrations in Henan Province in 2021. It is evident that the period between 23:00 and 06:00 experiences the highest levels of  $PM_{2.5}$  throughout the day, while the period from 13:00 to 18:00 experiences the lowest levels. Traffic emissions are a dangerous source of air pollution that cannot be ignored [43]. The escalation in  $PM_{2.5}$  concentration is attributed to heating difficulties and traffic congestion [44]. It is worth noting that the winter season in Henan Province is characterized by coal-fired heating hours during morning and night, as well as a peak traffic flow. As temperatures drop, the roads become more susceptible to freezing, leading to reduced vehicle speeds and consequently a rise in vehicle exhaust. In the non-heating seasons of fall and summer, the peak traffic periods also occur in the morning and evening, resulting in higher  $PM_{2.5}$  concentrations [45]. To mitigate this issue, the Henan Province government implemented a traffic strategy of limiting traffic during the day and resuming at midnight for heavier diesel trucks. However, this strategy has led to an increase in  $PM_{2.5}$  concentrations at night [46]. In winter, coal combustion is the primary contributor to the rise in  $PM_{2.5}$  concentrations in Henan Province. Additionally, due to high pressure, atmospheric stratification becomes more stable, leading to an increase in  $PM_{2.5}$  concentration [47].

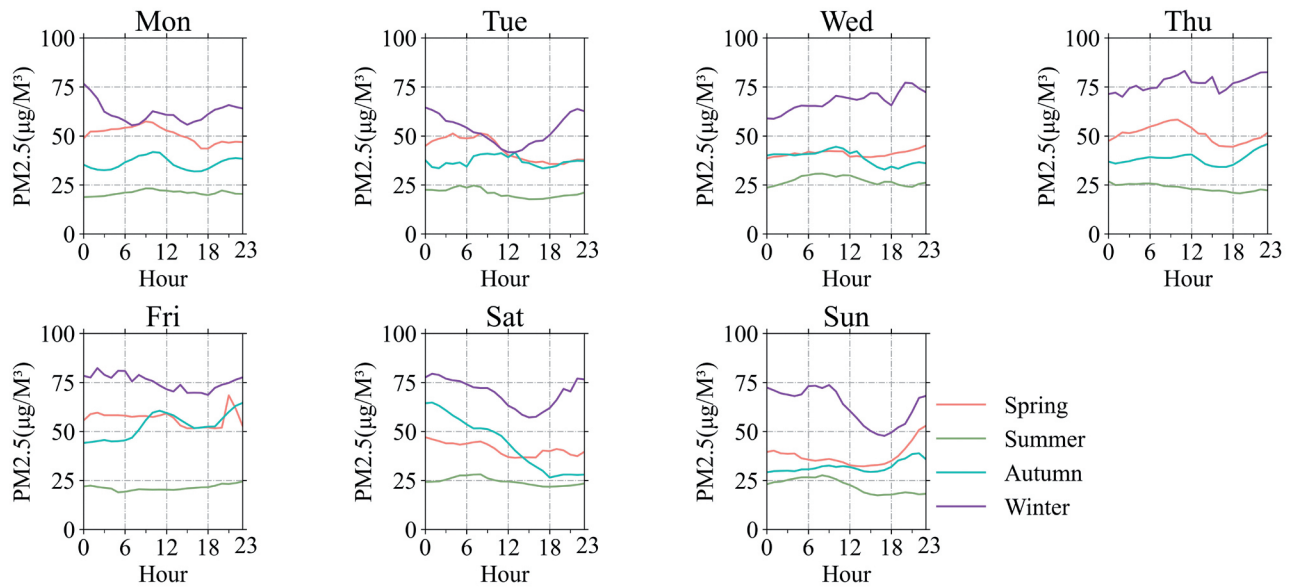


Fig. 6. Daily variations in  $PM_{2.5}$  concentrations in Henan Province during the four seasons of the week in 2021.

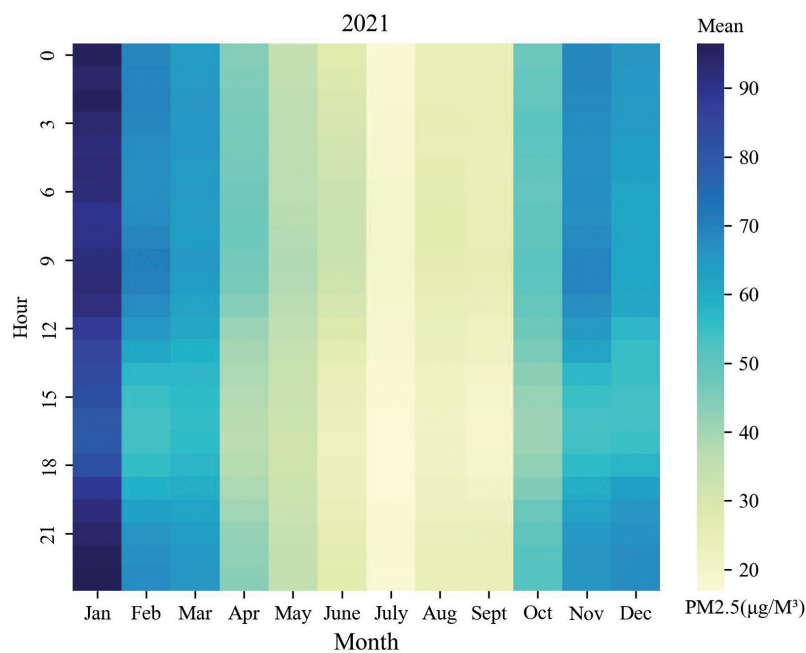


Fig. 7. Monthly hourly  $PM_{2.5}$  concentration changes in Henan Province in 2021.

### Spatial Distributions in $PM_{2.5}$ Henan Province

#### *Spatial Distribution of Annual Average $PM_{2.5}$ Concentrations*

Fig. 8 depicts the spatial distribution of the average annual concentration of  $PM_{2.5}$  in Henan Province in 2021. Evidently, the distribution of  $PM_{2.5}$  concentrations is heterogeneous. As illustrated in Fig. 8, the annual average concentration of  $PM_{2.5}$  in Henan Province exhibits a spatial pattern of high levels in the northeast and low levels in the southeast. Moreover, the cities

of Luohe and Kaifeng also demonstrate higher concentrations of  $PM_{2.5}$ , whereas Xinyang and other cities in southeastern Henan Province exhibit low levels of  $PM_{2.5}$ .

#### *Spatial Distribution of Seasonal Average $PM_{2.5}$ Concentrations*

Fig. 9 illustrates the spatial distribution of the seasonal average concentration of  $PM_{2.5}$  in Henan Province in 2021. During spring, summer, and autumn,  $PM_{2.5}$  concentrations in Henan Province exhibit a



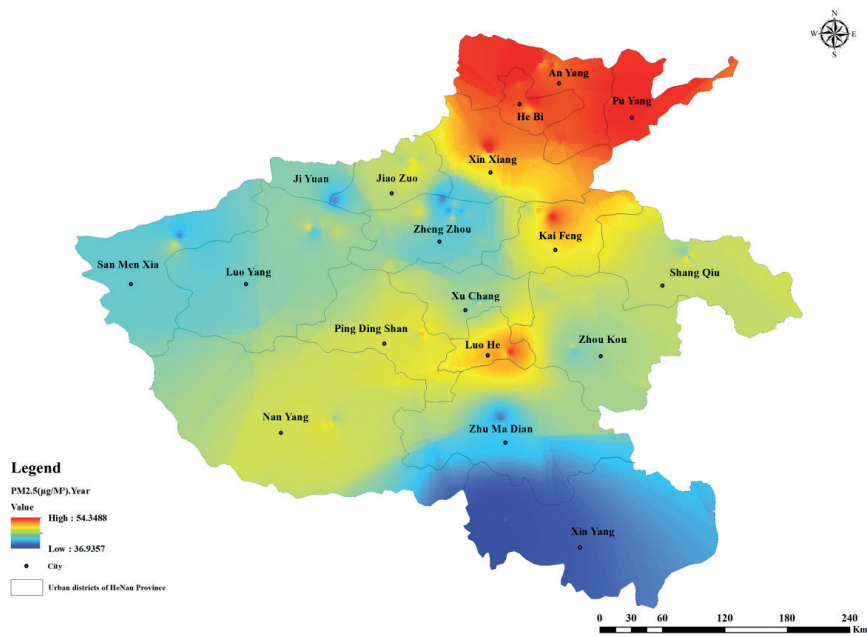


Fig. 8. Spatial distribution of annual average PM<sub>2.5</sub> concentrations.

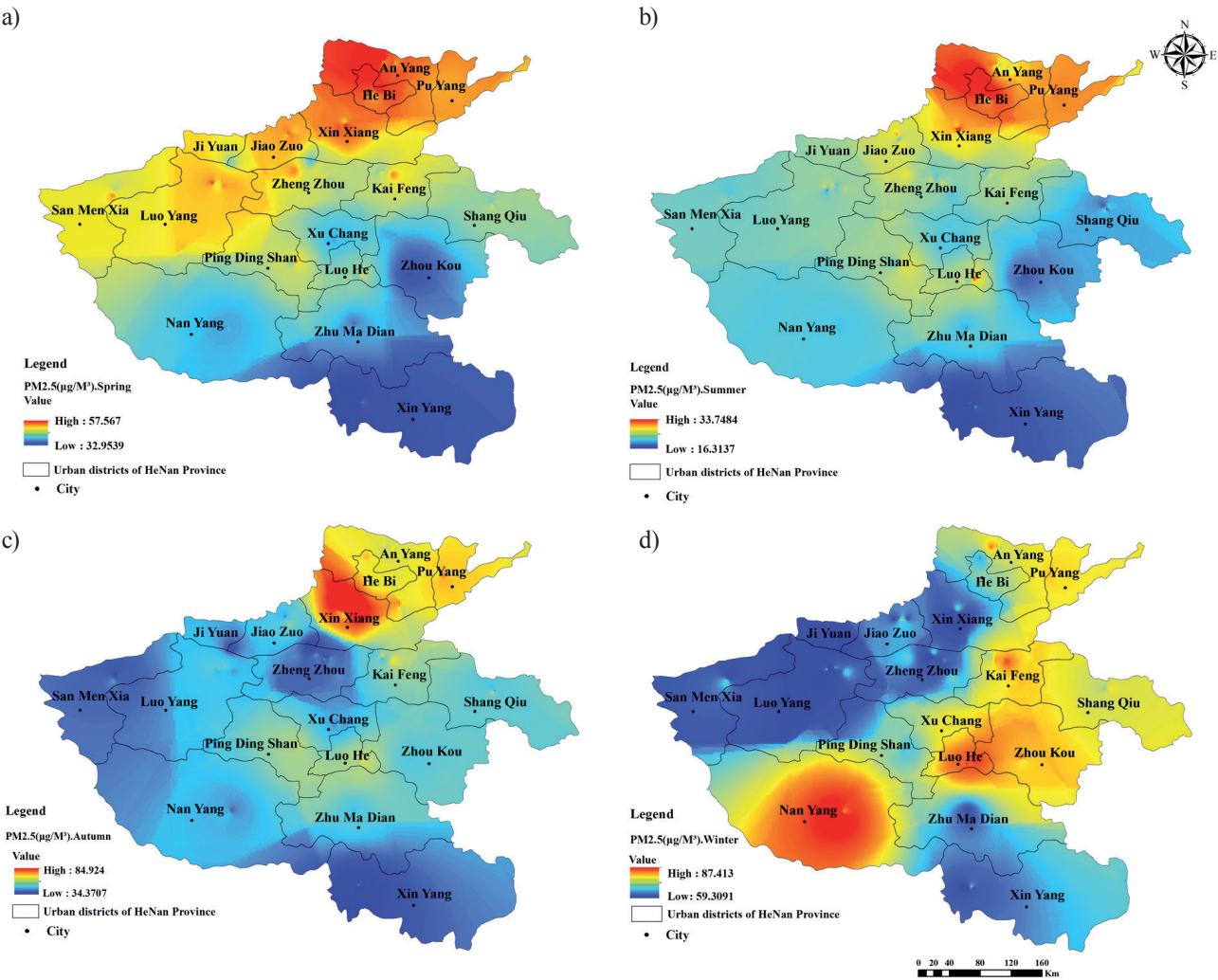


Fig. 9. Spatial distribution of PM<sub>2.5</sub> concentration in Henan in different seasons.

geographical pattern of high levels in the central and northeastern regions and low levels in the southeastern region. However, during winter,  $PM_{2.5}$  concentrations demonstrate a geographical pattern of high levels in the southwest and east-central regions, and low levels in the northwest and southeast regions. The primary reason for this distribution is the presence of the central and northeastern regions on the plains, with a high concentration of cities, high population density, high private automobile ownership, high power consumption, and high anthropogenic emissions [48]. Increased vehicle emissions and higher population density will increase air pollution [49]. Additionally, the cultivated land in Henan Province is predominantly situated in the central and northeastern regions, with significant vegetation cover in the southern mountainous areas. Moreover, the high number of windy days in spring, the dry climate, and the increased amount of dust on the ground, along with a considerable amount of suspended particulate matter generated during the sowing season in spring, contribute to the increase in  $PM_{2.5}$  concentrations, resulting in a spatial and temporal pattern of higher  $PM_{2.5}$  concentrations in the central and northeastern part of Henan Province and lower concentrations in the southeast part of the province [50].

#### Spatial Autocorrelation of $PM_{2.5}$ Concentrations

During the winter season in Henan province, the dispersion of  $PM_{2.5}$  levels is influenced by a variety

of factors, including the local topography, industrial composition, and regional mobility. Henan's terrain exhibits higher elevations in the northwest and lower elevations in the east, with prevailing northwesterly winds during the winter season. The city of Nanyang, situated within a basin topography, experiences a stable structure that obstructs the dilution and diffusion of pollution, resulting in elevated levels of  $PM_{2.5}$  concentrations [51].

The regional industrial structure is indicative of the degree of industrial advancement and the level of human engagement in the region. As industrial growth intensifies, so too does the level of human activity, resulting in elevated emissions and a consequent rise in  $PM_{2.5}$  concentration [52].

$PM_{2.5}$  concentrations are closely related to the topographical structure of the area, weather conditions, traffic density, and human activity [53]. In general, the concentration of  $PM_{2.5}$  in the northeastern region was observed to be higher than that in other areas. This can be attributed to the rapid pace of industrialization, high population density, extensive mineral resource utilization, significant heavy industry contribution, and elevated levels of both vehicular and passenger traffic in the cities of Anyang, Puyang, Hebi, and Xinxiang in northeastern Henan. Additionally, the central and eastern sections of Henan Province are located in the plains, adjacent to the highly polluted regions of Beijing-Tianjin-Hebei, Anhui, and Shandong Provinces, and are thereby subjected to increased levels of pollution transmission [54]. Conversely, the western half of Henan

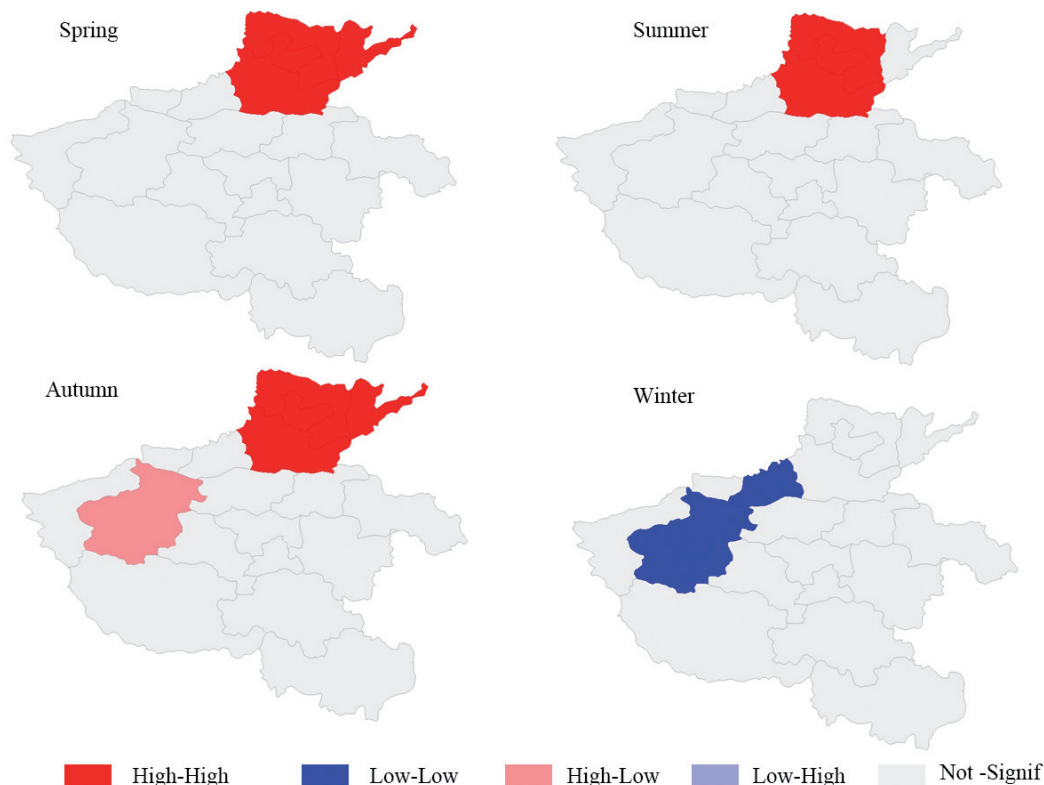


Fig. 10. Spatial agglomeration of  $PM_{2.5}$  concentrations seasonal average in Henan Province in 2021.

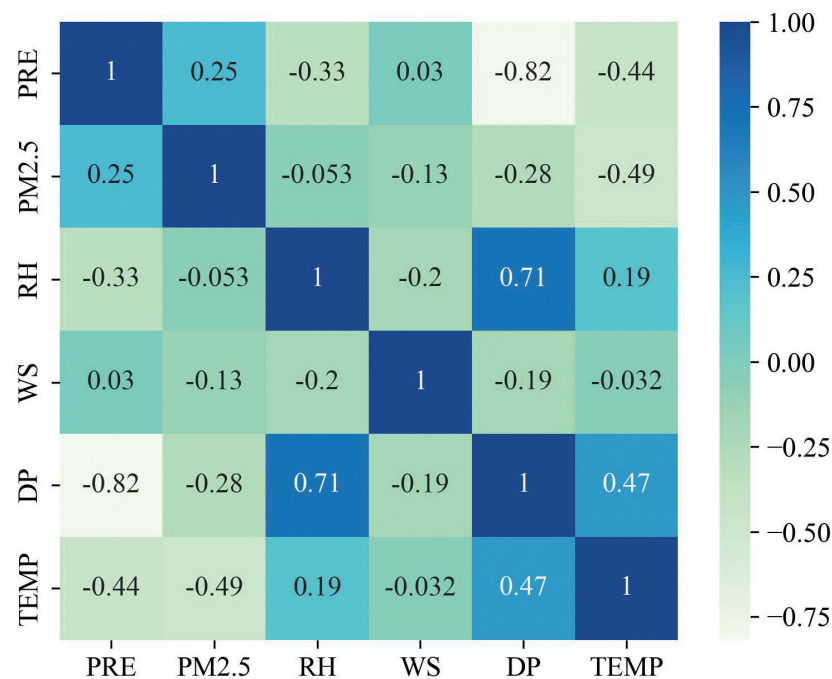


Fig. 11. Correlation coefficients between daily  $PM_{2.5}$  concentrations and meteorological factors in Henan Province in 2021.

Province is characterized by hilly terrain, which serves as a natural barrier against pollutants arriving from the northwest and is therefore less affected by pollution dispersion. As a result,  $PM_{2.5}$  concentrations are higher in the east and central regions, and lower in the west.

### Correlation Analysis

Fig. 11 illustrates the association between daily concentrations of  $PM_{2.5}$  and a diverse range of meteorological variables in Henan Province during the year 2021. The depicted results reveal that  $PM_{2.5}$  concentrations display a significant positive correlation with air pressure (PRE), with a correlation coefficient of 0.25. Conversely, the concentration of  $PM_{2.5}$  exhibits a negative correlation with temperature (TEMP), dew point temperature (DP), wind speed (WS), and relative humidity (RH), with correlation coefficients of -0.49, -0.28, -0.13, and -0.053, respectively.

Fig. 12 illustrates the daily variations in the concentration of  $PM_{2.5}$  and meteorological factors in Henan Province throughout the year 2021. The average annual concentration of  $PM_{2.5}$  was  $46.88 \mu g/m^3$ , with significant fluctuations observed. The maximum concentration of  $PM_{2.5}$  was recorded on January 24<sup>th</sup>, with a daily average concentration of  $221.8 \mu g/m^3$ . Additionally, elevated concentrations were also observed on January 3<sup>rd</sup> and between January 15<sup>th</sup> and 26<sup>th</sup>, indicating a strong correlation between  $PM_{2.5}$  emissions and meteorological factors. High-pressure systems can result in a stable atmospheric structure that is unfavorable for pollution dilution and diffusion, leading to the formation of an inversion layer and the

accumulation of pollutants. Continual high-pressure weather conditions can exacerbate air pollution [10].

Between June 14<sup>th</sup> and 29<sup>th</sup>, there was a notable decrease in  $PM_{2.5}$  levels despite the low wind speed. This occurrence can be attributed to the strengthening of vertical air convection as temperature rises, which leads to increased diffusion rates of atmospheric pollutants and ultimately, a reduction in their concentrations [55-56]. Additionally, the high air temperature, humidity, and dew point temperature during this period contributed to the decrease in  $PM_{2.5}$  concentration. The rise in dew point temperature resulted in increased water vapor content in the air, leading to larger particle sizes and sinking, thereby contributing to the reduction of  $PM_{2.5}$  concentration [57]. Furthermore, the increase in relative humidity increased the likelihood of precipitation, ultimately leading to a decrease in  $PM_{2.5}$  concentration [58].

On the 25<sup>th</sup> of October, an elevated concentration of  $PM_{2.5}$  was observed despite elevated dew point temperatures. This phenomenon was ascribed to low wind speeds, which impact the concentration of pollutants in two ways: firstly, through the dispersion of pollutants via airflow, which affects the surrounding area, and secondly, through the dilution of pollutants. As wind speed increases, the dilution effect is strengthened, leading to a faster diffusion rate of pollutants and reducing their accumulation [59]. Conversely, a decrease in wind speed results in an increase in air pressure, which leads to increased stability of air at ground level, slowing the dispersion of pollutants and exacerbating air pollution. These findings have been documented in prior research [60].



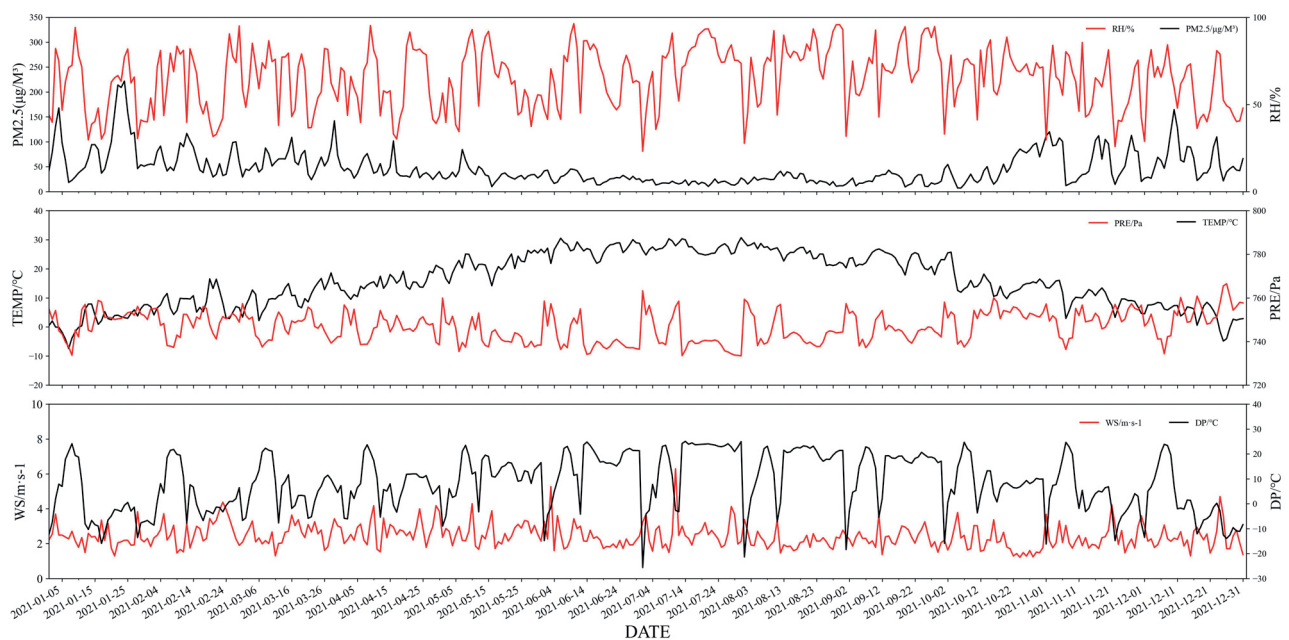


Fig. 12. Daily  $PM_{2.5}$  concentrations and changes in meteorological factors in Henan Province, 2021.

## Conclusions

### Conclusions

By conducting an inquiry into the spatiotemporal fluctuations of  $PM_{2.5}$  concentrations and the correlation between  $PM_{2.5}$  levels and meteorological factors in Henan Province throughout the year 2021, the ensuing findings were obtained.

To begin with, it should be noted that within the province of Henan, there exists a notable degree of temporal variability with regard to concentrations of  $PM_{2.5}$  particulate matter. The study reveals that during the spring, summer, autumn, and winter seasons, the respective seasonal averages of  $PM_{2.5}$  concentrations were 46.63, 23.53, 45.1, and 72.26  $\mu\text{g}/\text{m}^3$ . Excellent Weather is most frequently observed in spring, with proximity in autumn and winter; Good Weather is most commonly observed in summer, with the least frequency in spring and a closer proximity in autumn and winter. Specifically, both seasonal and monthly averages of  $PM_{2.5}$  concentrations exhibit a U-shaped trend, with the concentrations even displaying a distinctive ‘anti-weekend effect’. Additionally, the daily average of  $PM_{2.5}$  concentrations demonstrates a pulse-type fluctuation, with peak concentrations observed during morning and evening hours. As for overall air quality, it is worth noting that summer exhibits the most favorable air quality, followed by spring and autumn. In contrast, winter is associated with the poorest air quality, with minimal differences between weekdays and weekends and particularly pronounced air pollution during morning and evening hours.

Furthermore, it is noteworthy that the distribution of  $PM_{2.5}$  concentrations in Henan Province displayed

a significant degree of heterogeneity, with higher concentrations primarily observed in the northeast region of the province and relatively lower concentrations in the southeastern region. During the winter season, the concentrations of  $PM_{2.5}$  were observed to be higher in the southwest and east-central regions, whereas the concentrations in the southeast and northwest regions were relatively lower. This uneven distribution can be attributed to a multitude of factors, including topography, regional industrial structure, and the proliferation of neighboring regions. Moreover, spatial autocorrelation analysis revealed a positive spatial autocorrelation in  $PM_{2.5}$  concentrations in Henan Province, with high-pollution cities predominantly concentrated in the northeastern region, forming a high-high agglomeration. The government should strengthen the prevention and control of air pollution in the northeastern part of Henan Province, especially in winter.

Thirdly, the concentration of  $PM_{2.5}$  exhibits a negative correlation with temperature (TEMP), dew point temperature (DP), wind speed (WS), and relative humidity (RH), with correlation coefficients of -0.49, -0.28, -0.13, and -0.053, respectively. It was determined that  $PM_{2.5}$  concentrations were positively correlated with air pressure, but negatively correlated with air temperature, dew point temperature, and wind speed. No significant correlation was observed between  $PM_{2.5}$  concentrations and relative humidity. The study revealed that meteorological conditions characterized by elevated air pressure, reduced wind speed, lower temperature, dew point temperature, and relative humidity were conducive to air pollution and an increase in  $PM_{2.5}$  concentrations. Notably, meteorological factors played a significant role in  $PM_{2.5}$  concentrations during the winter and spring seasons,

with moderate and severe pollution events occurring more frequently.

Changes in  $PM_{2.5}$  concentrations are significantly influenced by human activity, and scientific research into regional and temporal variations in air pollution will guide the identification of preventive measures to avoid the negative effects of air pollution on people's health.

### Limitations and Future Research

This paper examines the temporal and spatial variation of  $PM_{2.5}$  concentrations in Henan Province in 2021 and explores the relationship between  $PM_{2.5}$  concentrations and meteorological elements, but the study period is short, and regional and cyclical variations in  $PM_{2.5}$  concentrations will be monitored over a longer time scale in future studies. The spatial and temporal variation of  $PM_{2.5}$  concentrations during the COVID-19, when the government implemented scientific controls and human activities were significantly reduced, is also explored.

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### Conflict of Interest

The authors declare no conflict of interest.

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