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Removal Effect of Precipitation on Atmospheric Particulate Matter ($PM_{2.5}$) in Bengbu City

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Abstract Based on the monitoring data of $PM_{2.5}$ concentration in Bengbu Environmental Monitoring Station and precipitation observation data of Bengbu National Meteorological Observation Station from 2016 to 2019, the influence of precipitation on $PM_{2.5}$ mass concentration in Bengbu City was analyzed. The results show that precipitation had a washing and removal effect on $PM_{2.5}$ in the air, and the removal effect was related to precipitation level, precipitation intensity, precipitation duration and $PM_{2.5}$ concentration. The removal effect of precipitation on $PM_{2.5}$ increased with the increase of precipitation level, and the seasonal difference was obvious. Precipitation intensity was positively correlated with the removal effect of $PM_{2.5}$, but the average removal rate began to decline when precipitation intensity exceeded 10 mm. With the increase of precipitation intensity, the proportion of positive removal showed an overall upward trend, but there was a low-value area as precipitation intensity was 3 – 10 mm. Precipitation duration was also positively correlated with the removal effect of $PM_{2.5}$, and there was a low-value area when precipitation duration was 10 – 15 h. When $PM_{2.5}$ concentration was low before the precipitation process began, the removal effect was not good, and the average removal rate was negative. As $PM_{2.5}$ concentration was high before the precipitation process started, the removal effect was obvious.

Key words Precipitation; $PM_{2.5}$; Removal efficiency; Bengbu

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$PM_{2.5}$, also known as fine particulate matter, refers to aerosol particles with a diameter less than or equal to 2.5 μm in the atmosphere, and can be suspended in the air for a long time. Due to its small particle size, large area and strong activity, it is easy to carry toxic and harmful substances, and has a great impact on atmospheric environmental quality and human health[1]. Since the 1990s, with the acceleration of urbanization, atmospheric environmental pollution events have increased significantly, and their impact on economic and social development has been increasingly intensified[2].

China is the world's largest population country and a developing country. China's economy is in a period of rapid development. With the increasing demand for energy, the rapid expansion of urban population, and the emergence of a large number of industrial and mining enterprises, all kinds of pollution into the atmosphere have made air pollution more and more serious. Many domestic research results show that the proportion of fine particulate matter in China's air is on the rise, and fine particulate matter has become the main air pollutant affecting all regions. How to improve the quality of urban air environment and how to balance environment and development have become major issues that need to be solved urgently.

Based on the daily monitoring data of air pollution, surface meteorological observation data and radiosonde data in 120 key cities for environmental protection in China, Zhang Ying *et al.* [3] analyzed the air quality of typical cities in China and its correlation with pollution meteorological parameters. The results show that air quality index (AQI) in typical Chinese cities decreased from north to south; it was high in winter and low in summer in northern cities, and the variation was significantly greater than that in southern cities. Li Wenjie *et al.* [4] studied the spatial and temporal distribution characteristics of air pollution index (API) and its relationship with meteorological elements in Beijing, Tianjin and Shijiazhuang. Jiang Di *et al.* [5] found that there was a close relationship between $PM_{2.5}$ concentration and meteorological elements such as precipitation, wind speed, mixed layer thickness and relative humidity. In addition, the temporal and spatial distribution characteristics of particulate pollutants ($PM_{2.5}$ and PM_{10}) in Beijing, Shanghai, Shijiazhuang, Xi'an and Wuhan and their relationship with meteorological conditions were analyzed[6 – 10]. The removal effect of precipitation on particulate matter in Beijing, Wuxi, Guiyang and Hefei was studied[11 – 14].

At present, the domestic research on fine particulate pollutants ($PM_{2.5}$) is mostly concentrated in the Beijing – Tianjin – Hebei, Yangtze River Delta and other economically developed regions or a few central cities, and the research on small and medium-sized cities in Anhui Province is relatively rare. In this paper, the relationship between precipitation and $PM_{2.5}$ concentration in Bengbu was studied, and the removal effect of precipitation of different levels and intensities on $PM_{2.5}$ was explored, so as to provide reference for the monitoring, early warning and pollution prevention of $PM_{2.5}$ in cities.

1 Data and methods

1.1 Data sources The meteorological data used in this paper were the daily and hourly observation data of precipitation in

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Bengbu National Meteorological Observation Station (No. 58221) from January 1, 2016 to December 31, 2019, with a temporal resolution of 1 d and 1 h, respectively.

The daily and hourly data of $PM_{2.5}$ concentration from January 1, 2016 to December 31, 2019 came from six urban environmental monitoring stations in Bengbu, including Department Store, the Second Water Plant (adjusted to Tianjiabing Middle School in 2018), Bengbu College, High-tech Zone, Workers' Sanatorium and government of Huaishang District, with a temporal resolution of 1 d and 1 h, respectively. Missing test data were excluded before statistical analysis.

1.2 Methods Daily removal efficiency (RF) is calculated by the particle concentration on the day before the precipitation starts ($CON1$) and the particle concentration on the precipitation day ($CON2$) as follows:

$$RF = (CON1 - CON2)/CON1 \times 100\%$$

$RF > 0$ means positive removal, while $RF < 0$ means negative removal, and $RF = 0$ is zero removal.

The removal process was extracted and analyzed according to the rainfall process. The first occurrence of precipitation above 0.1 mm was as the start of the process, and the last occurrence of precipitation above 0.1 mm was as the end of the process.

The 1-h average particle concentration ($CON1$) before the start of the process was defined as the particle concentration before the removal process, and the 1-h average particle concentration ($CON2$) after the end of the process was defined as the particle concentration after the removal process. The average removal efficiency of n processes was calculated by the average concentration of aerosol particles before and after n processes:

$$\overline{RF} = \frac{\sum_{1}^{n}(CON1 - CON2)}{\sum_{1}^{n} CON1} \times 100\%$$

The removal process with $RF > 0$ is a positive removal process, while the removal process with $RF < 0$ is a negative removal process, and the removal process with $RF = 0$ is a zero removal process. The percentage of positive removal processes is the ratio of the number of positive removal processes to the total number of removal processes.

Air quality is divided into six levels according to the *Technical Regulation on Ambient Air Quality Index* (on trial) (HJ 633-2012) (Table 1).

Table 1 Air quality class and concentration of atmospheric particulate matter μg/m³

Air quality	*AQI*	$PM_{2.5}$ mass concentration	PM_{10} mass concentration
Excellent	0-50	0-35	0-50
Good	51-100	35-75	50-150
Light pollution	101-150	75-115	150-250
Moderate pollution	151-200	115-150	250-350
Heavy pollution	201-300	150-250	350-420
Serious pollution	>300	>250	>420

On the basis of the definition of 24-h precipitation in the *Classification Standard for Precipitation Intensity* (*Inland Part*) of China Meteorological Bureau, rainfall was divides into four grades: light rain (0.1-9.9 mm), moderate rain (10-24.9 mm), heavy rain (25-49.9 mm), as well as rainstorm and above (≥50 mm).

2 Distribution characteristics of precipitation and $PM_{2.5}$ concentration

Fig. 1 shows the monthly precipitation and average $PM_{2.5}$ concentration of Bengbu City from 2016 to 2019. The annual average precipitation of Bengbu City was 1 066.7 mm, and the annual average precipitation days were 105.8 d. According to the 30-year climate data from 1980 to 2010 released by the National Climate Center, the annual average precipitation in Bengbu City was 965.9 mm, and the annual average precipitation days were 102.4 d. Therefore, the precipitation in Bengbu City from 2016 to 2019 was normal.

Precipitation has a washing and removal effect on pollutants in the air, especially particulate matter. The precipitation of Bengbu City from 2016 to 2019 was more from May to August, but less from December to February. Correspondingly, $PM_{2.5}$ concentration was the lowest during July-August and highest in December. Precipitation had a significant negative correlation with $PM_{2.5}$ concentration, passing 99% confidence interval test. The monthly mean mass concentration of particulate matter was lower in months with more precipitation days and precipitation. In months with fewer precipitation days and less precipitation, the monthly mean mass concentration of particulate matter was higher.

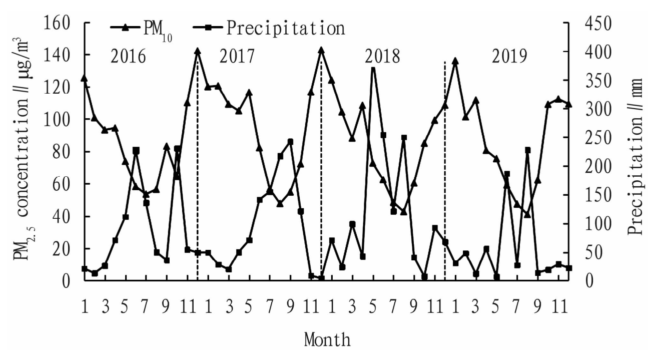

Fig. 1 Monthly precipitation and $PM_{2.5}$ concentration in Bengbu City from 2016 to 2019

3 Removal effect of precipitation on $PM_{2.5}$

3.1 Influence of precipitation grade on the removal Fig. 2 shows the $PM_{2.5}$ concentration under different levels of precipitation in Bengbu City from 2016 to 2019. It can be seen from the figure that generally, with the increase of precipitation level, $PM_{2.5}$ concentration declined, but the difference between seasons was obvious. The removal effect was most obvious in winter, followed by spring and autumn, and less obvious in summer. In winter, the average concentration of $PM_{2.5}$ on light, moderate and heavy rain days were 87.70, 41.33 and 45.50 μg/m³, respectively. The removal rate of light rain, moderate rain and heavy rain were

−14%, 31% and 37%, respectively. It can be seen that the washing effect of precipitation on $PM_{2.5}$ became more and more significant with the increase of precipitation level.

$PM_{2.5}$ concentration and removal rate on different grades of rain days in autumn and spring were lower than that in winter. The removal effect of light rain and moderate rain on $PM_{2.5}$ in summer significantly reduced. The average concentration of $PM_{2.5}$ on light, moderate and heavy rain days in summer was 42.38, 23.40 and 38.00 $\mu g/m^3$, respectively, and the removal rate was −24%, 15% and 6%, respectively. In summer, $PM_{2.5}$ concentration even increased, and the removal rate decreased on heavy rain days. In Bengbu City, $PM_{2.5}$ concentration was the lowest from June to August. The phenomenon that $PM_{2.5}$ concentration rose and the removal rate declined on heavy rain days may be related to the low initial concentration of $PM_{2.5}$.

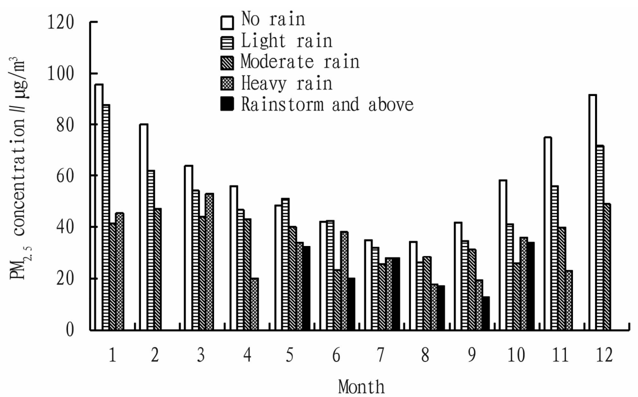

Fig. 2 $PM_{2.5}$ concentration on different levels of precipitation days in Bengbu City from 2016 to 2019

3.2 Influence of precipitation intensity on the removal effect

According to the classification of hourly precipitation in Bengbu City from 2016 to 2019 according to precipitation intensity, it is found that the removal effect of $PM_{2.5}$ had a good relation with precipitation intensity, and the removal effect became more obvious with the increase of precipitation intensity. As can be seen from Fig. 3, with the increase of precipitation intensity, the average removal rate became positive, and the upward trend was obvious. When precipitation intensity exceeded 10 mm, the average removal rate began to decline. With the increase of precipitation intensity, the proportion of positive removal showed an overall upward trend, but decreased slightly when precipitation intensity was 3 − 10 mm.

As can be seen from Table 2, when precipitation intensity was less than 1 mm, the removal effect of precipitation on $PM_{2.5}$ was not obvious. The proportion of positive and negative removal was equal, and the average removal rate was negative. When precipitation intensity increased to 1 − 3 mm, the removal effect of precipitation on $PM_{2.5}$ was significantly improved, and the proportion of positive and negative removal increased to 68.22%. The average removal rate changed from negative to positive value, increasing to 3.25%. As precipitation intensity increased to 3 − 10 mm, the removal effect of precipitation on $PM_{2.5}$ was improved, but the change was not obvious, and the proportion of positive removal decreased slightly to 65.29%, while the average removal rate increased significantly to 9.20%. When precipitation intensity increased to more than 10 mm, the removal effect of precipitation on $PM_{2.5}$ was not significantly improved, and the proportion of positive removal further increased to 69.64%, but the average removal rate reduced to 5.49%.

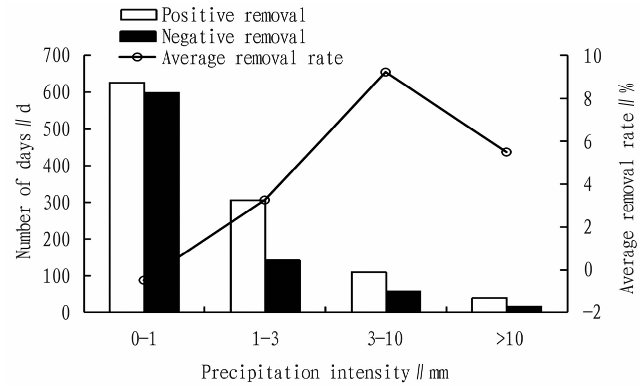

Fig. 3 Removal of $PM_{2.5}$ by precipitation of different intensity in Bengbu City from 2016 to 2019

Rainfall of more than 5 mm in Bengbu City mostly occurred from May to October, while the $PM_{2.5}$ concentration in Bengbu City from May to October was relatively low in the whole year. When precipitation intensity was 3 − 10 mm, the proportion of positive removal decreased slightly; as precipitation intensity exceeded 10 mm, the average removal rate decreased, which may be affected by the low $PM_{2.5}$ concentration before the precipitation started, which will be analyzed in detail below.

Table 2 Relationship between precipitation intensity and the removal rate of $PM_{2.5}$ in Bengbu City from 2016 to 2019

Precipitation intensity // mm	Number of positive removal samples	Number of negative removal samples	Average removal rate // %
0 − 1	625	598	−0.50
1 − 3	307	143	3.25
3 − 10	111	59	9.20
>10	39	17	5.49

3.3 Effects of the duration of precipitation on the removal effect

By classifying the precipitation in Bengbu City from 2016 to 2019 according to the duration of precipitation, it is found that there was a certain relationship between the removal effect of $PM_{2.5}$ and the duration of precipitation. As can be seen from Table 3, when the duration of precipitation was 1 h, the removal effect of precipitation on $PM_{2.5}$ was not obvious. The number of positive and negative removals was the same, and the average removal rate was negative. As the duration of precipitation was 2 − 3 h, the removal effect of precipitation on $PM_{2.5}$ was improved, and the proportion of positive removal was enhanced. The average removal rate turned positive. When the duration of precipitation increased to 4 − 9 h, the removal effect of precipitation on $PM_{2.5}$ steadily increased, and the proportion of positive removal reached 60%, while the average removal rate decreased slightly. As the duration of precipitation increased to 10 − 15 h, the removal effect of precipitation on $PM_{2.5}$ declined, and both positive removal and average removal rate decreased. The longer duration of precipitation mostly occurred from May to September, while the $PM_{2.5}$ concentration from May to September was low in the whole year. This decrease in the removal rate may be related to the $PM_{2.5}$ concentration before precipitation. When the duration of precipitation exceeded 16 h, the removal effect of precipitation on $PM_{2.5}$ was greatly improved, and the negative removal only existed sporadically. It can be seen that in general, the longer the duration of precipitation, the better the removal effect, the higher the positive removal rate.

Table 3 Relationship between the duration of precipitation and the removal rate of $PM_{2.5}$ in Bengbu City from 2016 to 2019

Duration of precipitation//h	Number of positive removal samples	Number of negative removal samples	Proportion of positive removal//%
1	235	227	50.87
2 – 3	270	212	56.02
4 – 9	379	242	61.03
10 – 15	123	92	57.21
>16	88	17	83.81

3.4 Effect of initial $PM_{2.5}$ concentration on the removal effect By analyzing the relationship between 648 precipitation processes and $PM_{2.5}$ concentration in Bengbu City from January 1, 2016 to December 31, 2019, it is found that the removal effect of precipitation on $PM_{2.5}$ was not only related to the time and intensity of precipitation, but also had a great relationship with $PM_{2.5}$ concentration before precipitation.

Seen from Table 4, when the $PM_{2.5}$ concentration before the precipitation process was less than 75 $\mu g/m^3$ (air quality was excellent or good), the removal effect of precipitation on $PM_{2.5}$ was negative, and the average removal rate was –3.56%, with little difference between positive and negative removal. As the $PM_{2.5}$ concentration before the precipitation process was 76 – 150 $\mu g/m^3$ (light and moderate pollution), the average removal rate turned positive, rising significantly to 13.99%, and the proportion of positive removal rose significantly. When the $PM_{2.5}$ concentration before the precipitation process was greater than 150 $\mu g/m^3$ (heavy pollution and above), the average removal rate rose to 34.58%, and all removal was positive. It can be seen that the removal effect of precipitation on $PM_{2.5}$ was closely related to the $PM_{2.5}$ concentration before the precipitation process. When $PM_{2.5}$ concentration was low, the removal effect of precipitation on $PM_{2.5}$ was not good, and the average removal rate was negative. However, as $PM_{2.5}$ concentration was high, precipitation had an obvious removal effect on $PM_{2.5}$.

Table 4 Relationship between the initial concentration and removal rate of $PM_{2.5}$ in Bengbu City from 2016 to 2019

Initial concentration// $\mu g/m^3$	Removal rate during the process//%	Number of positive removal samples	Number of negative removal samples
0 – 75	–3.56	281	268
76 – 150	13.99	55	35
>150	34.58	9	0

4 Conclusions

(1) Overall, the removal effect of precipitation on $PM_{2.5}$ rose with the increase of precipitation level, and the seasonal difference was obvious. The removal effect was most obvious in winter, followed by spring and autumn, while it was less obvious in summer.

(2) The removal effect of precipitation on $PM_{2.5}$ was greatly affected by precipitation intensity. As a whole, the removal effect was enhanced with the increase of precipitation intensity. However, when precipitation intensity exceeded 10 mm, and the average removal rate began to decline. With the increase of precipitation intensity, the proportion of positive removal also showed an upward trend, but there was a low-value area when precipitation intensity was 3 – 10 mm.

(3) Another important factor influencing the removal effect of precipitation on $PM_{2.5}$ was the duration of precipitation. In general, the longer the duration of precipitation, the better the removal effect, and the higher the positive removal rate. However, when the duration of precipitation was 10 – 15 h, the removal effect had a low-value area.

(4) The removal effect of precipitation on $PM_{2.5}$ was also affected by the concentration of $PM_{2.5}$ before precipitation. When $PM_{2.5}$ concentration was low before the process began, the removal effect was not good, and the average removal rate was negative. However, as $PM_{2.5}$ concentration was high before the process started, the removal effect was obvious.

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