RESEARCH ARTICLE



Characteristics of fine particulate matter (PM_{2.5}) at Jinsha Site Museum, Chengdu, China

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Abstract

Air pollution is a serious threat to ancient sites and cultural relicts. In this study, we collected indoor and outdoor $PM_{2.5}$ samples and individual particles at the Exhibition Hall of Jinsha Site Museum in June 2020, and then the chemical components, sources, morphology, and mixing state of the fine particulate matter were analyzed. Our results show that the indoor and outdoor $PM_{2.5}$ concentrations at the Exhibition Hall were 33.3±6.6 and 39.4±11.4 µg m⁻³, respectively. Although the indoor and outdoor concentrations of OC and EC were close, the proportion of secondary organic carbon in OC outdoor (33%) was higher than that indoor (27%). The $PM_{2.5}$ was alkaline both indoors and outdoors, and the outdoor alkalinity was stronger than the indoor alkalinity. SNA (SO_4^{2-} , NO_3^{-} , and NH_4^+) was the dominant component in the water-soluble inorganic ions; Na^+ , Mg^{2+} , and Ca^{2+} were well correlated ($R^2 > 0.9$), and CI^- and K^+ were also highly correlated ($R^2 > 0.8$). Enrichment factor analysis showed that Cu (indoor) and Cd were the main anthropogenic elements and that Cd was heavily enriched. Principal components analysis showed that the main sources of $PM_{2.5}$ at Jinsha Site Museum were motor vehicles, dust, secondary sources, and combustion sources. The individual particles were classified as organic matter, S-rich, soot, mineral, and fly ash/metal particles, and most of these particles were internally mixed with each other. At last, we proposed pollution control measures to improve the air quality of museums and the preservation of cultural relicts.

Keywords Fine particulate matter · Chemical composition · Sources · Morphology · Jinsha Site Museum

Introduction

Particulate matter (PM) in the atmosphere is of widespread concern as a result of its impact on the Earth's climate, the environment, and human health (Jan et al. 2017; Lee et al. 2017; Martins and da Graça 2018). Meanwhile, the chemical species present in PM can also damage ancient buildings, cultural relicts, and archeological sites (Cao et al. 2005; Hu et al. 2015; Spezzano 2021). High concentrations of PM can

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cause cultural relicts to peel, corrode, break, and twist and may cause damage to buildings (Lazaridis et al. 2018; Zorpas and Skouroupatis 2016). There have been many studies on the sources of PM and the danger posed by its pollution to different types of museum. Hanapi and Din (2012) measured the concentrations of PM in several museums in Malaysia and found that the mass concentration of PM exceeded the indoor air quality limit and the standard for total suspended particles and PM₁₀ in Malaysia, threatening both human health and the country's cultural heritage. Kontozova Deutsch et al. (2008) found that the presence of tourists led to the accumulation of suspended PM inside some European churches and museums. Chianese et al. (2012) compared the mass concentrations of PM inside and outside the Museum of Capodimonte and found that dust and organic matter were transferred from the surrounding park into the museum by both the wind and the movement of tourists. Santis et al. (1992) measured the concentrations of indoor and outdoor air pollutants in the Uffizi Gallery in Florence and found that the indoor concentrations of HONO far exceeded the outdoor concentrations, which

may be a result of a heterogeneous reaction between the walls and the exposed surfaces of the cultural relicts.

According to previous studies, compared with PM_{10} (particles with the aerodynamic diameter smaller than 10 μm), PM_{2.5} (particles with the aerodynamic diameter smaller than 2.5 µm) is easier to enter display cases, deposit on objects, and thus soil the surface of cultural relicts (Wang et al. 2015; Janssen et al. 2013). At the same time, the fact that PM_{25} is more harmful to human health than PM_{10} has been reported by many studies (Lyu et al. 2017; Li et al. 2017a). In addition, most of the chemical components in PM are mainly distributed in $PM_{2.5}$ (Huang et al. 2016). Therefore, PM_{2.5} was usually taken as the key research target in many previous studies on the characteristics of air pollution in museums. For example, Zorpas and Skouroupatis (2016) found that the PM_{2.5} mass concentrations in the Cypriot Archeological Museum and the Byzantine Museum in Cyprus were high both outdoors and indoors and that the presence of tourists increased the mass concentration of indoor PM_{2.5}. Yang et al. (2009) showed that both indoor and outdoor PM_{2.5} concentrations in Han Yangling Museum were mainly secondary ions, such as sulfate, nitrate, and ammonium. The monitoring conducted in Plantin-Moretus Museum, Belgium, found that sulfur-rich particles were frequently observed indoors during summer, while calcium-rich and calcium- and silicon-rich particles were dominating during winter months (Gysels et al. 2002). The study on single particle analysis showed that the relative abundance of carbonrich particles inside the Royal Museum of Fine Arts, Belgium, was greater than outside (Krupińska et al. 2012). These results are of great value in understanding and evaluating the impact of atmospheric PM on cultural relicts in museums and on human health.

The Jinsha Site was announced as a National Key Cultural Relicts Protection Unit by the State Council of China in 2006, and Jinsha Site Museum is built on the original site. Unexplored cultural relicts-such as excavated and backfilled ivory, wild boar fangs, antlers, sunken wood, pottery, and jade-are all preserved at this site. The efficient preservation of these cultural relicts is important to studies of the ancient Shu civilization. However, Jinsha Site is located in Chengdu, one of the most polluted cities in China with an average annual $PM_{2.5}$ concentration of 43 µg m⁻³ in 2019. This PM_{2.5} concentration exceeded the first-level standard $(35 \ \mu g \ m^{-3})$ of the GB3095-2012 ambient air quality standard for China by >20% and was several times the World Health Organization guidelines $(10 \ \mu g \ m^{-3})$ for PM_{2.5}. Therefore, the impact of this high level of PM2 5 pollution on the indoor air quality of Jinsha Site Exhibition Hall deserves attention because it affects both the preservation of relicts and the site and the health of visitors. In addition, the chemical composition of PM is complex, and different components have different effects on different cultural relicts and human health. However, most previous studies have focused on just one type of particle or one class of PM, and few studies have reported a comprehensive determination of the overall chemical composition of PM.

In this study, we collected $PM_{2.5}$ and individual aerosol particles both indoor and outdoor of the Jinsha Site Exhibition Hall and analyzed the chemical components, sources, morphology, and mixing state of the particles. This information is important if we are to provide a better environment for the preservation of cultural relicts and a better visitor experience for tourists.

Materials and methods

Sampling site and sample collection

An indoor observation site was set up at the ivory site of Pit No. 1 at Jinsha Site Exhibition Hall. The outdoor site was located in the square outside the east gate of the Exhibition Hall, about 100 m from Chengdu's middle ring road.

Two TH-150C samplers (Wuhan Tianhong, China) were used to continuously collect indoor and outdoor PM_{2.5} in June, 2020. The samplers used a Pall quartz fiber filter membrane (d = 90 mm) and a flow rate of 100 L \min^{-1} . The sampling periods were 08:30–20:00 h and 20:30-08:00 h, respectively, for daytime and night-time sampling. Each sample was collected over a 11.5-h period. Four field blanks were also collected before and after the sampling period and analyzed at the same time as the PM_{2.5} samples. After sampling, the quartz filters were placed in individual petri dishes and stored at -20°C before weighing and subsequent PM2.5 chemical composition (including carbonaceous components, water-soluble inorganic ions, and trace elements) analysis. The air flow rate of the sampler was calibrated before the start of the collection period to ensure that the PM_{2.5} sampler worked at the specified flow rate.

Individual particles were collected on copper (Cu) transmission electron microscopy (TEM) grids coated with carbon film (carbon type-B, 300-mesh copper; Tianld Co., China) by a DKL-2 sampler (Genstar Electronic Technology, China). The sampler had a cascade impactor with 0.5 mm diameter jet nozzles at a flow rate of 1.0 L min⁻¹ (Li et al. 2016, 2020). The sampling duration varied from 45 to 300 s depending on the particle loading estimated from the pollution levels. The copper grids were placed in sealed, dry plastic capsules and stored in a desiccator at 25°C and $20 \pm 3\%$ relative humidity for subsequent TEM analysis.

Sample analysis and data processing

PM_{2.5} chemical and individual particle analysis

The two carbonaceous components—namely, organic carbon (OC) and elemental carbon (EC)—were determined according to the EPA/NIOSH (TOT) method using a Sunset Labs thermal/optical carbon aerosol analyzer. A Dionex ICS-90 ion chromatography system was used to determine eight water-soluble inorganic ions (SO_4^{2-} , NO_3^- , NH_4^+ , K^+ , Mg^{2+} , Ca^{2+} , Na^+ , and Cl^-). The concentrations of trace elements (Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, and Pb) were determined using an Agilent 7500a inductively coupled plasma mass spectrometer. More detailed information about the sample pretreatment, instrument optimization, and quality control methods are reported by Huang et al. (2021).

The individual particles were analyzed by TEM at an accelerating voltage of 200 kV using a JEOL JEM-2100 microscope coupled with an energy-dispersive X-ray spectrometer. Energy-dispersive X-ray spectrometry can detect elements with atomic weights heavier than C (such as C, O, Al, S, K, Ca, Fe, Si). The distribution of aerosol particles on the TEM grids was not uniform, with coarser particles occurring near the center and finer particles occurring on the periphery. Therefore, to make sure that the analyzed particles were representative of the entire size range, four areas were chosen from the center to the periphery of the sampling spot on each grid. A total of 950 and 1106 aerosol particles were collected indoors and outdoors, respectively.

Data analysis

Secondary organic carbon (SOC) SOC is formed by the photochemical reactions of volatile hydrocarbons (Wang et al. 2019a). The concentration of SOC can be obtained by:

$$SOC = OC - EC(OC/EC)_{min}$$

where OC is the concentration of OC ($\mu g m^{-3}$), EC is the concentration of EC ($\mu g m^{-3}$), and (OC/EC)_{min} is the lowest observed OC/EC ratio (Han et al. 2015).

Enrichment factor (EF) The EF method is an analytical technique proposed by Zoller et al. (1974) to express the degree of enrichment of an element in atmospheric particulates. The EF calculation can be used characterize the degree to which the concentration of an element is affected by human activity and therefore to determine whether the element is from a crustal, anthropogenic, or mixed source (Reimann and De Caritat 2000). The formula is:

$$EF = (Ci/C_{reference})_{sample}/(Ci/C_{reference})_{crust}$$

where $(Ci/C_{reference})_{sample}$ is the ratio of the trace element to the reference element in PM_{2.5} and $(Ci/C_{reference})_{crust}$ is the ratio of the trace element to the reference element in the Earth's crust (Nayebare et al. 2018). An EF < 10 is indicative of a significant crustal source with a negligible influence from anthropogenic source; if 10 < EF < 100, then this element is mainly from mixed source (crustal and anthropogenic source), whereas EF > 100 indicates that all of this element is derived from human activity—that is, it has an anthropogenic source (Chan et al. 1997; Sutherand 2000).

Results and discussion

PM_{2.5} mass concentration

The average mass concentration of PM2.5 was slightly higher outdoors than indoors during the whole study period, with average values of 39.4 \pm 11.4 and 33.3 \pm 6.6 µg m⁻³, respectively (Fig. 1). The outdoor sources of PM_{2.5} are complex and include contributions from motor vehicles, biomass burning, coal combustion, cooking, road dust, industrial sources, and pollutants transported from the areas surrounding Chengdu (Li et al. 2017b; Tao et al. 2014). There is no obvious source of indoor PM2.5 emissions, and therefore this PM2.5 was mainly sourced from outside, although the semi-closed structure of the Exhibition Hall (especially during the closed period at night) reduced the transmission of pollutants to the interior. These results are similar to those found in previous studies of the five great civilization museums of the Yangtze River (Hu et al. 2015). The difference between the indoor and outdoor concentrations of PM2 5 in our study was much lower than that reported by Li et al. (2014a) in the Pottery Depot of the Terracotta Warriors and Horses Museum of Qin Shihuang (indoor, 62.8 μ g m⁻³; outdoor, 113.4 μ g m⁻³). This can be attributed that the semi-enclosed nature of the Jinsha Site Exhibition Hall, especially during the daytime, when there is a continuous air exchange between indoors and outdoors. By contrast, the Pottery Depot of the Terracotta Warriors and Horses Museum is almost completely enclosed, which effectively limits the transmission of pollutants from outdoors to



Fig. 1 Indoor/outdoor and open/closed days PM2.5 mass concentrations.

indoors. The difference in PM_{2.5} mass concentrations between indoors and outdoors was significantly increased on days when the Exhibition Hall was closed, with differences of 17.0±5.1 μ g m⁻³ when it was closed and 3.5±6.0 μ g m⁻³ when it was open. This further illustrates the important role of air exchange between indoors and outdoors in the transmission of air pollution at Jinsha Site Exhibition Hall.

The outdoor PM_{2.5} mass concentration during the daytime (40.9±6.3 μ g m⁻³) was slightly higher than that at night (38.0 ±14.8 μ g m⁻³). By contrast, the indoor PM_{2.5} mass concentrations during the daytime (33.7±5.7 μ g m⁻³) and night-time (32.9±7.3 μ g m⁻³) were similar. A comparative study found that when the museum was closed during the daytime, the average indoor PM_{2.5} mass concentration was 29.8±3.0 μ g m⁻³, which is lower than the average PM_{2.5} mass concentration of 34.6±5.8 μ g m⁻³ when the museum was open during the day and also lower than that at night (32.6±7.3 μ g m⁻³). Human activity during the days when the museum was open may be an important reason for the increase in PM_{2.5} mass concentration between day and night was also seen at the Emperor Qin's Terra-cotta Museum (Hu et al. 2009).

It must been noted that our study was carried out during the coronavirus disease 2019 pandemic period, when the museum adopted a single-day flow limit of 1000 people. The number of visitors was therefore significantly less than before the pandemic, and the impact of human activities on the indoor air quality was greatly reduced.

Chemical composition of PM_{2.5}

Carbonaceous component

The OC in the atmosphere can be divided into primary OC emitted directly by primary emission sources (including natural and anthropogenic sources) and SOC formed through oxidation of reactive organic gases followed by gas-to-particle conversion processes in the atmosphere (Bozzetti et al. 2016; Huang et al. 2014; Gelencsér 2004). The EC is mainly derived from the incomplete burning of fossil fuels and biomass (Luo et al. 2021). The difference between the indoor and outdoor concentrations of OC was $0.6\pm 2.4 \ \mu g \ m^{-3}$ throughout the observation period, whereas the difference in EC was $0.1 \pm 0.4 \ \mu g \ m^{-3}$ (Fig. 2). The concentrations of carbonaceous components were similar in the two environments as a result of the frequent air exchange between indoors and outdoors.

The OC/EC ratio is generally considered to be an important indicator of the source of $PM_{2.5}$. SOC is considered to be present when the OC/EC ratio is >2 (Chatterjee et al. 2021). In our study, the outdoor and indoor OC/EC ratios at the Exhibition Hall were 5.9 and 5.7, respectively, clearly indicating the presence of SOC. Meanwhile, the proportion of outdoor SOC in OC (33%) was higher than that of indoor (27%).



Fig. 2 Indoor and outdoor concentrations of carbon components (OC, EC, SOC) of $\text{PM}_{2.5}$

In addition, the indoor concentrations of OC, EC, and SOC were similar during the night $(7.7\pm1.2, 1.5\pm0.3, \text{ and } 1.6\pm0.8 \ \mu\text{g m}^{-3}$, respectively) and during the day $(7.3\pm0.7, 1.2\pm0.2, \text{ and } 1.5\pm0.9 \ \mu\text{g m}^{-3}$, respectively). The outdoor concentrations of EC were similar during the day and night $(1.4\pm0.5 \text{ vs. } 1.3\pm0.3 \ \mu\text{g m}^{-3})$, whereas OC was lower during the night $(7.1\pm1.7 \ \mu\text{g m}^{-3})$ than during the day $(9.2\pm2.7 \ \mu\text{g m}^{-3})$.

Water-soluble inorganic ions

Water-soluble inorganic ions (WSIIs) are important components of PM2.5 and can contribute to haze pollution (Wu et al. 2018). The indoor and outdoor average mass concentrations of WSIIs were 13.2 \pm 5.5 and 13.2 \pm 6.0 µg m⁻³, accounting for 39.3 and 33.5%, respectively, of the total PM_{2.5}. Among the WSIIs, SO_4^{2-} , NO_3^{-} , and NH_4^+ (SNA) were the dominant ion components, accounting for 69.9 and 59.2% of the total indoor and outdoor WSIIs, respectively (Fig. 3). The SNA components were mainly derived from the secondary conversion of their gaseous precursors (e.g., SO₂, NO_x, and NH₃) (Xie et al. 2020). The concentrations of SO_4^{2-} , NO_3^{-} , and NH_4^{+} were as follows: indoor, 5.3 ± 2.4 , 0.7 ± 0.7 , and 3.2 ± 2.4 µg m⁻³, respectively, and outdoor, 4.5±2.1, 0.6±0.5, and 2.8 $\pm 1.7 \ \mu g \ m^{-3}$, respectively. Ca²⁺ is a typical tracer of soil and construction dust (Liu et al. 2017), and its indoor concentration $(1.3\pm0.7\mu g m^{-3})$ was lower than the outdoor concentration (2.3 \pm 2.1 µg m⁻³). This is because the outdoor sampling site was located in the center of a square with a much higher contribution from soil dust. In addition, the indoor (0.5 ± 0.3)



Fig. 3 Indoor and outdoor WSIIs compositions

and 0.1±0.1 μ g m⁻³) and outdoor (0.6±0.3 and 0.2±0.2 μ g m⁻³) concentrations of K⁺ and Mg²⁺ were both similar.

 $PM_{2.5}$ acidity We used the ratio of the anion and cation equivalents to calculate the acidity of the indoor and outdoor $PM_{2.5}$ (Cheng and Zhang 2017):

$$\begin{split} AE &= [CI^{-}]/35.5 + \left[SO_{4}^{2-}\right]/48 + [NO_{3}^{-}]/62 \\ CE &= [\ Na^{+}]/23 + [NH_{4}^{+}]/18 + [K^{+}]/39 + \left[Mg^{2+}\right]/12 + \left[Ca^{2+}\right]/20 \end{split}$$

where AE represents the anion equivalent in the sample and CE represents the cation equivalent in the sample.

The calculation shows that the indoor and outdoor ratios of AE/CE were 0.53 and 0.38, respectively, indicating that both the indoor and outdoor $PM_{2.5}$ were alkaline. The outdoor $PM_{2.5}$ was more alkaline than the indoor $PM_{2.5}$, consistent with the higher alkaline ions concentrations in the observations and the differences between the indoor and outdoor concentrations. These results are also consistent with those at the Qianhu Campus of Nanchang University (Huang et al. 2012). Previous studies have shown that both alkaline or acidic particles could cause serious damage to cultural relicts and affect their color (Hu et al. 2015; Mašková et al. 2017). Moreover, these particles could cause serious harm to human skin and respiratory system (Nowatzki 2008).

The existing forms of SNA The main component of WSIIs is SNA, and the existing form of SNA is important in the analyses of the formation of PM2.5 pollution. Previous studies have shown that NH4⁺ usually preferentially combines with SO_4^{2-} to form (NH₄)₂SO₄ or NH₄HSO₄, and then the remaining NH₄⁺ will combine with NO₃⁻ to form NH₄NO₃ (Li et al. 2017; Wang et al. 2019b). The regression equations for NH_4^+ and SO_4^{2-} at the indoor and outdoor monitoring points were v = 3.5641x - 0.0201 and y = 3.2919x + 0.002, respectively. The slopes were both >2, indicating that the SO_4^{2-} in both the indoor and outdoor atmosphere combined with NH₄⁺ to generate (NH₄)₂SO₄, and there was some excess NH₄⁺ remaining. The further linear fitting of the indoor and outdoor NH_4^+ and $NO_3^{-} + 2SO_4^{2-}$ concentrations showed that the slopes of the indoor and outdoor regression equations were both >1 (1.8 and 1.6, respectively), indicating that the NH₄⁺ combined with SO_4^{2-} and NO_3^{-} and there was some excess NH_4^{+} remaining. Both the indoor and outdoor NH_4^+ mainly existed as $(NH_4)_2SO_4$ and NH_4NO_3 , and the excess NH_4^+ was available to combine with other anions (such as Cl^{-}).

Ion correlation The Pearson correlation analysis was carried out on the WSIIs in the indoor and outdoor $PM_{2.5}$, and the results were very similar. We therefore use the results for the outdoor $PM_{2.5}$ in further discussions. Table 1 shows that the correlation coefficients (R^2) between the SNA components were >0.5, consistent with their similar mechanisms of formation (secondary reactions). The correlation coefficients (R^2) between Na⁺, Mg²⁺, and Ca²⁺ were all >0.9, indicating that these three ions have a high homology, closely related to their sources in soil and construction dust (Huang et al. 2018; Liu et al. 2017; Yu et al. 2020). Cl⁻ and K⁺ also showed a strong correlation ($R^2 > 0.8$), which may be related to contributions from combustion sources, such as coal combustion and biomass burning.

Trace elements

The total outdoor concentration of trace elements was slightly higher than the indoor concentration throughout the study period, with average values of 4.0 ± 1.7 and $2.7\pm0.5 \ \mu g \ m^{-3}$, respectively. The total contribution of Al and Fe accounted for 85.9 and 86.8% of the outdoor and indoor trace elements, respectively (Fig. 4).

We used Al as a reference element to calculate the EF of trace elements in $PM_{2.5}$ (Table 2). Apart from Cu, which had a mixed source outdoors and an anthropogenic source indoors, there was no difference in the degree of enrichment of other trace elements, and they had the same level of enrichment both indoors and outdoors. Al, V, Mn, Fe, and Co had a crustal source; Cr, Ni, Cu (outdoor), Zn, As, and Pb had a mixed source; and Cu (indoor) and Cd had an anthropogenic source. The EF value of Cd both indoors and outdoors was >100, and almost all the Cd was from human activity.

Principal components analysis (PCA)

PCA was performed with the chemical components quantified in the PM_{2.5} filters to identify the main sources of PM_{2.5} at the Jinsha Site. We used the outdoor observations for source analysis because there is no unique indoor emission source in the Jinsha Site Exhibition Hall, and the indoor PM_{2.5} is mainly from the transmission of outdoor air pollutants. Table 3 shows that the cumulative contribution rate of the four principal components reached 82.1%, and we therefore assume that these components represent the main sources of PM_{2.5}.

In factor 1, the OC, EC, Al, Mn, Fe, Ni, Cu, Zn, As, Cd, and Pb had higher loading values, and the variance explanation ratio reached 36.4%. The OC mainly comes from combustion sources such as fossil fuels (Cao et al. 2006). The EC mainly comes from tailpipe exhaust fumes and is attributed to poor vehicle maintenance (Song et al. 2006). Zn, Cu, and Pb come from the mechanical wear of motor vehicles, gasoline combustion, and tire wear (Hou et al. 2019), whereas Ni is characteristic of fuel combustion (Fan et al. 2021). Factor 1 can therefore be comprehensively identified as sourced from motor vehicles.

	Na ⁺	$\mathrm{NH_4}^+$	K ⁺	Ca ²⁺	Mg ²⁺	Cl	NO_3^-	$\mathrm{SO_4}^{2-}$
Na ⁺	1	0.102	0.344	0.999**	0.907**	0.469*	0.159	0.112
$\mathrm{NH_4}^+$		1	0.289	0.102	-0.013	0.188	0.857**	0.738**
K^+			1	0.327	0.128	0.821**	0.320	0.154
Ca ²⁺				1	0.921**	0.451*	0.146	0.119
Mg ²⁺					1	0.256	-0.064	0.053
Cl						1	0.359	0.207
NO_3^-							1	0.518*
$\mathrm{SO_4}^{2-}$								1

 Table 1
 Correlation coefficients among WSIIs in outdoor PM_{2.5} at the Jinsha Site Museum.

**Correlation significant at $p \le 0.01$

*Correlation significant at $p \le 0.05$

The loading values of Ca²⁺, Mg²⁺, Na⁺, V, Cr, and Co were higher in factor 2, and the variance explanation ratio was 22.1%. Ca2+ generally comes from soil dust or building construction. Mg²⁺ mainly comes from soil (Cao et al. 2006). Na⁺ can come from dust or industrial smelting, such as steelmaking (Han et al. 2007; Silva et al. 2000). V may be derived from soil, wind, or sand (López et al. 2011). Cr may be derived from cement production dust or the metallurgical industry (Li et al. 2021). Co is characteristic of the metallurgical chemical industry (Hsu et al. 2021). V, Cr, and Co may originate from the formation of industrial dust, indicating that the dust sources are mixed with soil, sand, construction, and industrial dust. Liang et al. (2018) reached a similar conclusion in the analysis of PM2.5 fugitive dust sources in Guivang. Factor 2 can therefore be identified as a source of dust.

Factor 3 was dominated by SNA components, and the variance explanation ratio was 14.4%. The main source of SNA is the secondary conversion of gaseous pollutants (SO₂, NO_x, and NH₃) (Tang et al. 2021). This is consistent with the results of Huang et al. (2021) that secondary sources are related to SNA. Factor 3 can therefore be identified as a secondary source.

The characteristic elements in factor 4 were K⁺ and Cl⁻, and the variance explanation ratio was 9.3%. K⁺ and Cl⁻ are indicators of biomass combustion and coal combustion, respectively (Luo et al. 2018). Therefore this factor can be identified as a combustion source. Boman et al. (2004) analyzed PM from the residential combustion of pelletized biomass fuels and found that KCl was the dominant inorganic phase, consistent with our results.

Classification and mixing state of individual particles

In our study, all the individual particles measured by TEM were classified as five major aerosol components based on their morphology and elemental composition (Li and Shao 2009): organic matter (OM); S-rich, soot, mineral, and fly ash/metal particles (Fig. 5). The morphology of the OM particles was stable under irradiation from the TEM electron beam. The OM particles were mainly composed of C and O, and their morphology was either regular spherical and irregular. In addition, there were semi-dome-like OM particles, mainly in the form of organic coatings. The S-rich particles were more sensitive to the TEM electron beam and were prone to sublimation. Therefore the S-rich particles had a foam-like



Fig. 4 Compositions of trace elements in indoor and outdoor $PM_{2.5}$.

Table 2 Enrichment factors (EF) for trace elements.

EF	Al	V	Cr	Mn	Fe	Со	Ni	Cu	Zn	As	Cd	Pb
Outdoor	1	1	37	2	1	2	27	66	74	18	573	39
Indoor	1	1	12	2	1	1	24	130	70	24	452	23

structure, and the main elements were C, O and S. Soot particles, derived from the incomplete combustion of fuels and other sources, were composed of C and O, mainly chains or clusters of carbon spheres. The mineral particles were regular rectangular or angular irregular in shape. Because they mainly come from construction and ground dust, the particles were mainly composed of C, O, S, and Ca and also contained small amounts of crustal elements such as Fe and Al. The fly ash/ metal particles had a very small particle size and smooth surfaces and mainly came from industrial activities. The main elements were C, O, and Si and metals such as Fe and Zn.

Pósfai and Buseck (2010) described the mixing state of an aerosol particle including externally mixed (separated in the

Table 3 Rotation factor load

air) and internally mixed (an aggregate of different phases). Through the analysis of the mixing state of particles, the sources and formation mechanism of them can be analyzed (Li et al. 2014b). In this study, most of the particles existed in the form of internal mixing and presented a variety of mixed forms (Fig. 6). According to the mixing state of particles, we can infer their sources and formation mechanism in the atmosphere. For example, the pre-existing OM particles in the atmosphere can provide a reaction interface for the condensation of gaseous precursors, such as SO₂, and heterogeneous reactions, which favors the formation of OM-S particles (Fig. 6a, b). Mineral particles are rich in alkaline substances, and their surface is an important interface for secondary reactions of acidic gaseous pollutants (SO_2, NO_x) to form mixed particles of mineral dust and sulfate (Fig. 6i). Although the contribution of metal particles in PM2.5 was low, it has been the focus of previous studies. This is because metals present a serious threat to human health and involved in the formation of some PM_{2.5} species, such as OM and sulfate. Fig. 6 c, d, e, and g show that the fly ash/metal particles were widely mixed with other types of particle.

matrix of chemical components in	Components	Factor 1	Factor 2	Factor 3	Factor 4
outdoor $PM_{2.5}$.	OC	0.809	-0.220	0.072	0.260
	EC	0.456	-0.260	0.650	0.318
	Na ⁺	-0.097	0.876	0.090	0.301
	NH4 ⁺	-0.049	-0.033	0.948	0.127
	K ⁺	-0.076	0.125	0.200	0.895
	Ca ²⁺	-0.081	0.889	0.090	0.279
	Mg ²⁺	0.063	0.960	-0.032	0.062
	Cl	0.050	0.291	0.170	0.842
	NO ₃ ⁻	-0.077	-0.084	0.838	0.301
	SO_4^{2-}	0.131	0.113	0.843	-0.056
	Al	0.934	0.198	0.003	-0.062
	V	0.352	0.857	-0.157	-0.087
	Cr	0.125	0.909	-0.073	-0.035
	Mn	0.908	0.366	-0.078	-0.001
	Fe	0.878	0.009	0.097	-0.080
	Co	0.404	0.543	-0.066	0.039
	Ni	0.807	0.234	-0.040	0.050
	Cu	0.894	-0.104	-0.158	0.114
	Zn	0.715	0.121	-0.370	0.061
	As	0.830	0.147	0.175	-0.075
	Cd	0.901	0.060	0.214	-0.163
	Pb	0.927	0.048	0.222	-0.107
	Characteristic value	8.011	4.853	3.164	2.043
	Variance contribution rate (%)	36.413	22.059	14.380	9.288
	Cumulative variance contribution rate (%)	36.413	58.472	72.852	82.140
	Source	Motor vehicles	Dust	Secondary sources	Combustion sources



Fig. 5 TEM images of different types of particle.



Fig. 6 TEM images of individual mixed particles.

Conclusions and suggestions

In order to investigate the characteristics of atmospheric particulate pollution in Jinsha Site Museum, we collected indoor and outdoor PM_{2.5} samples and individual particles at the Exhibition Hall of Jinsha Site Museum in June 2020, and then the chemical components, sources, morphology, and mixing state of the fine PM were analyzed. The results show that the indoor and outdoor PM2 5 mass concentrations at Jinsha Site Exhibition Hall were 33.3 ± 6.6 and $39.4\pm11.4 \ \mu g \ m^{-3}$, respectively. The opening and closing of the museum had an important impact on indoor and outdoor PM2 5 concentration levels. The indoor and outdoor OC/EC ratios were both >2, and their $PM_{2.5}$ were both alkaline. SO_4^{2-} , NO_3^{-} , and NH_4^+ (SNA) were the dominant ion components, accounting for 69.9 and 59.2% of the total indoor and outdoor WSIIs, respectively. The main sources of PM2 5 at Jinsha Site Museum were motor vehicles, dust, secondary sources, and combustion sources. All individual particles were classified as OM, S-rich, soot, mineral, and fly ash/metal particles. Most of these particles were internally mixed with each other, which is crucial in analyzing the sources and mechanism of formation of particles in the atmosphere.

In order to improve the air quality of Jinsha Site Museum and provide better preservation and sightseeing environment for cultural relicts and tourists, we put forward the following suggestions for improving the air quality based on the results of this study. Firstly, to reduce the outdoor pollution sources, the dust on the bare ground around the Exhibition Hall should be reduced by spraving with water, and the area of greening around the Exhibition Hall could be further improved by planting taller trees to block the transfer of pollutants from the surrounding areas. Secondly, to reduce indoor pollution, the air tightness of the Exhibition Hall should be improved and the air exchange between indoors and outdoors reduced by a curtain system at the entrance and exit. Air purification equipment should be installed to remove the existing indoor pollutants. Green building materials should be used for secondary decoration to reduce potential sources of indoor pollutants.

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution J. L. Deng, L. M. Jiang, and J. K. Zhang designed the research. J. L. Deng, L. M. Jiang, W. W. Miao, J. K. Zhang, G. M. Dong, K. Liu, and J. C. Chen conducted the experiments. J. L. Deng, J. K. Zhang, T. Peng, Y. Fu, Y. P. Zhou, X. Huang, and M. Q. Hu analyzed the data. J. L. Deng and J. K. Zhang wrote the paper. J. L. Deng, J. K. Zhang, F. Wang, and L. Xiao reviewed and commented on the paper.

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Declarations

Ethics approval and consent to participate Not applicable

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