



OPEN

Characteristics and analysis of PM_{2.5} particles in a light-polluted atmosphere in winter

Feng Hu^{1,2✉}, Xinglei Wang¹ & Qi Li²

To study the micro-morphological characteristics of PM_{2.5} and its effect on ambient air quality, a 7500F scanning electron microscope (SEM) was utilized in this study to examine the micromorphology and elemental composition of PM_{2.5} and its impact on ambient air quality during heavily polluted weather in Yining City in the winter of 2018–2019. The results revealed the presence of numerous large solid shapes, small strip shapes, and a few irregular shapes. Additionally, the quantity of PM_{2.5} particles adsorbed on the glass fiber filter membrane was high, indicating a significant impact of PM_{2.5} particles on the urban area. Based on the analysis of particulate matter, heating time, and environmental conditions of samples during the winter heating season, it was concluded that the PM_{2.5} sample is rich in N, S, P, C, Na, Ge, Rb, Zn, Fe, Mg, Al, Mo, Pt, and Pb. The findings suggest that the urban area is predominantly influenced by industrial dust, road dust, construction cement dust, vehicle exhaust dust, and coal combustion during winter heating. The analysis and evaluation of the sample data indicate that PM_{2.5} in the urban area is influenced by human activities.

Keywords PM_{2.5}, Microstructure characteristics, SEM, Heating season, Ambient air quality

Atmospheric particulate matter reflects the presence of solid or liquid particles in the atmosphere. Its composition is intricate, with diverse sources. Due to their smaller volume and larger specific surface area, PM_{2.5} particles can absorb more harmful substances that may enter the human body through the respiratory system, posing risks to human health¹. Some researchers have utilized electron SEM technology to capture microscopic images, studying the microscopic morphology and surface features of PM_{2.5} in detail, leading to a deeper understanding of the harm caused by PM_{2.5}².

In recent years, single-particle analysis technology has provided micro-morphology and composition information of specific particles intuitively. It offers the advantages of short sampling time and small sample quantity. This technology is widely used in PM_{2.5} studies, including atomic force microscopy³, scanning electron microscopy, and transmission electron microscopy^{4,5}. X-ray fluorescence spectrum (XRF)⁶: among various single-particle analysis techniques, electron microscopy (scanning electron microscope and transmission electron microscope) is the only method that can simultaneously observe the morphology and analyze the composition of PM_{2.5}^{7–10}. It plays a significant role in studying the morphology, composition, particle size distribution, particle aggregation characteristics, and source analysis of particulate matter. Compared with transmission electron microscopy and scanning electron microscopy, the sample requirements are simple, and the analysis speed is fast, making it more suitable for PM_{2.5} studies. Scanning electron microscopy technology with an energy spectrum has been widely applied in mineral and material analysis^{11–13}.

Given this, this paper adopts scanning electron microscopy (SEM/ED) analysis technology to conduct a comprehensive study on atmospheric particulate matter PM_{2.5} in Yining City during 2018–2019. The focus is on the mild pollution weather in winter to reveal its morphological characteristics, main chemical composition, chemical composition of single amorphous particles, and trace element characteristics. After 2018, heavy pollution occurred several times in Yining City. The research results from 2018 to 2019 provide certain data references for the comprehensive control of PM_{2.5} and the continuous improvement of air pollution.

¹Key Laboratory of Pollutant Chemistry and Environmental Treatment, College of Chemistry and Environmental Sciences, Yili Normal University, Yining 835000, China. ²Yili Prefecture Product Quality Institute, Yining 835000, China. ✉email: tnj8181@aliyun.com

The study provides new insights and understanding of PM_{2.5} concentration, regional tectonic and geomorphological dynamics, and potential climate and environmental impacts in Yining City. Fine particles from human activities and nature can enter the atmospheric circulation and influence regional and even global climate¹⁴. Xiaoyu Jiao using U isotopes, Results show that dust originating from the TP undergoes long-range transport and constitutes potentially significant component of the Asian and Northern Hemisphere atmospheric dust load¹⁵.

Materials and methods

Sample collection

The sampling point was selected on the roof of the Film Environmental Protection Bureau building (43° 92' N, 81° 23' E, 125 m), approximately 15 m above the ground and 300 m away from the South Ring Road, with no factories or enterprises nearby. This sampling point can be considered representative of the thorough mixing of atmosphere and traffic flow in the downtown area of Dining. The sampling period for four PM_{2.5} samples was from June 2018 to July 2019. The glass fiber filter membrane was preheated at 450 °C for 4 h and then placed in a drying dish after cooling. A TH-150C medium-flow PM_{2.5} cutting head was used for sampling; the sampling flow rate was 100 L/min, and meteorological parameters such as on-site temperature and air pressure were recorded. After sampling, the filter membrane must be equilibrated in a constant temperature and humidity test chamber for 24 h before analysis.

Sample analysis

Using the Hitachi JSM-7500FSEM scanning electron microscope (SEM), the maximum resolution is 1.0 nm (15 kV) and 1.4 nm (1 kV). The magnification is 1000×, the working voltage is 20 kV, the acceleration current is 15 MA, and the working distance is 15 nm. The micromorphology and composition of the collected PM_{2.5} particles were analyzed. The glass fiber filter membrane itself interferes with the energy spectrum analysis. The premise of the energy spectrum analysis assumes that the laser only falls on the particles. To prepare the samples, use pollution-free stainless steel scissors to gently cut about 1/10 of each sample filter film. Fix it on the sample tray and cut out an appropriate size of conductive adhesive with stainless steel scissors. Paste the clipped filter film sample on the metal post in order with conductive adhesive, press it flat, place the metal column with the sample in the automatic ion sputtering instrument, and plate 20 nm thick gold under vacuum conditions. To improve the electrical conductivity of the sample, it must meet the requirements of electron microscope observation. Fix the metal column with the sample in the sample table, level it (ensuring the surface of the metal column is at the same level as the sample table), and note the fixing order of these samples. The sample table of the prepared sample was placed in the SEM for observation and analysis, with magnifications ranging from 1000 to 10,000 times.

PM_{2.5} concentration

See Table 1.

Result and analysis

Evaluation of ambient air quality for PM_{2.5}

Firstly, literature analysis was used in this study. Through literature collection, the development history of China's Air Quality Index and information resources were sorted out. The latest progress of China's AQI-related work was deeply analyzed, along with its evaluation indicators and classification concentration limits. Then, based on the Air Quality Index (IRAQI) and AQI calculation method given in the "Environmental Air Quality Index (AQI) Technical Regulations (Trial)" issued by the Ministry of Environmental Protection, the data on PM_{2.5} from June 2018 to July 2019 were statistically analyzed¹⁶. Secondly, one-fifth of the samples were weighed (see Figs. 1, 2), and then the concentration and AQI value of atmospheric particulate matter PM_{2.5} were calculated according to the formula; refer to Table 1.

Figure 1 illustrates the weight trend of the selected samples in 2018. It can be inferred from the figure that the weight of the samples decreased significantly in August, indicating a decrease in atmospheric particulate matter PM_{2.5} pollution and its impact. The weight of samples notably increased in November and December, suggesting high pollution levels of atmospheric particulate matter PM_{2.5} in December and February of the following year, with light pollution weather. Possible reasons for this include the lush trees in summer, which have

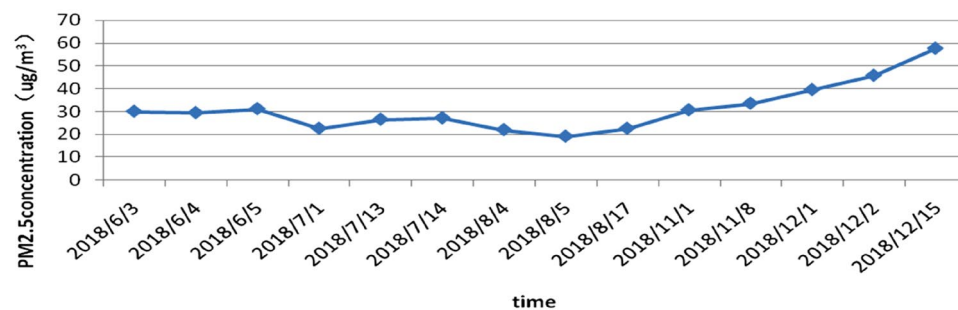


Figure 1. Trend of PM_{2.5} concentration in 2018.

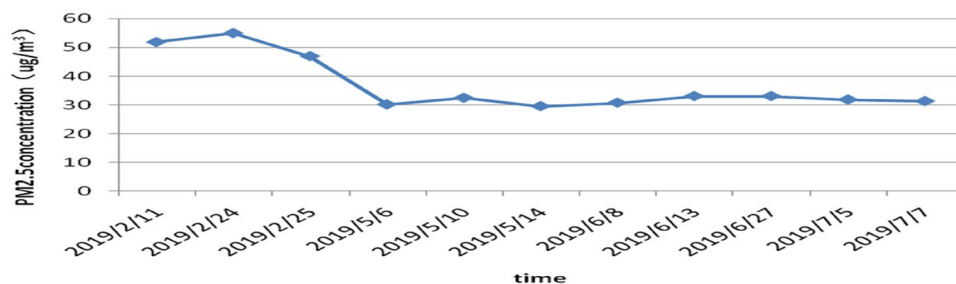


Figure 2. Trend of PM2.5 concentration in 2019.

Time	Weight (g)	PM2.5 concentration ³	QI	time	Weight (g)	PM2.5 concentration/Mme ³	AQI
Sample weight, concentration, and AQI statistical table							
2018/6/3	0.072	30.1	79.7	2018/12/2	0.082	45.9	91.1
2018/6/4	0.071	29.5	78.5	2018/12/15	0.098	57.8	102.2
2018/6/5	0.074	31.25	82.0	2019/2/11	0.088	51.8	85.2
2018/7/1	0.059	22.6	65.0	2019/2/24	0.093	54.9	99.5
2018/7/13	0.066	26.6	72.8	2019/2/25	0.083	46.9	86.5
2018/7/14	0.067	27.2	74.0	2019/5/6	0.072	30.1	85.0
2018/8/4	0.058	22.0	63.8	2019/5/10	0.076	32.4	84.3
2018/8/5	0.053	19.1	58.1	2019/5/14	0.071	29.5	78.6
2018/8/17	0.059	22.6	65.0	2019/6/8	0.073	30.7	81.0
2018/11/1	0.073	30.7	81.0	2019/6/13	0.077	33.0	85.4
2018/11/8	0.078	33.6	86.6	2019/6/27	0.077	33.0	85.4
2018/12/1	0.080	39.6	72.8	2019/7/5	0.075	31.8	83.1

Table 1. Sampling time, PM2.5 index, corresponding concentration value, and AQI value statistical table.

an adsorption effect on PM2.5, and the stable summer climate that prevents PM2.5 accumulation. Additionally, winter meteorological conditions hinder PM2.5 diffusion, leading to continuous accumulation near the ground due to increased ground inversion frequency, elevating PM2.5 content. Figure 2 displays the sample weight trend in 2019, showing a significant increase in February. This could be attributed to the low local temperature in February, which hinders diffusion. Additionally, the formation of a low-pressure air mass in February may impede PM2.5 dispersion.

Morphological characteristics of PM2.5

Morphological characteristics of PM2.5 in a non-heating period

To observe the microscopic morphology of PM2.5, scanning electron microscopy (SEM) was used to analyze the collected samples. Figure 3 displays SEM images of PM2.5 particles captured at various magnifications (1000–10,000 times). The figure includes images labeled as follows: a: 2018.6.5; b: 2018.7.13; c: 2019.5.6; d: 2019.5.10.

The particle morphology of PM2.5 observed by SEM is shown in Fig. 3. The fibers and their attachment to PM2.5 particles can be seen, and the fibers are quartz fiber filter membranes. As can be seen from the PM2.5 figures at different magnifications, PM2.5 particles do not adhere uniformly to the membrane surface but loosely to it, and the membrane voids are visible. A closer look reveals that PM2.5 particles are mostly long chains, with chain-like aggregates of soot generally coming from motor vehicle exhaust or coal-burning. The coal-burning fly ash is spherical; regular spheres are less common in chains. In the non-heating season, the central and residential heating boilers in Yining have all stopped working. The source of particulate matter may be mainly motor vehicle exhaust. Some scholars have studied Yining. There are irregular clumps attached to the long chain. Zhang Qianghua and others¹⁷ think the irregular clumps are mainly smoke-dust complexes, biomass, and primary minerals. Some researchers¹⁸ have studied the micro-morphology of PM2.5 in many cities of Guizhou and found that the irregular aggregates are mostly composed of sulfate. According to the references, the clumps are not the same in different areas. Further analysis of irregular clumps requires the combination of microscopic Raman spectroscopy and Chemometrics methods¹⁹, or TEM EDX²⁰ and aerosol time-of-flight mass spectrometry (ATO FMS) observations, which is my future research direction.

Morphological characteristics of PM2.5 in the heating season

Figure 4 shows the SEM images of PM2.5 particles collected at different magnifications (1000–10,000 times). Figures a: 2018.12.2; b: 2018.12.15; c: 2019.2.11; d: 2019.2.24.

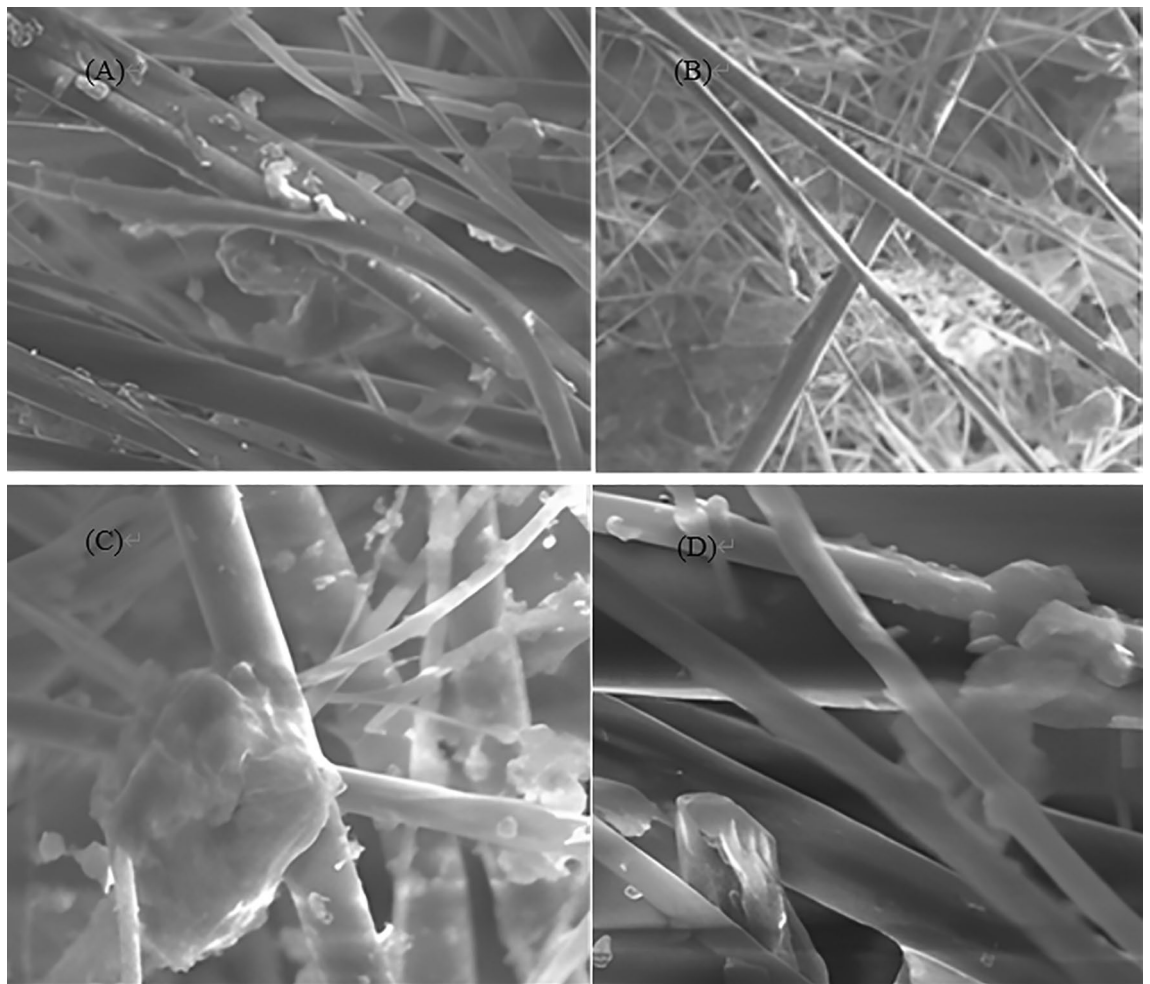


Figure 3. Microtomography of PM_{2.5} on non-polluted days.

Through SEM observation, the particle morphology characteristics of PM_{2.5} are depicted in Fig. 4. The glass fibers in the filter membrane adsorb particles with complex shapes, varying sizes, and different forms. The particles mainly exhibit a few large-volume long strips, small-volume irregular shapes, spherical particles (such as coal fly ash and tarball), oval shapes, cluster-like dust aggregates (chain, fluffy, and dense), flocculant, patellar and mineral particles (both regular and irregular), and other forms. Through SEM observation and comparison with literature data, ITIS concluded that the atmospheric particles in Yining City primarily consist of soot aggregates, coal-fired fly ash, motor vehicle exhaust dust, industrial dust, and other unidentified particles. Additionally¹⁶, temperature inversion is less likely to occur during non-heating periods, and more frequent rainfall and strong winds facilitate the dispersion and elimination of PM_{2.5}.

Compared with the scanning results during the non-heating period, on mild PM_{2.5} pollution days in Yining City, there was an increase in the number of spherical and chain particles. More bar or irregular block particles were detected, and some surfaces showed soot aggregates. In the classification of PM_{2.5} particles, they can be categorized into three types: large-volume elongated strips, small-volume cubes, and small-volume cubes with an amorphous structure. The elongated strips are primarily sourced from coal dust, vehicle exhaust dust, construction cement dust, industrial dust, soil dust, and road dust. The amorphous structure mainly originates from the characterization of secondary pollutants. The main reasons for this situation are as follows: firstly, the high concentration and intensity of local pollutant emissions, notably the significant increase in coal burning during the heating period; secondly, the rise in exhaust emissions from motor vehicles due to low temperatures, leading to an increase in the release of PM_{2.5} and its precursors (sulfur dioxide, nitrogen oxides, etc.); and thirdly, unfavorable meteorological conditions for the dispersion of atmospheric pollutants. The increased occurrence of ground temperature inversion in winter causes pollutants to continuously accumulate near the ground, resulting in the progressive buildup of PM_{2.5} from primary emissions and secondary conversion in the lower atmosphere, reaching high concentration levels.

Natalie Mahowald's research focuses on evaluating the relative contributions of different dust sources to the dust sink using an end-member mixed analysis model and constrained least squares methods to derive the proportion of dust in each sediment or dust sample. The comparison of model data is designed to produce a consistent view across different time scales and wider spatial and environmental domains. So far, most efforts

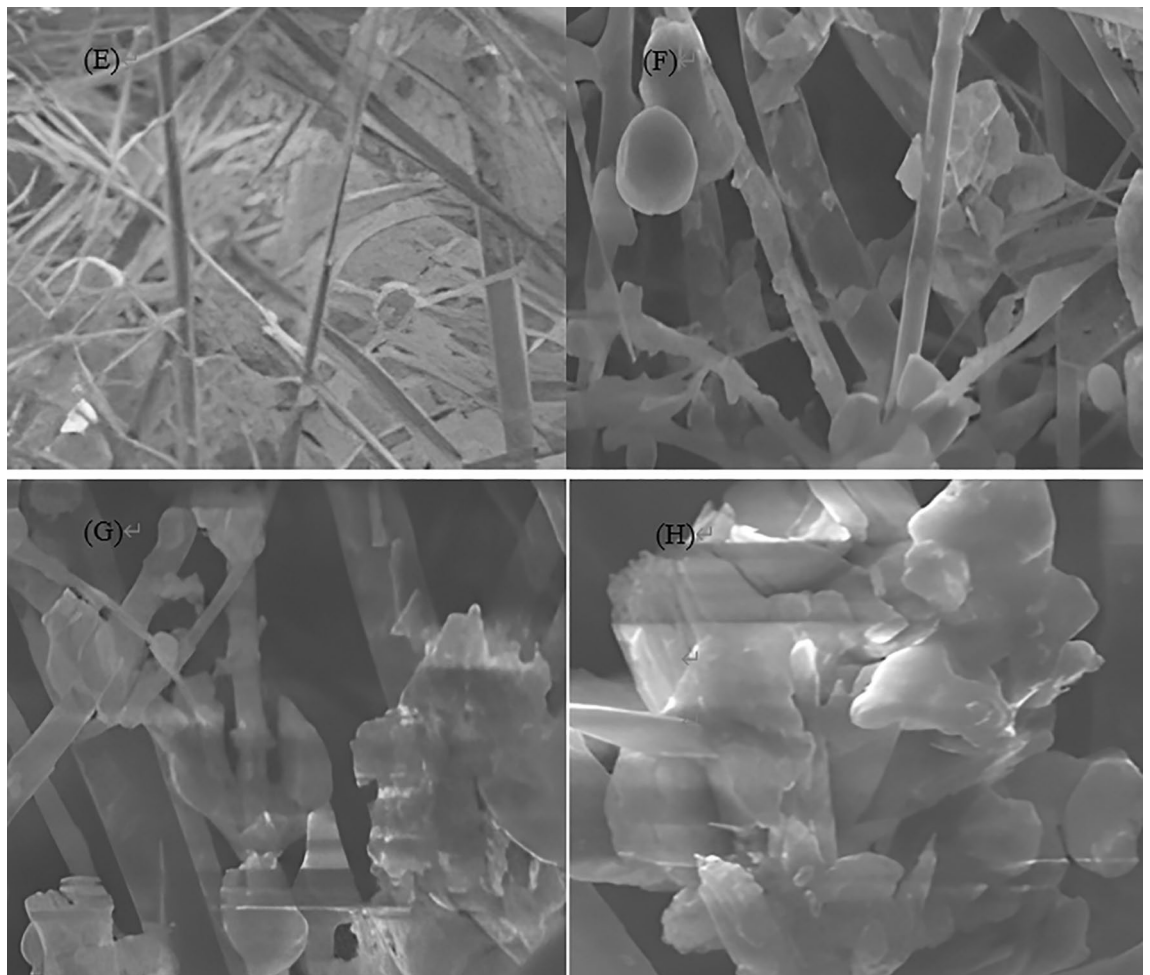


Figure 4. Microtomography of PM_{2.5} in light-pollution days.

have focused on emissions and airborne dust. These smaller particles (< 50 μm) are entrained into the boundary layer, from where they can be transported over long distances²¹. The continuous accumulation of pollutants near the ground in winter may be the common result of increased emissions of local pollutants, dust, and long-distance transport, which needs further study.

The chemical composition of PM_{2.5} was analyzed using energy spectrum analysis

To determine the composition of each element in the sample PM_{2.5} (refer to Fig. 5), this study conducted an energy spectrum analysis of the sample. In Figure (a): December 2, 2018, (b): February 11, 2019, and (c): June 8, 2019.

To understand the main chemical composition of PM_{2.5}, the sample's chemical composition was analyzed through energy spectrum scanning. The results revealed that the primary chemical components of PM_{2.5} included O, S, P, C, N, Na, Ge, Rb, Fe, Mg, Al, and others.

Table 2 displays the atomic percentages in the energy spectrum analysis diagram. The analysis reveals that element C has a higher atomic ratio, reaching up to 16.48% and 12.14% in (a) and (b) respectively. The dominance of coal combustion in the energy structure leads to the oxidation of hydrocarbon emissions from combustion, resulting in the production of various organic acids, polycyclic aromatic hydrocarbons, and other organic particles formed through homogeneous and heterogeneous nucleation. Some samples may lack certain elements, with no fixed pattern, possibly linked to automobile exhaust emissions and other urban pollution sources. It is theorized that gaseous NO_x and SO₂ emitted from vehicle exhausts enter the atmosphere and form through nucleation under specific physical chemistry conditions. Elements Na and Mg may be present in the form of soluble inorganic ions like Na⁺ and Mg²⁺, potentially originating from soil dust. Chlorine (Cl) is absent in the energy spectrum analysis, with its presence typically associated with combustion and serving as an indicator of industrial soot pollution characteristics. Yining's industrial enterprises are actively promoting clean energy and have made significant progress in controlling industrial soot emissions²².

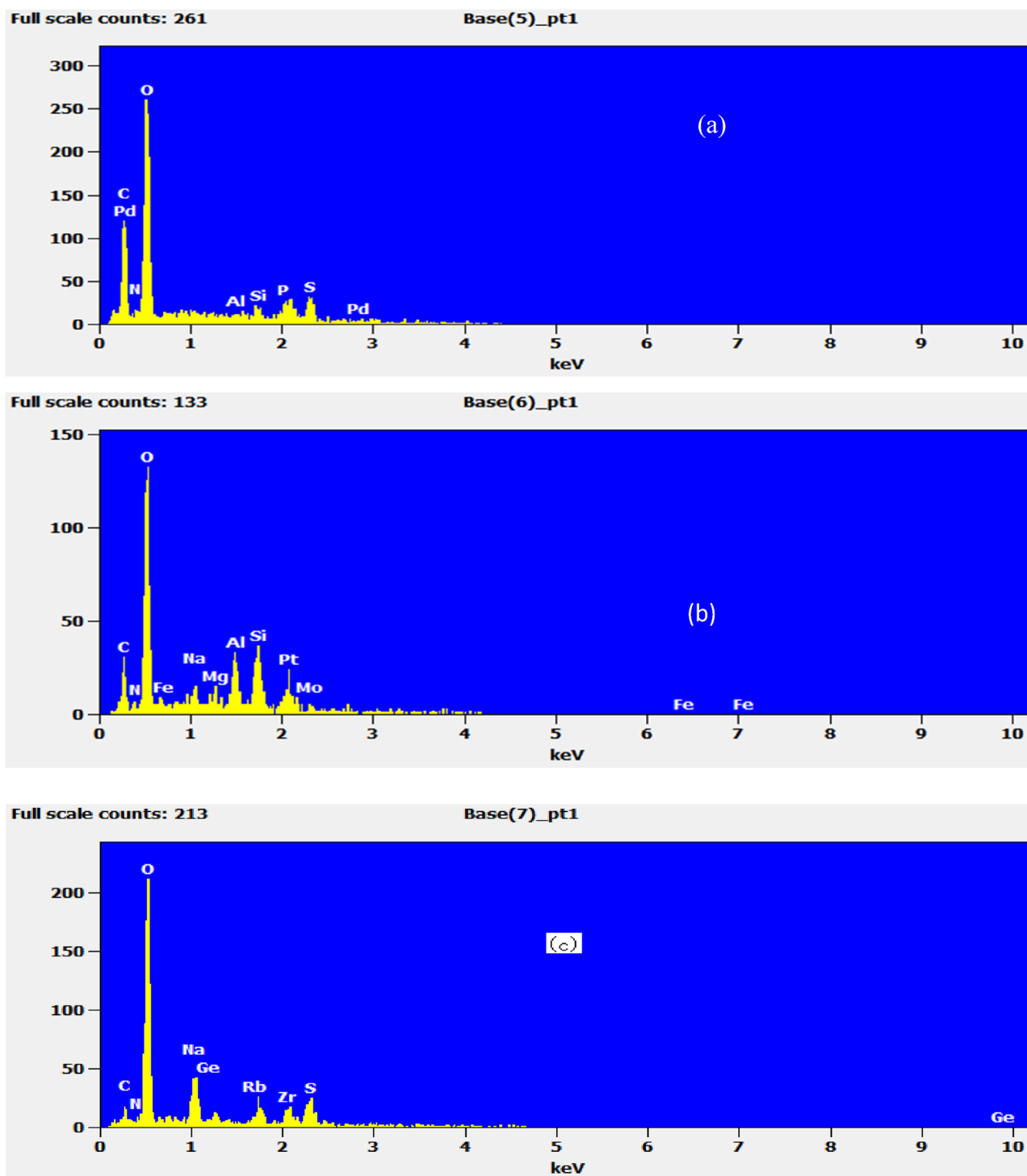


Figure 5. Energy Spectrum Analysis of Particulate Matter PM_{2.5}

Conclusions

PM_{2.5} is a significant threat to public health, and China prioritizes the regulation of PM_{2.5}. The aim of this research was to examine the morphological characteristics and primary components of PM_{2.5}. The study utilized scanning electron microscopy to observe and analyze the microscopic structure of fine particles in the atmosphere from 2018 to 2019. The findings revealed that during mildly polluted conditions, glass fibers intertwined to create a tubular film. Particulate matter loosely adhered to the glass film's surface, forming larger three-dimensional shapes, as well as smaller long strips and irregular shapes. The composition included over ten trace elements. Moreover, the adsorption rate notably increased in winter, suggesting that mild pollution in the urban area was primarily due to winter heating. Automobile exhaust emissions emerged as a significant pollution source in the urban area, and there might also be long-distance input of PM_{2.5}.

Element	Element percentage/%		
	(a)	(b)	(c)
C	16.48	12.14	8.48
O	60.15	57.26	62.06
Si	6.56	7.89	–
Na	–	4.38	9.45
Al	2.21	6.61	–
Mg	1.89	4.22	–
S	4.89	–	8.21

Table 2. Results of the Energy Spectrum Analysis Diagram.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 18 March 2024; Accepted: 7 August 2024

Published online: 24 January 2025

References

- Krpec, K. *et al.* Impact of boiler type, heat output, and combusted fuel on emission factors for gaseous and particulate pollutants. *Energy Fuels* **30**, 8448–8456. <https://doi.org/10.1021/acs.energyfuels.6b00850> (2018).
- Bile, J. *et al.* Ambient air quality measurement with low-cost optical and electrochemical sensors: An evaluation of continuous year-long operation. *Environments* **8**, 114. <https://doi.org/10.3390/environments8110114> (2021).
- Shi, Y. *et al.* Nanoscale characterization of PM_{2.5} airborne pollutants reveals high adhesiveness and aggregation capability of soot particles. *Sci. Rep.* **5**(3), 181–183. <https://doi.org/10.1038/srep11232> (2015).
- Silval, F., Moreno, T. & Query, X. An introductory TEM study of Fe-nano minerals within coal fly ash. *Sci. Total Environ.* **407**(17), 4972–4974. <https://doi.org/10.1016/j.scitotenv.2009.05.044> (2009).
- Salcedo, D. *et al.* Characterization of ambient aerosols in Mexico City during CMA-2003 campaign with Aerosol Mass Spectrometry: Results from the CENICA Supersize. *Atmos. Chem. Phys.* **6**(4), 925–946. <https://doi.org/10.5194/acp-6-925-2006> (2006).
- Bartosz, S. & Jacek, G. Commercially available chemical sensors employed for the detection of volatile organic compounds in outdoor and indoor air. *Environments* **4**, 21. <https://doi.org/10.3390/environments4010021> (2019).
- Birmili, W. *et al.* Micro-scale variability of urban particle number and mass concentrations in Leipzig, Germany. *Meteorol. Zeitschrift* **2**, 155–165. <https://doi.org/10.1127/0941-2948/2013/0394> (2013).
- Hui, Y. *et al.* Microscopic morphology and elemental composition of size-distributed atmospheric particulate matter in Urumqi China. *Environ. Earth Sci.* **69**, 2139–2150. <https://doi.org/10.1007/s12665-012-2043-y> (2013).
- Gautam, S. *et al.* Occupational exposure to particulate matter in three Indian opencast mines. *Air Dually Atmos. Health* **9**, 143–158. <https://doi.org/10.1007/s11869-014-0311-6> (2018).
- Song, F. & Yuan, G. Size distributions of trace elements associated with an ambient particular matter in the affinity of a major highway in the New Jersey-New York metropolitan area. *Atmos. Environ.* **45**, 6714–6723. <https://doi.org/10.1016/j.atmosenv.2011.08.031> (2011).
- Chen, Y. *et al.* Chemical composition, structural properties and source apportionment of organic macromolecules in atmospheric PM₁₀ in a coastal city of Southeast China. *Environ. Sci. Pollut. Res.* **24**(6), 5877–5887. <https://doi.org/10.1007/s11356-016-8314-5> (2019).
- Sun, Y. *et al.* Long-term real-time measurements of aerosol particle composition in Beijing, China: Seasonal variations, meteorological effects, and source analysis. *Atmos. Chem. Phys.* **15**, 14549–14591. <https://doi.org/10.5194/acp-15-10149-2015> (2015).
- Jansen-Turóczy, B. *et al.* Sampling and characterization of resuspended and respirable road dust. *J. Aerosol Sci.* **65**, 69–76. <https://doi.org/10.1016/j.jaerosci.2013.07.006> (2013).
- Li, L. *et al.* Uranium isotopic constraints on the provenance of dust on the Chinese Loess Plateau. *Aeolian Res.* **15**, 53–71. <https://doi.org/10.1130/G45130.1> (2014).
- Jiao, X., & Dong, Z. Uranium isotopic composition and constraints on the provenance of the Qinghai-Tibet Plateau's surface dust. *J. Geophys. Res. Earth Surf.* **127**, e2021JF006480. <https://doi.org/10.1029/2021JF006480> (2022).
- Siepká, D. *et al.* Combining Raman microspectrometry and chemometrics for determining quantitative molecular composition and mixing state of atmospheric aerosol particles. *Microchem. J.* **137**, 119–130. <https://doi.org/10.1016/j.microc.2017.10.005> (2018).
- Zhang, Q., Shi, Y., Li, D., *et al.* Micro-morphology character of PM₁₀ and its mineral composition in Nanjing typical areas. *Chin. J. Environ. Eng.* **04**, 527–531 (2008).
- Du, D. Microcosmic characteristics and sources of PM_{2.5} in typical acid rain cities of Guizhou Province. Guiyang: Guizhou University. <https://xueshu.baidu.com/usercenter/paper/show?paperid=746a14524845da2cbfaef9c40dd41b23> (2015).
- Smith, S. *et al.* Comparative study of single particle characterization by Transmission Electron Microscopy and time-of-flight aerosol mass spectrometry in the London atmosphere. *Atmos. Environ.* **62**, 400–407. <https://doi.org/10.1016/j.atmosenv.2012.08.028> (2012).
- Gonzalez, T. *et al.* Chemical and morphological characterization of TSP and PM_{2.5} by SEM-EDS, XPS, and XRD collected in the metropolitan area of Monterrey. *Mexico. Atmos. Environ.* **143**, 249–260. <https://doi.org/10.1016/j.atmosenv.2016.08.053> (2018).
- Mahowald, N. *et al.* The size distribution of desert dust aerosols and its impact on the Earth system. *Aeolian Res.* **15**, 53–71. <https://doi.org/10.1016/j.aeolia.2013.09.002> (2014).
- Li, Z., Zhou, J., Lu, N., *et al.* Research on characteristics and formation mechanism of Shijiazhuang PM_{2.5} pollution during and after heating period using SPAMS. *Sci. Technol. Eng.* **17**(14), 110–119. http://en.cnki.com.cn/Article_en/CJFDTotal-KXJS201714017.htm (2017).

Author contributions

In this study, Feng Hu was responsible for the experimental analysis, Xinglei Wang was responsible for the data collation, and Qi Li was responsible for the data statistics. Editor and three anonymous reviewers for their helpful comments and suggestions that largely improved the quality of the paper. Conceptualization: Feng HU has read and agreed to the published version of the manuscript.

Funding

Yili Prefecture Science and Technology Plan Project (YZ2022Y005).

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to F.H.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024