Analysis of the Dust-Concentration Distribution Law in an Open-Pit Mine and Its Influencing Factors

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ABSTRACT: In this study, a solar-powered multipoint network monitoring method was used to record dust-particle concentrations and meteorological indicators in the Anjialing open-pit coal mine in the Pingshuo mining area. The factors influencing the concentrations of particulate matter of different maximum diameters (PM2.5, PM10, and total suspended particulates; TSPs) and the regularity of the spatial distribution were examined. The results show that the highest dust concentration and thus the most serious dust pollution occur in winter, and the lowest dust concentration is found in summer. There are peaks in dust concentration in December and January to February, and the pollution is more serious at these times. On a given day, the pollution is higher between 11:00 and 13:00, but it does not exceed the 24 h air concentration limits specified in the Chinese Ambient Air Quality Standard (GB3095-2012). It was found that the PM2.5 and PM10 concentrations are positively correlated with humidity and air pressure, and they are negatively correlated with wind speed, temperature, and noise. The TSP concentration is positively correlated with temperature and negatively correlated with humidity. The results of this study provide theoretical guidance and a reference for the distribution law of dust concentration in open-pit coal mines.

1. INTRODUCTION

At present, there are 376 open-pit coal mines in China, and these have an annual production capacity of 950 million tons, accounting for 17.8% of the country’s total coal production capacity. Open-pit mining occupies an important position in China’s coal industry.1 Since open-pit coal mining is conducted in a semiopen space, operations such as perforation, blasting, mining, loading and transportation, and rock and soil dumping generate dust to varying degrees.2–4 Among these processes, blasting, and transportation generate the largest amounts of dust. Due to the strong diffusivity and volatility of dust,5 it can have a negative impact on the atmospheric environment and disrupt the ecological balance.6

At present, the main dust indicators for domestic urban air-quality monitoring include the total suspended particulates (TSPs) and particulate matter (PM) with diameters below a certain threshold in μm (PM10, PM2.5, and PM1).7 These suspended particles can be inhaled into the human body, damage people’s respiratory systems, and endanger human health.8

At present, there are two methods for dust research: numerical simulation and actual measurement. Numerical simulation9–12 is mainly used to model the open-pit mine through calculation software and use the finite-element method to simulate the dust diffusion and analyze the diffusion law. However, the numerical simulation method is ideal and cannot fully reflect the dust distribution in the open-pit mine. It is mainly used to verify the actual measurement results. In terms of actual measurement, Du13 and Chen measured and analyzed the source intensities of the dust-producing points of drilling, blasting, shovel loading, vehicle transportation, and dumping operations in open-pit mines. They studied the dust production of these different sources and found that the most important ones affecting the dust from open-pit mines are blasting work and car dust. His conclusion lays a foundation for the follow-up study of dust in open-pit mines, but the observation time is short and the observation range is small. Pochwala et al.14 developed a low-cost air-pollution monitoring system to understand the sources of dust production and the direction of diffusion in the atmosphere. However, considering the wing problem of the UAV, when it flies, the nearby dust may escape to other places due to the power problem, which may ultimately lead to inaccurate results. Wang et al.15 analyzed dust pollution from the perspective of combining the production and metering conditions of the Harwusu open-pit coal mine in Northwest China, providing a basis for prevention and control. However, this experiment only analyzed the open-pit coal mine in alpine areas, and there was not enough...
experiment to support whether the results were widely used. Wang et al.\textsuperscript{16} carried out research on dust control in the Zhungeer mining area in China. Only several monitoring points were arranged near some areas. The monitoring range is small, the monitoring time is short, and the data volume is limited. Therefore, it is difficult to truly reflect the distribution of air pollutants in the area, and it is impossible to obtain the real dust transport law so as to know dust control. However, monitoring systems for open-pit mines are still not perfect, and it is difficult to quantify changes in the actual indicators of open-pit coal mine dust at different stages of dust generation and diffusion.

In ground-based monitoring systems, due to the influence of the on-site operating environment, there are generally few monitoring points providing insufficient coverage; the monitoring times are also short, and there is a lack of continuity. These factors lead to a decrease in analysis accuracy. Furthermore, the monitoring technology and instruments used are not sufficiently advanced, meaning that errors remain a major issue.

In this study, taking the Anjialing Coal Mine in Pingshuo Mining Area, Shuozhou City, as the example research object, a ground-based monitoring system employing solar-powered wireless multipoint networking was used to analyze the variations in the dust concentrations in an open-pit mine over time. With the measured dust data, Kriging interpolation\textsuperscript{17} was first used to analyze the open-pit coal mine concentration distribution and explore the diffusion law. The distribution of dust produced in each segment of the mine was directly reflected. Finally, the measured data and meteorological factors were analyzed by data analysis and gray correlation analysis,\textsuperscript{18} and the distribution characteristics and diffusion laws of dust concentration in open-pit coal mines were preliminarily obtained. The results provide a strong basis for the prediction, evaluation, and effective management of open-pit coal mine dust.\textsuperscript{19}

\section*{2. RESEARCH AREA AND METHODS}

\subsection*{2.1. Study Area.} Shuozhou City is located in the northern part of Shanxi Province, at the southwestern end of the Datong Basin, bordering Linyi to the south and Datong to the north.\textsuperscript{20}
The coal reserves of Shuozhou are about 49.41 billion tons, accounting for one-sixth of the province’s reserves. This is mainly distributed in the Pingshuo, Shuonan, Shanyin, Huairen, and Youyu mining areas, with a coal-bearing area of 1644.95 square kilometers. A location map of this area is shown in Figure 1.

Pinglu District of Shuozhou City is in a warm temperate semiarid zone with a dry climate. Spring, summer, autumn, and winter represent four distinct seasons, and there are large temperature differences between day and night, long and cold winters, short and hot summers, and changeable temperatures. The average annual temperature is 6.5 °C, the extreme minimum temperature is −32.4 °C, and the extreme maximum temperature is 37.9 °C. The average annual precipitation is 428.00 mm, and this is mostly concentrated in July, August, and September. The annual average wind speed is 2.8 ms⁻¹, the dominant wind direction is northwest, and the maximum instantaneous wind speed is 20 ms⁻¹.

2.2. Materials and Methods. The dust-particle data in this study were obtained from weather stations and ground-based monitoring stations. The weather station data used were provided by the National Meteorological Science Center. Data including the air pressure, average wind direction, average wind speed, temperature, and relative humidity were obtained at 1 h intervals, and the data from the required monitoring points were collected synchronously. A total of 16 ground-based monitoring stations were constructed in the mining area, providing longitude, latitude, temperature, humidity, wind speed, atmospheric pressure, PM2.5, PM10, TSP, wind direction, and noise data every 30 min. In Table 1, the distribution of monitoring points and data collection in the pit of the Anjialing open-pit mine are shown.

2.2.1. On-Site Dust Monitoring System and Its Layout in the Open-Pit Mine. The on-site monitoring system employs solar-powered ground stations using multipoint networking, and it was developed by Fengtu Internet of Things Technology Co., Ltd. An example of a monitoring station and its cloud-based interface are shown in Figures 2 and 3, respectively. LoRa wireless networking is used between each sensor of the monitoring system, and the data from the sensors are uploaded to the monitoring platform. The main parameters of the system are shown in Table 2.

The system consists of data collectors, sensors, wireless transmission systems, background data-processing systems, and an information monitoring and management platform. Each monitoring station can monitor PM2.5, PM10, TSP, environmental temperature and humidity, wind direction and speed, and noise. This is a networked platform with an integrated Internet architecture.

As noted, a total of 16 ground-fixed monitoring stations were arranged on the site. These are powered by solar energy, and a LoRa wireless network group is formed between the individual sensors to collect and upload the monitoring data to the management and control platform. To consider the impact of the detection mining area on the surrounding environment, the grid and fan methods were jointly used to arrange the monitoring points, and the distance between each monitoring point was 500 m. At the same time, a certain number of monitoring instruments were installed on the electric shovel to study the effect of local dust concentrations on the open-pit mine dust levels during mining and loading operations.

The layout of the 16 basic sampling points in the Anjialing open-pit mine is shown in Figure 4. This paper focuses on monitoring points 1–12 around the mine to analyze the dust migration law. As noted, the monitoring points obtained data from each sensor every 30 min. The monitoring points strictly followed the principle of being representative while not affecting mine operations; there were more points in the downwind direction and fewer points in the upwind direction.

2.2.2. Deployment Principle of Monitoring Substations. There are mainly two detection methods for dust detection. Under the condition of static wind, take the emission source as the center, draw an arc with a distance of 2–50 m, and set it in a fan-shaped range with the emission source; when the wind force is greater than 1.5 m/s, the detection equipment is mainly not located in the area with the maximum dust concentration in the downwind direction. The layout principle of monitoring points is shown in Figure 5.

2.2.3. Analysis of Gray Correlation Degree of Influencing Factors for Dust. Gray correlation analysis is a systematic analysis method that combines qualitative and quantitative approaches to measure the degree of correlation between various factors using the shapes of their change curves. The correlation degree is divided into low (0.0–0.3), moderate (0.3–0.6), high (0.6–0.8), and very high (0.8–1.0). If two factors vary consistently and their change trends are basically the same, the correlation between the two will be high; conversely, if they are inconsistent and their trends are different, their correlation will be low. Here, this method is used to analyze the relationships between the measured values of various meteorological factors and the measured values of concentrations of dust particles of different sizes.

The gray correlation coefficient $\xi(k)$ between $x_i(i)$ and $x_k(i)$ can be obtained using

$$
\xi(k) = \frac{\min_{1 \leq j \leq n, 1 \leq k \leq x} \min \{x_i(i) - x_0(i)\} + \rho \max_{1 \leq j \leq n, 1 \leq k \leq x} \max \{x_i(i) - x_0(i)\}}{\max_{1 \leq j \leq n, 1 \leq k \leq x} \{x_i(i) - x_0(i)\} + \rho \min_{1 \leq j \leq n, 1 \leq k \leq x} \min \{x_i(i) - x_0(i)\}}
$$

Figure 2. Photograph of a solar-powered monitoring station deployed in an open-pit coal mine as part of a multipoint network system, illustrating the main components.
in the above equation, \( \rho \in (0,1) \) is the resolution coefficient; a smaller value of \( \rho \) will mean that the difference between the correlation coefficients is greater, and the distinguishing ability will thus be stronger. Therefore, we generally let \( \rho = 0.5 \).

The gray correlation degree between the calculated influencing factors and the measured value of the dust-particle concentration is then

\[
    r_i = \frac{1}{n} \sum_{k=1}^{n} \xi(k), \quad k = 1,2, \ldots, n
\]

Figure 3. Example of the cloud-based platform showing monitoring data indicators.

Table 2. Main Parameters of Solar-Powered Multipoint Network Monitoring Systems

| parameter          | value                                                                 |
|--------------------|------------------------------------------------------------------------|
| built-in sensors   | temperature, humidity, atmospheric pressure, noise, PM2.5, PM10, TSP, wind speed, wind direction |
| built-in sensor accuracy | temperature: ±0.01 °C, humidity: ±2% RH, atmospheric pressure: ±0.2 Pa, particle sensor: minimum resolution particle size 0.3 \( \mu \)m, TSP parameters: measurement range: 0.01–10,000 \( \mu \)g m\(^{-3}\); measurement accuracy: ±10% |
| Boise parameters   | range: 30–130 dB, frequency range: 31.5 Hz to 8 kHz, accuracy: ±1.5 dB |
| PM2.5 + PM10 parameters | effective range of particle mass concentration: 0–1000 \( \mu \)g m\(^{-3}\), the maximum range of particle concentration: ≥1000 \( \mu \)g m\(^{-3}\) |
| data upload intervals | 30–65 535 s                                                                 |
| wind-speed parameters | measurement range: 0–30 and 0–60 m, resolution: 0.1 ms\(^{-1}\), measurement accuracy: ±1 ms\(^{-1}\) |
| wind direction parameters | wind direction range: 0–360°/16 azimuth resolution: 1° measurement accuracy: ±3° |
where $\xi(k)$ is the correlation coefficient between the $k$-th element of the comparison sequence $x_i$ and the $k$-th element of the reference sequence $x_0$, and $r_i$ is the calculated gray relational degree.

3. RESULTS

3.1. Seasonal Variation Characteristics of Dust Concentration. Through the analysis of the field monitoring data, it was found that the concentrations of PM2.5, PM10, and TSP were different at different monitoring points during different seasons (Figure 6).

The seasons were divided according to the meteorological convention, with March to May defined as spring, June to August as summer, September to November as autumn, and December to February as winter. According to the analysis of the data from the 12 ground-based monitoring points, from a seasonal point of view, the average values of PM2.5, PM10, and TSP were the highest in winter and the lowest in summer. In winter, the average values of PM2.5, PM10, and TSP were 97.04, 125.90, and 345.52 $\mu g \cdot m^{-3}$, respectively; the corresponding average values in summer were 67.28, 88.89, and 272.37 $\mu g \cdot m^{-3}$. The specific details of the test data are listed in Table 3.

The on-site dust monitoring data show that the seasonal changes in PM2.5, PM10, and TSP concentration in Anjialing open-pit mine are consistent and conform to the general trend of atmospheric dust concentrations. It is found that the average dust concentration in summer and autumn is relatively low, the air quality is relatively good and the stability is relatively high; the dust concentration is always the highest in winter.

Taking PM10 as an example, it can be seen in Figure 7 that the annual average PM10 dust concentration distributions are greatly affected by wind speed, wind direction, and the actual working conditions on-site. According to statistics from the Bureau of Meteorology, the wind direction in Pinglu District, Shuozhou City, Shanxi Province is mostly northwesterly, and it can also be seen that the dust concentration in the eastern part of the mine is notably higher than in other areas. According to the actual situation on-site, the mining operations are advancing eastward, and the dust concentration is affected by the northwesterly wind. Higher dust concentrations can be seen to the right of the image in Figure 7. The dust concentration in the dump site is also relatively high, but the dust spreads eastward, being affected by the wind direction. The dust concentration inside the mine pit is higher than that outside, and the concentration in the stope is higher than that in the ends.

3.2. Monthly Variation Characteristics of Dust Concentration. Two different monitoring sites in the mine pit and at the edge of the mining area in the nondisturbed area were selected to monitor the dust concentration for 12 consecutive months. Data analysis was carried out for the monthly average concentrations of these different locations, and the results are shown in Figure 8. Among the monitoring points, no. 1 is the
Table 3. Dust Concentrations of 12 Monitoring Points in Anjialing Open-Pit Mine in 2020

|       | PM2.5 Spr. | PM2.5 Sum. | PM2.5 Aut. | PM2.5 Wint. | PM10 Spr. | PM10 Sum. | PM10 Aut. | PM10 Wint. | TSP Spr. | TSP Sum. | TSP Aut. | TSP Wint. |
|-------|------------|------------|------------|-------------|------------|------------|------------|------------|----------|----------|----------|----------|
| point 1 | 44.17      | 51.93      | 51.18      | 64.32       | 91.56      | 105.80     | 107.52     | 126.37     | 216.29   | 240.39   | 245.76   | 289.49   |
| point 2 | 73.52      | 71.63      | 74.70      | 75.41       | 94.84      | 91.32      | 95.19      | 95.62      | 293.75   | 282.82   | 290.26   | 295.12   |
| point 3 | 95.35      | 70.46      | 96.26      | 106.57      | 123.21     | 89.68      | 123.11     | 136.37     | 318.79   | 280.03   | 339.19   | 362.43   |
| point 4 | 84.36      | 73.36      | 80.07      | 99.69       | 109.99     | 93.49      | 102.15     | 127.06     | 298.56   | 286.71   | 301.99   | 342.00   |
| point 5 | 52.85      | 31.25      | 51.75      | 56.26       | 62.09      | 39.08      | 65.62      | 66.24      | 210.86   | 190.34   | 237.27   | 237.74   |
| point 6 | 81.99      | 77.25      | 102.36     | 109.51      | 123.10     | 97.56      | 128.95     | 125.28     | 318.96   | 292.30   | 346.30   | 369.53   |
| point 7 | 96.21      | 78.71      | 101.09     | 112.60      | 130.64     | 100.39     | 129.40     | 144.07     | 270.85   | 298.91   | 350.21   | 400.13   |
| point 8 | 93.46      | 76.20      | 101.51     | 112.24      | 130.26     | 97.17      | 129.78     | 143.44     | 350.28   | 293.12   | 361.37   | 402.08   |
| point 9 | 91.03      | 69.75      | 92.68      | 101.20      | 127.02     | 88.81      | 111.73     | 127.96     | 300.90   | 278.46   | 314.60   | 347.49   |
| point 10| 81.50      | 65.46      | 81.80      | 88.33       | 105.36     | 83.23      | 104.51     | 112.80     | 305.61   | 266.43   | 305.93   | 316.87   |
| point 11| 122.09     | 68.64      | 121.32     | 124.60      | 149.5      | 87.44      | 155.57     | 159.79     | 399.11   | 276.03   | 396.57   | 404.18   |
| point 12| 105.35     | 72.74      | 88.85      | 113.78      | 130.13     | 92.66      | 113.59     | 145.74     | 353.75   | 285.26   | 322.28   | 379.22   |

Figure 7. Distribution map of annual average PM10 dust concentration in the Anjialing open-pit mine.

Figure 8. Monthly average dust concentration levels at monitoring point no. 1 and no. 8.
location of the viewing platform at the edge of the mining area
and no. 8 is located inside the mine.

It can be seen in the figure that due to the influence of
different on-site operations, the mine dust concentration
changes in a wave-like manner. The general dust concentration
at monitoring point no. 1 is significantly lower than that at no.
8. According to the analysis of the site conditions, process
operations such as perforation, blasting, mining and loading,
transportation, and soil dumping in the open pit are
accompanied by a large amount of dust, resulting in a high
centrated dust concentration in the pit. The concentration
is significantly lower at the edge of the mining area due to the
influence of the diffusivity of the dust itself. From March to
April, monitoring point no. 3 is mostly perforated works, and
the dust concentration here is relatively low; from June to
August, due to the influence of the atmospheric environment,
the dust concentration is at its lowest level.

According to the diffusivity of dust, from November to
December, the dust concentration gradually increased, the
atmospheric wind speed gradually increased, the temperature
gradually decreased, and the dust concentration in the mine
was also significantly affected. The dust concentration peaked
from November to December, and it was relatively high from
January to February. Shuozhou has a long and cold winter: the
ground temperature drops sharply, thermal radiation is obvious
at night, and the temperature of the atmosphere near the
ground is lower than that in the upper atmosphere. Due to the
influence of this temperature-inversion layer, it is difficult for
dust to diffuse. Conversely, in summer and autumn, due to
frequent sandstorms and high temperatures, the concentration
is relatively low.

3.3. Diurnal Variation Characteristics of Dust Concentration.
Figure 9 shows the change curves of the PM2.5,
PM10, and TSP mass concentrations at the Anjialing
monitoring site on a certain day. It can be seen from these
plots that the variations in these different measures across the
day are consistent. On this particular day, the sun rose between
05:00 and 06:00, and the dust concentration then decreased. It
decreased again between 08:00 and 10:00 when the early-shift
workers in the mine left and the mining machinery became
inactive for a period. Overall, after sunrise, the machinery and
equipment were working, people were busy, and the
centration trend generally increased. The peak concen-
tration was reached between 11:00 and 13:00. The slight dip
around 12:00 was the result of workers taking turns to have

Figure 9. Variations in concentrations of TSP, PM10, and PM2.5 across a single day.
their lunch breaks, so the dust concentration was slightly reduced.

In the afternoon, the solar radiation is slightly weakened, the airflow gradually increases, and the dust concentration gradually decreases. The lowest value of the day was reached at 20:00. In the system of shift work, the mine work does not stop, and it can be seen that the dust concentration gradually increases through the night until reaching a small peak between 02:00 and 04:00. The concentration value then decreases again as the sun rises.

These results show that the dust concentration is closely related to both human activity at the site and atmospheric changes.

Ambient air concentration limits are specified in the Chinese Ambient Air Quality Standard (GB3095-2012), as shown in Table 4. As an industrial zone, the open-pit coal mine is a second-class ambient air function area, and the secondary concentration limit is thus applicable. The 24 h average values of the obtained dust concentration were calculated, and the values for PM2.5, PM10, and TSP were 74.38, 95.19, and 289.66 μg·m⁻³, respectively. It can be seen in the figure that the dust concentration does not exceed the national level II limit standard after 14:00, but it will exceed the national limit in the early morning; especially at noon, the problem of small particle concentration exceeding the national limit is more prominent. In addition, the changes in PM2.5, PM10, and TSP were significantly consistent. Comparing the obtained data with the national standard, it can be seen that although the three types of dust with different particle sizes did not exceed the national standard, they were all near the critical values, meaning that the mine should be taking corresponding preventive measures.

### 3.4. Spatial Distribution of Dust in Anjialing

#### 3.4.1. Concentration Distributions of Dust with Different Particle Sizes

Kriging interpolation analysis was carried out based on the measured dust concentrations of the Anjialing open-pit mine in winter and summer throughout the year; it was found that the overall dust distributions in the two seasons were roughly the same. The spatial distributions of dust concentration at three different times of day are shown in Figures 10−12. It can be seen that the dust distribution has the characteristics of variation and zonality as a whole, and this is closely related to the wind direction, wind speed, and various mining links. At 06:00, dust accumulation occurs in the upper part of the mine, and the dust is greatly affected by the wind.

According to meteorological information, the wind direction in summer is mainly from the north, and the dust was therefore blown from the north to the south; the dust concentration in the mine was thus higher in the south. There are different depths in the stope, and working areas with large stope depths have many dust sources and high dust concentrations. As the depth of the stope decreases, it expands to the periphery near the ground, and the concentration decreases.

The blasting process at the working face in the Anjialing mining area generally begins at 12:00, and the perforation blasting area is located at the northwest corner of the pit, near the explosive factory. It can be seen in Figure 11 that around 12:00, the dust concentration is high at the northwest corner of the pit, that is, the blasting and coal-mining position. At 18:00, due to the basic completion of all tasks at the working face in the mining area, there is a shift change, and there are no ongoing mining or soil-dumping operations. At this time, the dust concentration is again higher in the coal-mining part of the mine.

#### 3.4.2. Factors Affecting the Distribution of Dust

Using the solar-powered multipoint network ground-based monitoring system of Anjialing open-pit coal mine, the measured meteorological data and the measured dust concentration were subjected to Pearson correlation analysis and gray correlation analysis, and the results are shown in Tables 5 and 6. The relationships between different meteorological factors and the concentrations of the dust of each particle size were studied. It can be seen in Table 5 that PM2.5 and PM10 are correlated with wind speed, temperature, humidity, air pressure, and noise at a significance level of 0.01; this correlation is positive for humidity and air pressure, while it is negative for wind speed, temperature, and noise. TSP was found to be correlated at the 0.01 significance level with temperature and humidity, having a positive correlation with temperature and a negative correlation with humidity.
These results show that the dust concentrations of PM2.5 and PM10 in the Anjialing open-pit coal mine are affected by wind speed, temperature, humidity, air pressure, and noise. The TSP concentration is affected by temperature and humidity; it increases with increasing temperature and with decreasing humidity. There is no significant correlation between TSP and wind speed, temperature, or noise.

It can be seen in Table 6 that the gray correlation degree between each meteorological factor and the dust concentration is above 0.6, showing a medium-to-high correlation. Among these, PM2.5, PM10, and TSP have the highest correlations with air pressure, indicating that air pressure is the most important factor affecting these dust concentrations; this is followed by wind speed and noise. PM2.5, PM10, and TSP all have low correlations with temperature.

4. DISCUSSION

4.1. Temporal and Spatial Distributions of Dust Concentration. This study found that dust pollution in Anjialing open-pit coal mine is slightly higher in winter and spring than in summer and autumn. Pollution is the most serious in summer, and it is relatively low in spring. The average values of PM2.5, PM10, and TSP in summer can reach 89.26, 113.63, and 323.16 μg·m⁻³, respectively. This conclusion is consistent with the conclusion of global open-pit mines and conforms to the general law of atmospheric dust.

According to the analysis of the monthly variation characteristics of the dust concentration, it peaked in June to July and November. It can again be seen from this that the dust concentration is high in summer and autumn. During these periods, a large amount of dust accumulates, and it is difficult...
for it to spread. In summer, due to the changes in temperature in the morning and evening, an inversion layer is likely to appear above the mine,\textsuperscript{30} making it difficult for dust-particle pollutants to spread, and their concentration will increase.\textsuperscript{31}

Monitoring point no. 13 is located at the junction of the Anjialing and Antaibao open-pit mines, and the Anjialing open-pit mine has a high level of dust in summer due to the increase in end-to-end transportation operations near the junction and the diffusion of dust during this period.\textsuperscript{32} Autumn and winter are the windy season in Shuozhou when windy weather is relatively frequent. Therefore, the dust will be affected by the wind and sand weather, which will increase the dust concentration.

In spring and winter, rainfall and snowfall increase, and atmospheric diffusion conditions are relatively good, which is conducive to the diffusion of pollutants.\textsuperscript{33} During the day, it was found that the dust concentration peaked between 11:00 and 13:00. The reason for this is that with the rise of the sun, the machinery and equipment begin to work, increasing the dust concentration.\textsuperscript{34} There are three shifts in the working system of the mine, and work is continuous. As such, the dust concentration gradually increases through the night until reaching a small peak between 02:00 and 04:00. Then, as the sun rises, the dust concentration decreases.

On the spatial scale, taking summer as an example for analysis, the dust distribution in the Anjialing open-pit coal mine is varied and zonal.\textsuperscript{35} At 06:00, the dust is affected by the wind, and its concentration increases from the north due to the increase of the stope depth. At 12:30, due to blasting operations,\textsuperscript{36} the dust is further aggravated. At 18:00, during the shift change, mine operations decrease, and the dust concentration gradually decreases as well. This is consistent with the dust concentration distribution being much lower than that at noon.\textsuperscript{37}

4.2. Analysis of Factors Affecting Dust Concentration.
Pearson and Gray correlation analyses were carried out on the concentrations of dust of different particle sizes. It was found that the dust concentration of PM2.5 and PM10 in the Anjialing open-pit coal mine is affected by wind speed, temperature, humidity, air pressure, and noise, positively correlated with humidity and air pressure, and negatively correlated with wind speed, temperature, and noise; The dust concentration of TSP in the Anjialing open-pit coal mine is affected by temperature and humidity, which is positively correlated with temperature and negatively correlated with humidity. Among these factors, air pressure is the most important, followed by wind speed and noise. The possible reasons for this are as follows. (1) Air pressure is an important factor affecting atmospheric convection. When the ground pressure is low, there is an updraft over it, and there is airflow from the ground around the mine toward its center. PM aggregates, thereby aggravating air pollution.\textsuperscript{38} (2) Wind speed mainly affects the movement of pollutants in the downwind direction. When the wind speed increases, dust particles float and diffuse with the wind direction, increasing the dust concentration in the air.\textsuperscript{39,40} (3) Temperature has an impact on air quality and the degree of pollution. In the air column above the mine, when the temperature changes, the air quality changes significantly.\textsuperscript{41} This is the so-called inversion-layer phenomenon.\textsuperscript{42−44} (4) Rainfall and snowfall have the effect of scavenging and removing pollutants from the air. Under the action of precipitation, the dust particles suspended in the air are dissolved in water, which can remove a certain amount of dust from the air and increase the air quality.\textsuperscript{45}

The gray correlation degree between the concentrations of PM2.5, PM10, and TSP and meteorological factors are all above 0.6, indicating that air pollution is jointly affected by meteorological factors such as wind speed, temperature, humidity, air pressure, and noise, resulting in pollution and the reduction of air quality.

5. CONCLUSIONS

In this study, the temporal and spatial distribution characteristics of the dust concentration in the Anjialing open-pit mine were examined. The main conclusions can be summarized as follows.

(1) Temporal characteristics. The Anjialing open-pit coal mine has the highest dust concentration in winter and the lowest in summer. The concentration was found to peak in December and January to February. The dust concentrations were found to be at their greatest from 11:00 to 13:00.

(2) Pollution characteristics. The changes in dust concentration were monitored throughout the day, and they were compared with the ambient air concentration limits stipulated in the Chinese Ambient Air Quality Standard (GB3095-2012). It was found that the 24 h average concentrations of PM2.5, PM10, and TSP were 74.38, 95.19, and 289.66 μg·m\textsuperscript{-3}, respectively. Although the concentrations of the three different particle sizes did not exceed the national standard, they were all in the vicinity of the critical values, meaning that the mine should take corresponding preventive measures.

(3) Spatial characteristics. A ground-monitoring system using solar-powered multipoint networking was used to study the diffusion law of the dust concentration in the Anjialing open-pit mine. It was found that the dust distribution is varied and zonal. It has a greater impact.

(4) Correlated factors. The dust concentration in Anjialing open-pit coal mine is affected by wind speed, temperature, humidity, air pressure, and noise. The PM2.5 and PM10 concentrations were found to be positively correlated with humidity and air pressure, and they were negatively correlated with wind speed, temperature, and noise. The TSP concentration was found to be positively correlated with temperature, and it was negatively correlated with humidity. The concentrations of the dust of different particle sizes are jointly affected by meteorological factors including wind speed, temperature, humidity, air pressure, and noise, resulting in air pollution.

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Notes
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REFERENCES
(1) Zhao, H.; Mao, K. J.; Qu, Y. M.; Fu, E. S. Development status and key technology of driverless and new energy trucks in open-pit coal mine in China. China Coal 2021, 47, 45–50.
(2) Zhao, H. Z.; Zhen, X.; Li, M. J. Current development situation of open-pit coal mine in China. China Coal 2016, 25, 12–15+34.
(3) Zhang, X. H.; Lu, Y. T.; Yao, H.; Li, F. D.; Zhang, S. C. The temporal and spatial distribution characteristics of main air pollutants in China. Ecol. Environ. Sci. 2015, 24, 1322–1329.
(4) Tang, W. J. Study on Dust Distribution and Diffusion Mechanism in Open Pit Coal Mine; China University of Mining and Technology, 2018.
(5) Shen, L.; Zhang, D. Industrial dust and its properties. Metal World 1997, 6, 10–11.
(6) Xu, Z. J.; Wang, Y. Dust hazard and dust mechanism and control measures in open-pit coal mine. Inner Mongolia Coal Coal 2019, 23, 1–4.
(7) Wang, Z.-B.; Liang, L.-W.; Lin, X.-B.; Liu, H.-M. Control models and effect evaluation of air pollution in Jing–Jin–Ji urban agglomeration. Environ. Sci. 2017, 38, 4005–4014.
(8) Zhao, C. Y.; Li, Y. A.; Liu, X. L. PM2.5 and its impact on the health hazards. Refrig. Air Cond. 2013, 27, 5.
(9) Tang, W.; Li, F. A new circulating accumulation emission model for assessing dust emission from open pit mine. Sci. Rep. 2021, 11, 24243.
(10) Dendle, N.; Isokangas, E.; Corry, P. Efficient simulation for an open-pit mine. Simulat. Model. Pract. Theor. 2022, 117, 102473.
(11) Amaya, J.; Hermosilla, C.; Molina, E. Optimality conditions for the continuous model of the final open pit problem. Optim. Lett. 2021, 15, 991–1007.
(12) Huang, Z.; Gé, S.; Jing, D.; Yang, L. Numerical simulation of blasting dust pollution in open-pit mines. Appl. Ecol. Environ. Res. 2019, 17, 10313–10333.
(13) Du, C. F.; Chen, S. Analysis on dust resource intensity for open-pit mines and experimental study on the contribution rate. Ind. Saf. Environ. Protect. 2014, 40, 76–79.
(14) Pochwala, S.; Gardecki, A.; Lewandowski, P.; Somogyi, V.; Anweiler, S. Developing of low-cost air pollution sensor—Measurements with the unmanned aerial vehicles in Poland. Sensors 2020, 20, 3582.
(15) Wang, Y.; Du, C.; Xu, H. Key Factor Analysis and Model Establishment of Blasting Dust Diffusion in a Deep, Sunken Open-Pit Mine. ACS Omega 2020, 6, 448–455.
(16) Wang, Z. M. Pollution Characteristics and Diffusion Law of Dust at the Pit Bottom in Haerwusu Open-pit Coal Mine in Winter; China University of Mining and Technology, 2021.
(17) Wang, Z.; Zhou, W.; Jiskani, I. M.; Ding, X.; Luo, H. Dust pollution in cold region Surface Mines and its prevention and control. Environ. Pollut. 2022, 292, 118293.
(18) Knotters, M.; Brus, D. J.; Voshaar, J. O. A comparison of kriging, co-kriging and kriging combined with regression for spatial interpolation of horizon depth with censored observations. Geoderma 1995, 67, 227–246.
(19) Blom, M.; Pearce, A. R.; Stuckey, P. J. Short-term planning for open pit mines: a review. Reclamat. Environ. 2019, 33, 318–339.
(20) Yang, W. M. Research on Sustainable Development of Regional Economy Based on Coal Resources; Liaoning University of Engineering and Technology, 2006.
(21) Li, S.; Zhao, Y.; Xiao, W.; Yue, W.; Wu, T. Optimizing ecological security pattern in the coal resource-based city: A case study in Shouzhou City, China. Ecol. Indicat. 2021, 130, 108026.
(22) Edward, P.; El-Aasser, M.; Ashour, M.; Elshabrawy, T. Interleaved chirp spreading LoRa as a parallel network to enhance LoRa capacity. IEEE Internet Things J. 2020, 8, 3864–3874.
(23) Xie, N. M.; Liu, S. F. Research on evaluations of several grey relational models and methods to adapt grey relational axioms. Syst. Eng. Electron. Technol. 2009, 20, 304–309.
(24) Han, M.; Zhang, R. Q.; Xu, M. L. A variable selection algorithm based on improved grey relation analysis. Control Decis. 2017, 32, 1647–1652.
(25) Zhang, M.; Zhao, T.; Xiao, H. Temporospatial distribution and influencing factor analysis of dust concentration in Wuhai, Inner Mongolia. Earth Sci. Front. 2021, 28, 118–130.
(26) Li, L.; Zhang, R. X.; Sun, J. D.; He, Q.; Kong, L. Z.; Liu, X. Monitoring and prediction of dust concentration in an open-pit mine using a deep-learning algorithm. J. Environ. Health Sci. Eng. 2021, 19, 401–414.
(27) Lenanova, S. A. Dust content in the air: A case study of the Afanasievsky open pit mine (Russia), IOP Conference Series: Materials Science and Engineering; IOP Publishing, 2019; Vol. 663, No. 1, p. 012037.
(28) Tang, W.; Li, F.; Xiang, G.; Liu, M. Investigation on flow field characteristics in an open-pit coal mine. Environ. Sci. Pollut. Res. 2022, 29, 27585–27594.
(29) Swart, R.; Amann, M.; Raes, F.; Tuinstra, W. A good climate for clean air: Linkages between climate change and air pollution. An editorial essay. Climatic Change 2004, 66, 263–269.
(30) Liu, B.; Ma, X.; Ma, Y.; Li, H.; Jin, S.; Fan, R.; Gong, W. The relationship between atmospheric boundary layer and temperature inversion layer and their aerosol capture capabilities. Atmos. Res. 2022, 271, 106121.
(31) Perera, M. J. A. M.; Fernando, H. J. S.; Boyer, D. L. Turbulent mixing at an inversion layer. J. Fluid Mech. 1994, 267, 275–298.
(32) Birner, T.; Sankey, D.; Shepherd, T. G. The tropopause inversion layer in models and analyses. Geophys. Res. Lett. 2006, 33, L14804.
(33) Xue, X.; Xu, Y. Temporal and spatial distribution characteristics of air pollution index (API) and its correlation with the improvement of environmental tax law. J. Environ. Prot. Ecol. 2018, 19, 471–476.
(34) Wang, Y.; Du, C.; Xu, H. Key Factor Analysis and Model Establishment of Blasting Dust Diffusion in a Deep, Sunken Open-Pit Mine. ACS Omega 2020, 6, 448–455.
(35) Khan, A.; Niemann-Delius, C. A differential evolution based approach for the production scheduling of open pit mines with or without the condition of grade uncertainty. Appl. Soft Comput. 2018, 66, 428–437.
(36) Muchnik, S. Calculation and production of high-ecologically safe mass explosions in open pits. J. Min. Sci. 2004, 40, 597–604.
(37) Peng, C.; Chen, N.; Gao, B. Ultra-short-term wind power forecasting method combining multiple clustering and hierarchical clustering. Autom. Electr. Power Syst. 2020, 44, 173–180.
(38) Xiao, D.; Deng, S.; Deng, X.; Zhang, Y. Variation characteristics and influencing factors of atmospheric pollutants concentration in Dazhou, Sichuan. *Environ. Eng.* 2018, 36, 170–175+159.

(39) Aikawa, M.; Hiraki, T.; Eiho, J. Grouping and representativeness of monitoring stations based on wind speed and wind direction data in urban areas of Japan. *Environ. Monit. Assess.* 2008, 136, 411–418.

(40) Wang, Z. M.; Zhou, W.; Jiskani, I. M.; Ding, X. H.; Liu, Z. C.; Qiao, Y. Z.; Luan, B. Dust reduction method based on water infusion blasting in open-pit mines: a step toward green mining. *Energy Sources, Part A* 2021, 1–15.

(41) Zhou, Z.; Zhang, S.; Gao, Q.; Li, W.; Zhao, L.; Feng, Y.; Shi, L. The impact of meteorological factors on air quality in the Beijing–Tianjin–Hebei region and trend analysis. *Resour. Sci.* 2014, 36, 191.

(42) Fochesatto, G. J. Methodology for determining multilayered temperature inversions. *Atmos. Meas. Tech. Discuss.* 2015, 8, 2051–2060.

(43) Martilli, A. Numerical study of urban impact on boundary layer structure: Sensitivity to wind speed, urban morphology, and rural soil moisture. *J. Appl. Meteorol.* 2002, 41, 1247–1266.

(44) Zhen, J.; Lin, Q.; Yuan, Z.; et al. Discussion on the correlation between the stratification distribution of VOCs in the atmospheric boundary layer and the temperature inversion phenomenon. *The 11th National Aerosol Conference and the 10th Cross-Strait Aerosol Technology Seminar*, 2013; Vol. 158.

(45) Feng, J. J.; Shen, J. F.; Liang, R. Z.; Mo, C. H. Analysis on the relationship between PM10 and meteorological elements in Guangzhou. *Environ. Monit. China* 2009, DOI: 10.19316/j.jissn.