Spatial and Temporal Distribution Characteristics of PM_{10} Concentration in Yantai City and Its Relationship with Meteorological Factors

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Abstract Based on the monitoring data of PM_{10} concentration from six environmental monitoring stations and the ground meteorological observation data in Yantai City from 2019 to 2021, the spatial and temporal variation of PM_{10} concentration and its relationship with meteorological factors were studied. The results show that from the perspective of temporal variation, the annual average of PM_{10} concentration in Yantai City tended to decrease year by year. It was high in winter and spring and low in summer and autumn. In terms of monthly variation, the changing curve is U-shaped, and it was high in December and January but low in July and August. During a day, PM_{10} concentration had two peaks. The first peak appeared approximately from 09:00 to 11:00, and the second peak can be found from 21:00 to 23:00. From the perspective of spatial distribution, PM_{10} concentration was the highest in the development area and Fushan District. It was the highest in the west, followed by the east, while it was the lowest in the middle. The spatial difference rate was the highest in summer. Average temperature, relative humidity, wind speed and precipitation were the main meteorological factors influencing PM_{10} concentration in Yantai area. PM_{10} concentration was negatively correlated with average temperature and relative humidity, and the correlation was the most significant from June to October. It was negatively correlated with wind speed and precipitation, and the correlation was different in various months. The negative correlation was significant in summer and winter.

Key words Yantai City; PM_{10}; Spatial and temporal distribution; Meteorological factors; Correlation
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The quality of air as an essential necessity for human survival directly affects everyone's normal life and health. Data released by the Ministry of Ecology and Environment of the People's Republic of China in 2019 show that PM_{10} remains the main air pollutant in northern Chinese cities[1]. PM_{10} persists in the air for a relatively long time, not only affecting urban climate change and economic development, but also posing a significant threat to public health and urban traffic safety[2].

Air pollution is not only related to the emission of pollutants, but also affected by meteorological conditions[3–8]. Zhu Fang *et al.*[9] studied a severe pollution process in Shijiazhuang in January 2017, and found that unfavorable meteorological conditions would aggravate the pollution process. Yantai is an important node city in the Bohai Rim Economic Circle and the Jiaodong Economic Circle, and has been awarded the title of National Civilized City for six consecutive terms. As a coastal city, Yantai has relatively favorable conditions for meteorological diffusion, but haze weather still occurs frequently in recent years. Previously, some scholars have studied the seasonal variation and sources of PM_{10} in Yantai area and reached meaningful conclusions[10]. However, there is no research on its spatial variation and relationship with meteorological factors. Therefore, analyzing the spatial and temporal variation characteristics of PM_{10} concentration and its correlation with meteorological factors in Yantai City is of great significance for the governance of air pollution and the improvement of air quality in Yantai.

In this paper, based on the data of PM_{10} concentration from six environmental monitoring stations in Yantai City from 2019 to 2021, the temporal and spatial variation characteristics of PM_{10} concentration were studied, and its correlation with multiple meteorological factors was further explored to provide a scientific basis for further improving the formulation of plans for air pollution prevention and control and enhancing environmental quality in Yantai area.

1 General situation of the study area

Yantai, which is located in the northeast of Shandong Peninsula, is an important node city in the Bohai Rim Economic Circle and the Jiaodong Economic Circle. As all six environmental monitoring stations are concentrated in the main urban area of Yantai, the main urban areas of Yantai (including Zhifu District, Fushan District, Laishan District, Muping District, and Yantai Economic & Technological Development Area) were selected as the research

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object, and their area is 2 722.3 km^2, accounting for 19.6% of the city's total area. The permanent resident population accounts for 38.3% of the city's total population. The research area is shown in Fig. 1.

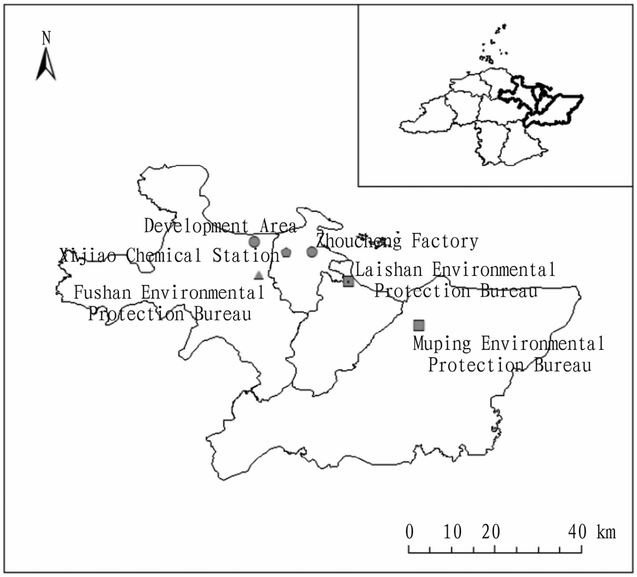


Fig. 1 Distribution of environmental monitoring stations in the study area

2 Data sources and research methods

2.1 Data sources The real-time monitoring data of PM_{10} concentration in six environmental monitoring stations in Yantai City from 2019 to 2021 were sourced from the National Urban Air Quality Real-time Release Platform of the China National Environmental Monitoring Centre. The observation data of meteorological factors (air pressure, average temperature, relative humidity, wind speed, precipitation and sunshine duration, *etc.*) were from Yantai Meteorological Bureau. The daily average is the average of data from 00:00 to 23:00, and the time is consistent with that of daily average of PM_{10} concentration. The data of precipitation and sunshine duration are the sum of data from 00:00 to 23:00.

2.2 Research methods The hourly data of PM_{10} concentration measured by six environmental monitoring stations in Yantai City from 2019 to 2021 were used to calculate the daily average and then monthly, quarterly and annual average. The seasons are divided according to meteorological standards, including spring (from March to May), summer (from June to August), autumn (from September to November), and winter (from December to February)[11]. On the time scale, Sigmaplot18.0 plotting software was used to plot on different scales, and the temporal variation characteristics were analyzed. On the space scale, the inverse distance weight spatial interpolation method of Arcgis10.0 was adopted. The data of six environmental monitoring stations were interpolated to analyze the spatial variation characteristics in different seasons. The correlation between PM_{10} concentration and meteorological factors was studied using the Pearson correlation analysis method of SPSS software.

3 Results and analysis

3.1 Temporal variation of PM_{10} concentration

3.1.1 Annual variation. According to the *Ambient Air Quality Standards* (GB 3095 – 2012), ambient air function zones are classified into two categories. The first category includes nature reserves, scenic spots and other areas that require special protection. The second category includes residential areas, mixed commercial, transportation and residential areas, cultural areas and rural areas. Among them, the annual average limit of PM_{10} concentration is 70 μg/m^3. The annual average of PM_{10} concentration in Yantai City was 78 μg/m^3 in 2019, exceeding the secondary standard limit (70 μg/m^3) by 11.4%. It was 60 μg/m^3 in 2020 and 59 μg/m^3 in 2021, 14.29% and 15.71% lower than the secondary standard limit, respectively. On the whole, the annual average of PM_{10} concentration showed a downward trend over the past three years.

3.1.2 Seasonal variation. Fig. 2 shows the variation of PM_{10} concentration in different seasons from 2019 to 2021. It can be seen that it was the highest in winter, up to 104, 75 and 90 μg/m^3, respectively from 2019 to 2021, followed by spring and autumn. In 2019, it was 87 μg/m^3 in spring and 72 μg/m^3 in autumn. In 2020, it was 65 μg/m^3 in spring and 58 μg/m^3 in autumn. In 2021, it was 85 μg/m^3 in spring and 47 μg/m^3 in autumn. It was the lowest in summer, only 47 μg/m^3 in 2019, 41 μg/m^3 in 2020, and 31 μg/m^3 in 2021.

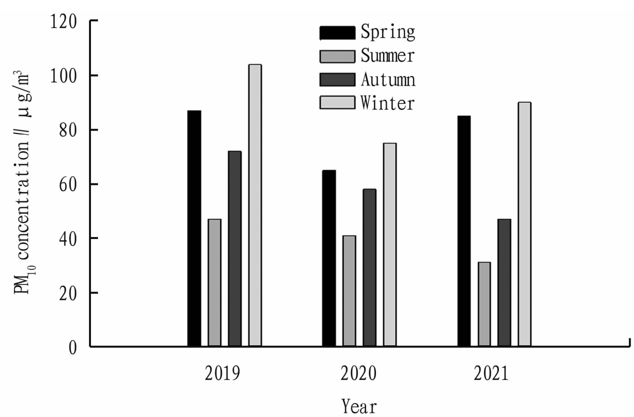


Fig. 2 PM_{10} concentration in each season from 2019 to 2021

3.1.3 Monthly variation. The monthly variation of PM_{10} concentration from 2019 to 2021 are shown in Fig. 3. Overall, the changing curves of PM_{10} concentration over the past three years were basically U-shaped. However, the highest and lowest values appeared in various months in different years. In 2019, PM_{10} concentration was the highest in January, reaching 118 μg/m^3, and then decreased month by month until August (only 39 μg/m^3). Afterwards, it gradually increased, slightly declined in November, and rose again in December. In 2020 and 2021, the changing curves of PM_{10} concentration over the past three years were slightly U-shaped. In 2020, PM_{10} concentration was the second highest in January, up to 83 μg/m^3, and then decreased. After February, it gradually increased again, reaching 79 μg/m^3 in April, and then dropped again. In August, it was the lowest, only 30 μg/m^3, and then rose again. The maximum was up to 91 μg/m^3 in December. In 2021, PM_{10} concentration was the highest in March, up to 119 μg/m^3, while it was the lowest in July and September, only 26 μg/m^3.

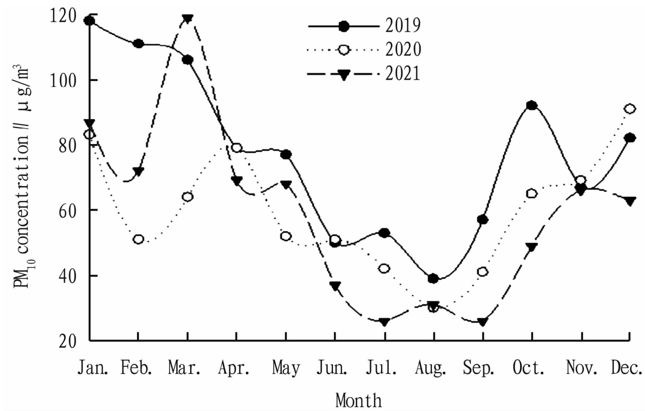
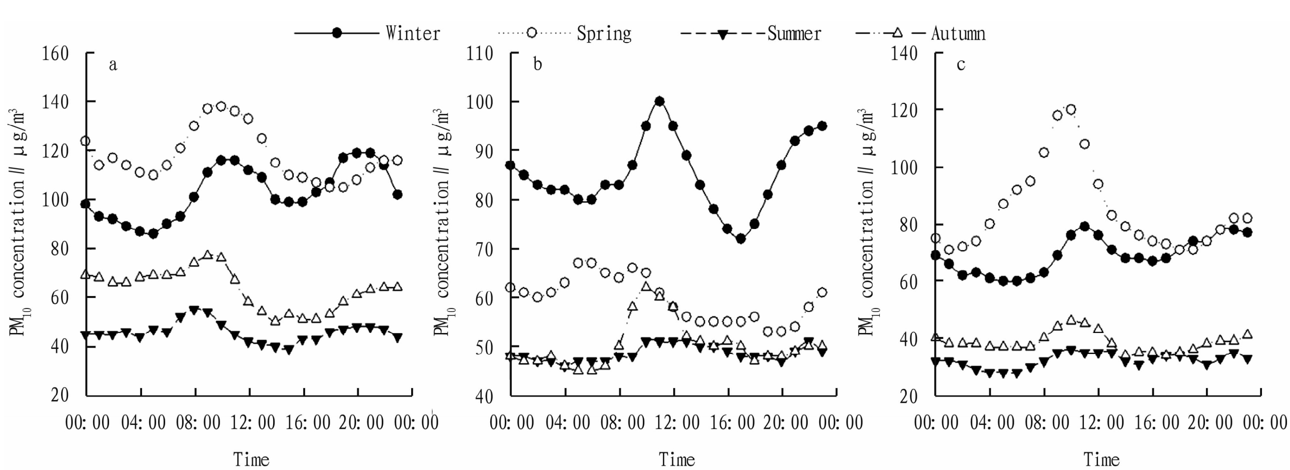


Fig. 3 PM_{10} concentration in each month from 2019 to 2021

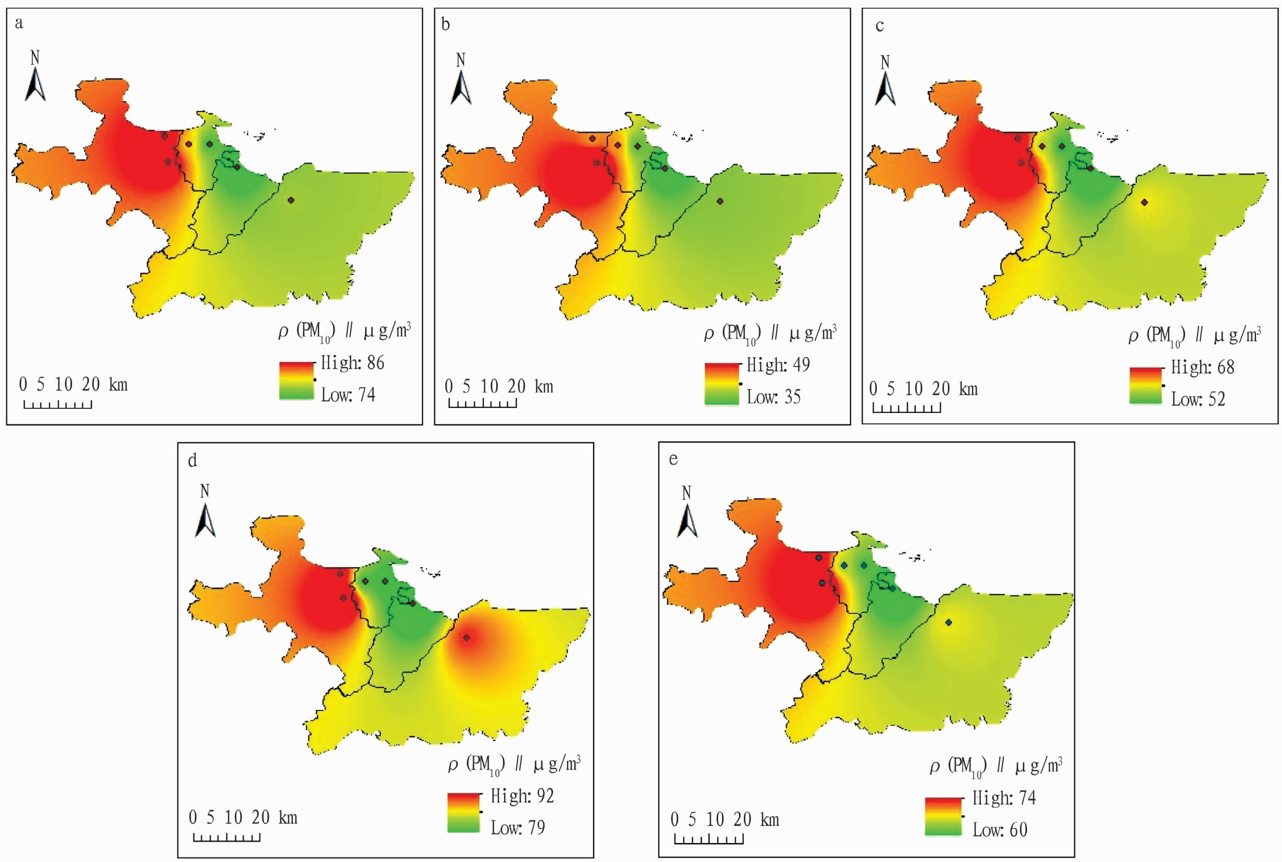
3.1.4 Daily variation. Fig. 4 reveals the daily variation of PM_{10} concentration in different seasons from 2019 to 2021. It can be seen that the daily variation curves of PM_{10} concentration in different seasons basically had two peaks, and especially in winter and spring, they were more obvious. The first peak appeared approximately between 09:00 and 11:00, and the second peak can be found between 21:00 and 23:00. The time of peak occurrence varied among the four seasons. It was the earliest in summer and the latest in winter. There was not much difference between spring and autumn. PM_{10} concentration reduced gradually from 00:00 to 08:00. In winter and spring, it fluctuated greatly, with a fluctuation range of about 10 μg/m^3. In summer and autumn, the fluctuation ranges were smaller, approximately 5 μg/m^3.

3.2 Spatial distribution characteristics of PM_{10} concentration The seasonal and annual averages of PM_{10} concentration in six environmental monitoring stations from 2019 to 2021 were calculated to analyze its spatial variation characteristics (Fig. 5). In spring, PM_{10} concentration ranged from 74.33 to 86 μg/m^3, which was higher than the secondary standard limit stipulated in China's *Ambient Air Quality Standards* (GB 3095-2012). It was the highest in the development area and the northeast of Fushan District and the lowest in Laishan District and the east of Zhifu District, with a spatial difference of 13.57%. PM_{10} concentration in summer was significantly lower than that in spring, varying from 35 to 48.67 μg/m^3, which was below the secondary standard limit. It was the highest in the center of Fushan District where the monitoring station of Fushan Environmental Protection Bureau is located, while it was lower in the east of Laishan District and Zhifu District, with a spatial difference of 28.09%. In autumn, PM_{10} concentration ranged from 52.33 to 68.33 μg/m^3, lower than the secondary standard limit, while it was higher in the development area and Fushan District, with a spatial difference of 23.42%. In winter, PM_{10} pollution was severe, and PM_{10} concentration varied from 79 to 92 μg/m^3. It was relatively high in the development area, Fushan District and Muping District. From the spatial distribution of the annual averages over the past three years, it can be seen that PM_{10} concentration was high in the development area and Fushan District. On the whole, PM_{10} concentration was the highest in the west, followed by the east, and it was the lowest in the central coastal areas, which is related to the industries and the main wind direction in the region. Yantai is mainly influenced by the northeast monsoon and marine cyclones. In winter, the northeast wind is dominant, while in summer, the southeast wind is dominant. The main terrain is low mountains and hills. During the summer half year, external pollutants can be horizontally transported to the northwest under the influence of the southeast wind. Moreover, there are many heavy industrial areas in the northwest, and the emissions of pollutants are relatively large. Therefore, PM_{10} concentration was relatively high in the development zone and Fushan District. In contrast, the emissions of pollutants are relatively small in Zhifu District and Laishan District . The coastal areas are affected by sea breezes, so pollutants diffuse more quickly, and the the pollution was the lightest.



Note: a. 2019; b. 2020; c. 2021.

Fig. 4 Daily variation of PM_{10} concentration in various seasons from 2019 to 2021



Note: a. Spring; b. Summer; c. Autumn; d. Winter; e. Average.

Fig.5 Spatial distribution of PM_{10} concentration

3.3 Analysis of the correlation between PM_{10} concentration and meteorological factors The correlation between PM_{10} concentration and various meteorological factors in Yantai City from 2019 to 2021 was studied using SPSS18.0. Table 1 presents the correlation coefficient between PM_{10} concentration and daily average temperature, relative humidity, wind speed, air pressure, precipitation and sunshine duration. The correlation between PM_{10} concentration and average temperature was negative. That is, when temperature is high, the vertical movement of the atmosphere is stronger, which is conducive to the diffusion of PM_{10}. Conversely, when an inversion layer appears, the vertical diffusion of PM_{10} will be hindered, thereby increasing PM_{10} concentration. Moreover, the temperature in Yantai from January to December showed a cool – warm – cold trend. Due to the influence of winter heating, PM_{10} concentration showed a high – low – high trend, so there was a negative correlation between the two.

PM_{10} concentration was mainly negatively correlated with relative humidity, and the negative correlation was significant especially from June to October. From June to October, Yantai area is often affected by the warm and humid air current from the southwest, so water vapor content in the air is relatively high. When relative humidity is high, precipitation is prone to occur. When raindrops fall, the particulate matter in the atmosphere can be removed through the dissolution or adhesion of raindrops. The correlation between PM_{10} concentration and wind speed was negative, especially in January, February, July, August, November and December. In January, February and December, Yantai is in the heating period, and due to the impact of coal combustion emissions, PM_{10} concentration increased. The increase in wind speed is conducive to turbulent exchange, thereby reducing the concentration of pollutants. In winter, the ground is in the frozen period, and a relatively high wind speed will not cause ground dust. Therefore, the negative correlation was significant. From March to June, the correlation was not significant because a relatively high wind speed at this time would cause ground dust, thereby offsetting part of the negative effect of wind speed on PM_{10} concentration.

The correlation between PM_{10} concentration and air pressure had no obvious law. Throughout the year, PM_{10} concentration and air pressure were extremely significantly positively correlated. The reason is that under the control of high pressure, there was mostly low pressure on the ground, and air flow moved downwards; the atmosphere was stable, which was not conducive to the diffusion of PM_{10}. Conversely, under the control of low pressure, air flow moved upwards, which was conducive to the generation of precipitation, so that PM_{10} concentration reduced. However, the correlation between PM_{10} concentration and air pressure varied in different months. PM_{10} concentration was negatively correlated with precipitation, and the negative correlation was extremely significant especially in January, July, August, September, November and December. In Yantai area, there is a considerable amount of precipitation in summer. Rainwater has the effect of removing and scouring PM_{10}, thereby reducing PM_{10} concentration. The correlation between PM_{10} concentration and sunshine duration was different at different time scales. Throughout the year, the two were negatively correlated. When PM_{10} concentration is high, atmospheric turbidity increases, reducing the penetration ability of sunlight and thus leading to a decrease in sunshine duration. However, the correlations in different months were inconsistent. The reason may be that there are commonalities among meteorological factors, and the correlation between the two cannot be described accurately.

To sum up, the meteorological factors influencing PM_{10} concentration in different months were not exactly the same. Among them, the main factors included average temperature, relative humidity, wind speed and precipitation.

Table 1 Correlation coefficients between PM_{10} concentration and meteorological factors in each month and throughout the year in Yantai from 2019 to 2021

Time	Average temperature	Relative humidity	Wind speed	Air pressure	Precipitation	Sunshine duration
January	-0.338**	-0.020	-0.277**	-0.201	-0.244**	-0.132
February	-0.319**	-0.050	-0.195	0.401**	-0.096	-0.160
March	-0.429**	-0.099	-0.189	-0.299**	-0.170	-0.139
April	-0.144	-0.015	-0.075	-0.273	-0.031	-0.042
May	0.079	-0.034	-0.094	0.052	-0.090	0.191
June	-0.333**	-0.458**	-0.048	-0.077	-0.202	0.154
July	-0.364**	-0.410**	-0.220*	-0.045	-0.313**	0.247**
August	-0.176*	-0.583**	-0.224**	0.252**	-0.266**	0.366**
September	-0.180*	-0.440**	-0.054	0.172	-0.298**	0.314**
October	0.069	-0.274**	-0.169*	-0.194*	-0.176	0.195*
November	-0.477**	-0.017	-0.338**	-0.148	-0.254**	0.202**
December	-0.472**	0.125	-0.297**	-0.607**	-0.294**	0.281**
A year	-0.333**	-0.287**	-0.150*	0.243**	-0.098	-0.120

Note: * and ** indicate a significant correlation at 0.05 and 0.01 levels (bilateral).

4 Conclusions

Based on the data of PM_{10} concentration from six environmental monitoring stations in Yantai City during 2019-2021, the spatial and temporal characteristics of PM_{10} concentration and its correlation with various meteorological factors were studied, and the following conclusions were reached.

(1) From the perspective of temporal variation, the annual average of PM_{10} concentration in Yantai City showed a decreasing trend year by year, and PM_{10} pollution was improved. Moreover, the annual averages of PM_{10} concentration in 2020 and 2021 were respectively 14.29% and 15.71% lower than the secondary standard limit. Besides, PM_{10} concentration had distinct seasonal variation characteristics. That is, it was high in winter and low in summer; it decreased in spring and rose in autumn. In terms of monthly variation, the changing curve is U-shaped, and it was high in December and January but low in July and August. During a day, PM_{10} concentration had two peaks, and they were more obvious especially in winter and spring. The first peak occurred approximately between 09:00 and 11:00, and the second peak appeared from 21:00 to 23:00. The time of peak occurrence changed among the four seasons. It was the earliest in summer and the latest in winter. There was not much difference between spring and autumn.

(2) From the perspective of spatial distribution, the annual average of PM_{10} concentration in the three years is shown as follows: west > east > center. It was the highest in Fushan District and the development area, while Zhifu District and Laishan District had the slightest pollution. In spring, it was the highest in Fushan District and the development area. In summer, it was the highest in Fushan District and the lowest in Laishan District, and the spatial difference rate reached 28.09%, which was the largest among the four seasons. PM_{10} concentration in autumn was significantly higher than that in summer, and the maximum appeared near the development area and Fushan Environmental Protection Bureau. In winter, it was high in the development area and Fushan District. Generally speaking, it was higher in the west than that in the center and east.

(3) Average temperature, relative humidity, wind speed and precipitation were the main meteorological factors affecting PM_{10} concentration in Yantai area. PM_{10} concentration was negatively correlated with average temperature and relative humidity, and the correlation was the most significant from June to October. It was negatively correlated with wind speed and precipitation, and the correlation varied in different months. The negative correlation was significant in summer and winter.

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as biomedicine and bio agriculture, and achieve high-quality development of the bio economy, thereby attracting more social capital investment. At the same time, it should encourage financial institutions to innovate financing models, such as implementing the "fund +" model, green bonds, *etc.* It also needs to strengthen the assessment and management capabilities of financial institutions for biodiversity related risks, and enhance their participation enthusiasm. In addition, supporting measures should be improved, including formulating relevant policies and regulations, and clarifying the sources and usage norms of funding for biodiversity conservation, thereby creating a favorable policy environment for biodiversity investment and financing. The investment and financing of biodiversity in Jilin Province require collaborative efforts from the government, financial institutions, enterprises, and society. By innovating and improving investment and financing mechanisms, solid financial support can be provided for biodiversity conservation, achieving coordinated and sustainable development of ecology and economy.

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