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Short- and long-term impacts of the COVID-19 epidemic on urban PM$_{2.5}$ variations: Evidence from a megacity, Chengdu

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HIGHLIGHTS

- Long-term impacts of the COVID-19 epidemic on urban PM$_{2.5}$ were analyzed.
- Emissions from transportation and industry reduced in the post-epidemic era.
- PM$_{2.5}$ concentration significantly dropped over workdays and holidays in the post-epidemic era.
- PM$_{2.5}$ concentration conversely increased during the Dragon Boat Festival in the post-epidemic era.

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ABSTRACT

As the new coronavirus pandemic enters its third year, its long-term impact on the urban environment cannot be ignored, especially in megacities with more than millions of people. Here, we analyzed the changes in the concentration levels, emission sources, temporal variations and holiday effects of ambient fine particulate matter (PM$_{2.5}$) and its chemical components in the pre- and post-epidemic eras based on high-resolution, long time-series datasets of PM$_{2.5}$ and its chemical components in Chengdu. In the post-epidemic era, the PM$_{2.5}$ concentration in Chengdu decreased by 7.4%, with the components of PM$_{2.5}$ decreasing to varying degrees. The positive matrix factorization (PMF) results indicated that the emissions from soil dust and industrial production were significantly lower during the COVID-19 lockdown period and post-epidemic era than those in the pre-epidemic era. In contrast, the contribution of secondary aerosols to PM$_{2.5}$ during these two periods increased by 2.7% and 6.6%, respectively. Notably, we found that PM$_{2.5}$ and its components substantially decreased on workdays and holidays in the post-epidemic era due to the reduced traffic volume and outdoor activities. This provides direct evidence that changes in the habitual behavior patterns of urban residents in the post-epidemic era could exert an evident positive impact on the urban environment. However, the higher PM$_{2.5}$ concentration was observed due to the increased consumption of regular (As$_4$S$_4$, Xionghuang in Chinese) and “sulfur incense” during the Dragon Boat Festival holiday in the post-epidemic era. Finally, we examined the potential effects of sporadic COVID-19 outbreaks on the PM$_{2.5}$ concentration in Chengdu, and there was no decrease in PM$_{2.5}$ during two local COVID-19 outbreak events due to the strong influence of secondary pollution processes.

1. Introduction

The COVID-19 pandemic broke out in China in late 2019 and has caused over 0.4 billion global infections and more than 60 million deaths as of this writing (https://coronavirus.jhu.edu/data, last accessed: May 1, 2021). To contain the spread of COVID-19 in China, a series of lockdown steps have been implemented to reduce human interaction since January 23, 2020, including enforcing strict quarantines, restricting private and public transportation, and encouraging social distancing. These prevention and control measures have achieved...
preliminary results in China, and the COVID-19 epidemic has been largely contained 30 days after the outbreak. As the epidemic has mostly remained under control in China, lockdown measures have been gradually canceled, people living in cities have increasingly started returning to their original lifestyles, and China has entered the post-epidemic era. In the post-epidemic era, the Chinese government has adopted the dynamic zero-COVID-19 strategy to minimize the negative influence on socio-economic activities stemming from coronavirus outbreaks. There is no doubt that the dynamic zero-COVID-19 policy in the post-epidemic era will inevitably affect the normal living habits of the population, especially urban residents. However, it remains unclear whether this dynamic zero-COVID-19 strategy will impact the urban environment.

To date, the short-term reduction effect of air pollutants during the COVID-19 lockdown period has been widely reported, particularly in the vehicular traffic and industrial sector (He et al., 2020; Kerr et al., 2021; Le et al., 2020; Selvam et al., 2020; Venter et al., 2020; Wang et al., 2020; Zhang et al., 2021). However, as the coronavirus pandemic enters its third year, its long-term impact on the environment cannot be ignored, especially in megacities with millions of people. Firstly, the COVID-19 epidemic has dramatically changed the work styles of urban residents. For example, teleworking has been increasingly popular in the post-epidemic era because it may avoid unnecessary human contact and reduce the risk of infection. Surprisingly, teleworking is also a major benefit to air quality improvement because it could be an effective approach to reduce traffic volume during peak time and improve air quality in a short term (days–weeks), particularly in urban areas, where high population density and the hotspots for traffic emissions have been found (Badia et al., 2021). Secondly, the lives and habitual behavior patterns of people can be impacted by the COVID-19 epidemic, e.g., the consumption and travel willingness of people during the holidays in the post-epidemic era have significantly decreased (O’Garra and Fouquet, 2022). Evidence has demonstrated that when habitual behavior patterns are disrupted, this can lead to long-term sustainable behavior changes (Brown et al., 2003; Verplanken and Roy, 2016). Nevertheless, whether a shift in habitual behavior patterns in the post-epidemic era could lead to long-term sustainable changes in the urban environment remains unknown.

Chengdu is the largest megacity in Sichuan Province, with an area of 14,335 km² and a population of over 20 million (Chengdu Statistical Yearbook, 2021). Chengdu is both the main industrial center of Sichuan Province and Southwest China, hosting staple industries including steelmaking, coal-fired power plants, automobile manufacturing, and aircraft production, and petrochemicals (Chengdu Statistical Yearbook, 2021). Higher population density, car ownership and industrial emissions intensity have made Chengdu one of the most polluted cities in China (Mao et al., 2019). PM2.5 (Particulate matter with aerodynamic diameter ≤2.5 μm), is the major air pollutant resulting in the degradation of air quality (Talbi et al., 2018), the deterioration of horizontal visibility (Li et al., 2019b), and the reductions in human well-being. PM2.5 concentration in the urban atmosphere fluctuates periodically under the influence of multiple factors, exhibiting obvious workday/weekend and holiday effects (Hua et al., 2021; Tan et al., 2013), which are useful tools to detect the influence of human-related activities on the urban atmosphere.

To answer these questions, this study aimed to (1) determine the changes in PM2.5 concentrations and emission sources in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era in a megacity; (2) identify changes of PM2.5 weekday/weekend and holiday effects from the shift in working and traveling styles of urban residents in the post-epidemic era; and (3) analyze the potential impact of sporadic COVID-19 outbreaks on the urban PM2.5 concentration. Data analysis could reveal the characteristics of PM2.5 and chemical component concentration variations in a megacity, provide more detailed information for a comprehensive assessment of the long-term effects of the COVID-19 epidemic in the post-epidemic era and offer a new perspective for decision-makers to reconsider the impact of the COVID-19 epidemic.

2. Methods

2.1. Sampling site and duration

Chengdu is located at the western edge of the Sichuan Basin in Southwest China and is surrounded by high mountains (Fig. 1a), with the Longquan Mountains to the east and the Qionglai Mountains to the west, forming a complex valley terrain (Liao et al., 2017). Continuous measurements were conducted at the Institute of Eco-environmental Research and Monitoring of Chengdu (104°02′42″ E, 30°39′13″ N), located in the Qingyang District, a region containing a combination of traffic, commercial, and residential activities (Fig. 1b). Sampling devices of PM2.5 and its chemical components were set on the roof of a building approximately 25 m above the ground. There occurred no tall buildings surrounding the site within a radius of approximately 1000 m and no obvious industrial emission sources nearby except vehicle emissions. Thus, this site could be considered a representative site of the urban environment in Chengdu.

To better illustrate the impacts of the COVID-19 epidemic on PM2.5 variations in a megacity, we divided the entire observation period into three periods, thereby defining February 2017 to January 23, 2020 as the pre-epidemic era (1078 days), January 24, 2020 to February 24, 2020 as the COVID-19 lockdown period (32 days), and March 25, 2020 to December 1, 2021 as the post-epidemic era (616 days). The entire observation period is long enough to represent the characteristics of air pollutant variations in the pre- and post-epidemic eras. Detailed information on government policies and resident behavior patterns during the different periods were provided in the Appendices (Table A1).

2.2. Measurement instruments and data sources

The hourly PM2.5 concentration was measured with a tapered element oscillating microbalance combined with a filter dynamic measurement system (TEOM-FDMS, TEOM 1405-F, Thermofisher Scientific Inc., USA.). The hourly concentrations of 19 trace elements (Al, Ca, Fe, Si, K, Cr, Mn, Ni, Cu, Zn, As, Se, Ag, Cd, Ba, Au, Hg, and Pb) in PM2.5 were measured via an ambient sampling device, namely, a CES Xact-625 monitor (Cooper Environmental Services, USA), which is an online sampling and analysis X-ray fluorescence spectrometer designed for high-temporal-resolution multi-element monitoring in ambient aerosols.

The hourly concentrations of ion components in PM2.5, including cations (Ca²⁺, K⁺, Na⁺, Mg²⁺ and NH₄⁺) and anions (NO₃⁻, SO₄²⁻ and Cl⁻) were measured by the In-situ Gas and Aerosol Composition (IGAC; Model S-611, Machine Shop, Fortelice International Co., Ltd., Taiwan). The working principle of all the online instrument and related quality control measures are presented in the Appendices. The real-time (30 min) traffic index used in this study were acquired from the traffic map by Amap (Amap, https://lbs.amap.com/api/webservice/summary) through its web application programming interface (API). Moreover, the hourly meteorological parameters, including the wind velocity, wind direction, atmospheric pressure, air temperature, and precipitation, were simultaneously measured at the Wenjiang National Meteorological Station (Fig. 1b).

2.3. Generalized additive model (GAM) analysis

A GAM model was used here to quantify the diurnal, weekday and holiday variations in PM2.5 and its composition concentrations. This method is extensively applied in air pollution domain (Ravindra et al., 2019), e.g., to assess the variations in concentrations of PM2.5 and NO₂ (Hua et al., 2021), and identify the changes in the ozone photochemical regime (de Foy et al., 2020). The data inputs to the GAM model included PM2.5 and its composition concentrations, meteorological parameters (air temperature, air pressure, wind speed and wind direction), and time vectors (inter-annual variation factors, seasonal factors, weekday
factors, hourly factors and holiday factors). The time vectors were defined as linear terms, while the meteorological variables were defined as smooth terms (Hua et al., 2021), and the model is described as Eq. (1):

$$\log(\text{Conc}_t) = \sum_{y=2017}^{2021} \alpha_y \cdot t_y + \sum_{s=\text{Spring}}^{\text{Winter}} \alpha_s \cdot t_s + \sum_{w=0}^{23} \alpha_w \cdot t_w + \sum_{h=0}^{23} \alpha_h \cdot t_h + \sum_{i=0}^{5 \cdot \text{ND}} a_i \cdot t_i + S_1(T) + S_2(P) + S_3(\text{WS}) + S_4(\text{WD}) + \epsilon$$

(1)

where Conc. is the hourly PM$_{2.5}$ and its composition concentration. The logarithm of all pollutants concentrations was adopted to transform the data from a log-normal to a normal distribution. The log-transformations may reduce the impact of outliers and data skew on the results, and lead to a smooth normal distribution of the model residuals ($\epsilon$).

The regression coefficient $\alpha$ was determined using least squares regression (de Foy, 2018). The categorical variable $t$ represents the temporal scale by year, season, weekday, hour, and holiday, i.e., $t_y$, $t_s$, $t_w$ and $t_h$ represents the annual, seasonal (Spring to Winter), weekday (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday), and hourly (from 0:00 to 23:00) variations, respectively. Meanwhile, holiday variations are represented by $t_h$, including Spring Festival (SF), Qingming Festival (QMF), Dragon boat Festival (DBF), Mid-autumn Festival (MAF) and National Day (ND). $S(\cdot)$ indicates the P-spline smoothing function that optimizes the fitting and controls the smoothness through a penalty term. $S_1(T)$, $S_2(P)$, $S_3(\text{WS})$ and $S_4(\text{WD})$ are the smoothers that characterize the non-linear influence of air temperature (T), air pressure (P), wind speed (WS) and wind direction (WD) on the measurements, respectively. All meteorological variables were scaled linearly to approximate the normal distribution of zero mean to reduce the effects of extreme observations. All the GAM analyses mentioned above were performed in the R environment (R Core Team, 2020).

As described by Hua et al. (2021), the model results can be interpreted using Eq. (2):

$$p = (e^\alpha - 1) \times 100\%$$

(2)

where $p$ represents the percentage difference in the concentration during the time intervals relative to the baseline.

2.4. PMF model

The positive matrix factorization (PMF) model, proposed by Paatero and Tapper (1993), is widely used in the source apportionment of air pollutants. Considering the continuity of data and balancing the anions/cations, 16 chemical component species (Ca, Fe, Cr, Ni, Cu, Zn, As, Se, Ag, Cd, Au, NH$_4^+$, NO$_3^-$, SO$_4^{2-}$, K$^+$ and Na$^+$) in PM$_{2.5}$ were imported into the PMF model (version 5.0). Subsequently, PMF solutions varying from 3 to 9 factors were considered, and the best solution was chosen based on the interpretability and uncertainty analysis with the bootstrap (BS) and displacement (DISP) methods. Ultimately, six factors were selected as the major emission sources of PM$_{2.5}$.
2.5. Definition of holiday periods and statistical analysis

In our study, non-holiday periods were defined as the 10 days before and after each holiday (Chen et al., 2019; Tan et al., 2009). Moreover, the considered holidays included the Spring Festival (SF), Qingming Festival (QMF), Dragon boat Festival (DBF), Mid-autumn Festival (MAF) and National Day (ND) based on national legal holiday arrangements issued by the State Council (Table A2). The holiday effects of air pollutants were examined through the significance of the differences in the concentration between holidays and non-holiday periods. Negative (positive) holiday effects indicated that the pollutant concentration was higher (lower) during the holidays than those during the non-holiday periods. The non-parametric Mann-Whitney test method was used to analyze the differences in air pollutants between holidays and non-holiday periods and between workdays and weekends, as there are no requirements for normal data distribution (Chen et al., 2019).

3. Results and discussion

3.1. Mass concentrations change during and after the COVID-19 lockdown

3.1.1. Mass concentrations change during the COVID-19 lockdown

Before accounting for meteorological variability, we observed a decrease in PM$_{2.5}$ concentration of 19.7% (−12.4 μg m$^{-3}$) during the COVID-19 lockdown period (Jan. 24, 2020 to Feb. 24, 2020) relative to a 3 years (2017–2019) average value for the same period (Fig. A1c). Growing evidence has demonstrated that the lockdown policy led to sharp reductions in anthropogenic PM$_{2.5}$ emissions over the national and regional scale (He et al., 2020; Le et al., 2020; Zhang et al., 2021). However, Chengdu presented a smaller drop in PM$_{2.5}$ than that in Hangzhou (−34.7%) and Shanghai (−38.1%) (Li et al., 2020; Shen et al., 2021). This might be attributed to the secondary pollution processes that generated more PM$_{2.5}$ during the lockdown period, counteracting the decreases in anthropogenic emissions. As for the components in PM$_{2.5}$, most elements had large drop in concentration with the start of lockdown, and the decline magnitude was strongly evident for Ca (−159.6%), Fe (−123.3%), and Mn (−122.2%), followed by Zn (−89.9%), Ba (−70.4%), Cr (−68.2%), Ni (−62.9%), Si (−52.2%), As (−41.3%), Pb (−33.3%), and Cd (−17.3%) (P < 0.01). Conversely, elements K, S, Cu, and Hg in PM$_{2.5}$ increased by 18.8%, 21.2%, 51.8 and 30.5% (P < 0.01), respectively, during the COVID-19 lockdown period.

These contradictory findings may be because of the increased firework-burning activities in the vast rural areas during the Spring Festival celebration (Chen et al., 2020). The restriction policies, however, only had a limited impact on water-soluble ions reductions. As an example, the concentration of SO$_{4}^{2-}$ was 7.8 μg m$^{-3}$ in 2017–2019 and 7.3 μg m$^{-3}$ during the control period in 2020, representing a 5.3% decrease. The concentration of Na$^{+}$ decreased by 43%, from 0.25 μg m$^{-3}$ in 2017–2019 to 0.15 μg m$^{-3}$ during the lockdown period in 2020. Meanwhile, the value of NH$_{4}^{+}$, which was 6.6 μg m$^{-3}$ in 2017–2019 and 10.6 μg m$^{-3}$ during the COVID-19 lockdown period in 2020, increased by more than 52%. In contrast, the concentrations of K$^{+}$, Mg$^{2+}$, Ca$^{2+}$ and Cl$^{-}$ during the COVID-19 lockdown period increased by 94.3%, 117.6%, 33.3%, and 35.3%, respectively, in comparison to those in the same period.

3.1.2. Mass concentrations change in the pre- and post-epidemic era

Overall, the daily PM$_{2.5}$ concentrations in the pre-and post-epidemic eras ranged from 7.4 to 177.0 μg m$^{-3}$ and 6.0–241.0 μg m$^{-3}$, with average values of 46.3 μg m$^{-3}$ and 42.9 μg m$^{-3}$, respectively (Fig. A1a and A1b). The daily PM$_{2.5}$ concentration in Chengdu declined by 7.3% (decline of 3.4 μg m$^{-3}$) in the post-epidemic era. However, despite a significant reduction in the PM$_{2.5}$ concentration in the post-epidemic era (P < 0.01), the PM$_{2.5}$ value in Chengdu was still higher than both the second reference limits listed in the National Ambient Air Quality Standards (NAAQS) of China (35 μg m$^{-3}$ for annual PM$_{2.5}$, GB 3095-2012) and the World Health Organization annual guideline value (10 μg m$^{-3}$ for annual PM$_{2.5}$). Megacities in China’s North China Plain, Yangtze River Delta, and Pearl River Delta also suffer from PM$_{2.5}$ pollution problems (Chang et al., 2018; Ma et al., 2020; Wu et al. 2019; Zheng et al. 2019; Zhou et al., 2016).

The mean concentrations of all chemical components varied significantly, and the difference was apparent (Table A3). The concentrations of total trace elements in PM$_{2.5}$ in the pre-and post-epidemic eras were 9.4 μg m$^{-3}$ (20.3% of PM$_{2.5}$) and 6.9 μg m$^{-3}$ (16.1% of PM$_{2.5}$). The Mann-Whitney U test results showed that the variations in elements Ca (−62.4%), As (−42.5%), Ba (−41.9%), Fe (−35.4%), K (−34.1%), Si (−32.2%), Pb (−32.1%), Cr (−30.3%), Ni (−25.1%), Hg (−22.3%), Se (−22.0%), Cu (−20.5%), Al (−19.7%), S (−18.3%), Zn (−14.6%), Mn (−11.2%) and Au (13.4%) were significant (P < 0.05), indicating that these elements decreased or increased significantly, but the variation in Cd (−13.5%) and Ag (−11.6%) was not statistically significant. It should be noted that even though the toxic element (e.g., Cd, As and Cr) in PM$_{2.5}$ greatly decreased in the post-epidemic era, their health risks to humans cannot be disregarded because their concentrations remained above the annual reference limits listed in the NAAQS (5 ng m$^{-3}$ for Cd, 6 ng m$^{-3}$ for As and 0.025 ng m$^{-3}$ for Cr, respectively).

Regarding the water-soluble ions, the concentration and the proportion of all water-soluble ions (including SO$_{4}^{2-}$, NH$_{4}^{+}$, NO$_{3}^{-}$, Ca$^{2+}$, K$^{+}$, Na$^{+}$, Mg$^{2+}$ and Cl$^{-}$) in the pre- and post-epidemic eras were 23.6 (51.0% of PM$_{2.5}$) and 20.7 μg m$^{-3}$ (48.2% of PM$_{2.5}$) (Table A4). Moreover, the concentration of all water-soluble ions was 13.1% lower in the post-epidemic era than that in the pre-epidemic era, of which, Mg$^{2+}$ was the major contributor, with a significant decline of 66.0%, followed by NH$_{4}^{+}$ (26.3%), SO$_{4}^{2-}$ (24.6%), Cl$^{-}$ (24.8%), K$^{+}$ (3.9%) and NO$_{3}^{-}$ (2.3%). In contrast, Ca$^{2+}$ and Na$^{+}$ concentrations increased by 135.0% and 29.5% in the post-epidemic era. Particularly, the proportion of SO$_{4}^{2-}$ and NH$_{4}^{+}$ in PM$_{2.5}$ decreased significantly in the post-epidemic era (P < 0.05), but the change in NO$_{3}^{-}$ was not statistically significant. The mean values of NO$_{3}^{-}$/SO$_{4}^{2-}$ were 1.4 and 1.8 in the pre- and post-epidemic eras, indicating that the fraction of SO$_{2}$ emission sources to PM$_{2.5}$ in the post-epidemic era was significantly lower than that of the NOx emission sources to PM$_{2.5}$ (Kong et al., 2020; Li et al., 2017a).

3.2. Temporal variation

3.2.1. Diurnal pattern

The diurnal scaling factors for PM$_{2.5}$ concentrations simulated by the GAM model for all periods in our study were presented in Fig. 2. The scaling factor tells us how much higher or lower the concentrations are for any given time (year, month, day, or hour) relative to the long-term average. For ease of interpretation, the scaling factors were converted to percentage differences from the chosen baseline.

The PM$_{2.5}$ concentration increased gradually in the morning, and reached a maximum in the morning traffic rush hour, and then decreased sharply until the afternoon traffic rush hour, and gradually went up until the next morning. Nevertheless, the profiles presented their particular features before, during and after the COVID-19 lockdown. During the same periods in 2017–2019, PM$_{2.5}$ concentrations increased rapidly in the morning and peaked at about 8:00 a.m., and then declined dramatically, and the valley value usually occurred at about 5:00 p.m. (Fig. 2a). In comparison, during the COVID-19 lockdown period in 2020 significantly lower PM$_{2.5}$ values were observed in the small hours, and subsequently a more gentle increase and a lower peak appeared in the morning (with the peak value declined by 13%). As expected, the decreased anthropogenic activity has successfully “flattened the curve” of diurnal PM$_{2.5}$ variations: fewer anthropogenic emissions led to a slower increase and lower peak PM$_{2.5}$ concentrations. Simultaneously, the chemical components in PM$_{2.5}$ also showed flatter diurnal patterns as the lockdown started (Fig. A2). For example, the
lockdown periods had significantly lower daily standard deviations of Ca, Fe, Mn, Al, S and Zn (8.9, 9.3, 0.8, 74.3, 154.0 and 11.0, respectively) than did the same periods in 2017–2019 (120.8, 89.2, 4.8, 310.0, 497.5 and 57.6, respectively).

The diurnal pattern of PM$_{2.5}$ in the post-epidemic era was similar to those in the pre-epidemic era with some notable differences (Fig. 2b). The daily highest and lowest PM$_{2.5}$ concentrations in the post-epidemic era declined by 5.5% and 5.2% relative to those in the pre-epidemic era, while the occurrence time of daily highest and lowest PM$_{2.5}$ lagged about 1-h. Interestingly, the nighttime (from 6:00 p.m. to 6:00 a.m.) PM$_{2.5}$ concentration in the post-epidemic era declined by 13.1% compared to the nighttime in the pre-epidemic era, much more than the reduction magnitude in the daytime (from 6:00 a.m. to 6:00 p.m.) (–6.8% compared to the daytime in the pre-epidemic era). Furthermore, the daily patterns of the chemical components in PM$_{2.5}$ were generally consistent between the pre- and post-epidemic eras, but their pattern shapes were varied due to the diverse emission sources (Fig. A3). All the elements, except for Al, Cu, Cd, Ag, Au and Hg, reached its higher concentrations in the morning (from 6:00 a.m. to 10:00 a.m.) and evening (from 6:00 p.m. to 9:00 p.m.) periods, and lower concentrations in the afternoon (from 1:00 p.m. to 5:00 p.m.). The peak concentrations of Fe, Ca, Si, Mn, Ba, Ni, Mg$^{2+}$ and Ca$^{2+}$ in the morning reflected the increased vehicle exhaust and non-exhaust emissions. The sinusoidal pattern of the elements K, Cr, As, Zn, Se, Pb, Cu, As, K$^{+}$ and Cl$^{-}$ was probably controlled by continuous local industrial emissions and oscillations in the height of the planetary boundary layer (Yu et al., 2019). But some elements did not exhibit clear diurnal variation, such as Al, Cd and Ag showed a moderate variation during the day, suggesting additional regional sources (Dall’Osto et al., 2013). Notably, Au and Hg typically reached their peak values at about 5:00 p.m., indicating that the diurnal patterns of these two elements were mainly controlled by regional transport. Finally, both SO$_4^{2-}$ and Cl$^{-}$ exhibited a similar pattern due to the same emission sources involving coal combustion.

The diurnal variations of PM$_{2.5}$ could be influenced by atmospheric mixing and dilution, planetary boundary layer height and ordinary traffic patterns (Dall’Osto et al., 2013). In the urban atmosphere, the morning’s higher PM$_{2.5}$ concentration could be associated with density anthropogenic activities (e.g., industrial production and vehicle transportation), while the afternoon’s lower PM$_{2.5}$ concentration could be attributed to favorable meteorological conditions, especially the higher planetary boundary layer and raised air temperature, which could better facilitate PM$_{2.5}$ diffusion (Jin et al., 2021; Yu et al., 2019; Zhou et al. 2016, 2019).

A 1-h delay in the occurrence time of both the maximum and minimum PM$_{2.5}$ concentrations was observed during the COVID-19 lockdown period and in the post-epidemic era, probably attributed to the decreased anthropogenic emissions in Chengdu, especially the markable decline in on-road emissions. The mean and maximum traffic index during the same period in 2019 were 1.06 and 1.16, in comparison, however, they were 1.01 (decline of 4.7%) and 1.02 (decline of 12.1%) during the COVID-19 lockdown period in 2020 (Fig. A4a). Similarly, the mean and maximum traffic index in the pre-epidemic era were 1.10 and 1.29, whereas they were 1.07 (a decline of 2.7%) and 1.18 (a decline of 8.5%) in the post-epidemic era (Fig. A4b). Traffic volume decreases much more in the morning and evening peak times than at other times during the lockdown periods and in the post-epidemic era. As a result, the reduced on-road emissions during morning and evening rush hours delayed the timing of the peak and valley PM$_{2.5}$ concentrations. Additionally, the great reduction of the nighttime PM$_{2.5}$ in the post-epidemic era may be because of the increased night precipitation (Fig. A4c and A4d). Precipitation could reduce the air PM$_{2.5}$ concentration by enhancing the wet scavenging process and weakening their suspension ability (Chang et al., 2018). During the night, the total number of precipitation events in the pre- and post-epidemic eras reached 507 and 680; moreover, the average amounts of each night precipitation event in the pre- and post-epidemic eras were 2.0 and 3.6 mm. Previous research has shown that moderate-intensity rainfall (2.0–6.9 mm/3h) eliminates PM$_{2.5}$ more efficiently than dose low-intensity rainfall (0.1–1.9 mm/3h) (Jin et al., 2021). Thus, the increased evening rainfall was the major reason that resulted in a lower night PM$_{2.5}$ concentration in the post-epidemic era.

### 3.2.2. Weekly pattern

During the same period in 2017–2019, PM$_{2.5}$ concentrations on workdays (from Monday to Friday) and weekends (Saturday and Sunday) were almost identical (59.1 ± 4.9 μg m$^{-3}$ vs. 59.1 ± 1.0 μg m$^{-3}$), without significant workday or weekend effect (Fig. 3a). In contrast, the weekly pattern of PM$_{2.5}$ has changed markedly as the lockdown started. The mean PM$_{2.5}$ concentrations on weekdays presented obvious reductions during the COVID-19 lockdown period in 2020, with average concentrations lower by 13.0% on weekly (59.1 ± 4.0 μg m$^{-3}$ vs. 51.4 ± 8.9 μg m$^{-3}$), by 6.1% on workdays (59.1 ± 4.9 μg m$^{-3}$ vs. 54.3 ± 8.0 μg m$^{-3}$) and by 25.2% on weekends (59.1 ± 1.0 μg m$^{-3}$ vs. 44.2 ± 8.5 μg m$^{-3}$), compared to those during the same period in 2017–2019. However, not all elements were consistent with the weekly patterns of PM$_{2.5}$ during the COVID-19 lockdown period (Table 1). For example, the Al, Ca, Fe, Si, Mn, Ni and Ba concentrations in PM$_{2.5}$ contrast elevated over weekends, namely 10%, 213%, 119%, 174%, 69%, 63% and 65% higher, respectively, during weekends than those on workdays. These paradoxical results (decreased PM$_{2.5}$ and increased crustal elements simultaneously, e.g., Al, Ca, Fe and Si etc.) that occurred during the COVID-19 lockdown period might be attributed to the impacts of plumes.
with lower PM$_{2.5}$ but higher crustal elements (Jin et al., 2021).

In the pre-epidemic era, the average PM$_{2.5}$ values on workdays and weekends were 39.2 ± 21.2 μg m$^{-3}$ and 38.2 ± 24.5 μg m$^{-3}$, respectively, and the mean PM$_{2.5}$ concentration was higher (2.5%) over workdays than on weekends, presented an evident workday effect. Correspondingly, almost all chemical components showed higher concentrations over the workdays, except for Ba, Au and Mg$^{2+}$ (Table 1). However, the workday effect of PM$_{2.5}$ was evident attenuated in the post-epidemic era due to changes in the travel habits of urban residents. Generally, although urban residents have more time and resources to travel for recreational purposes (Cui et al., 2019a), the willingness to travel on weekends was more likely to be dispelled considering the COVID-19 infection risk in the post-epidemic era.

Table 1
Mean concentrations of PM$_{2.5}$ and its chemical components between weekends and workdays.

|                   | Lockdown periods                   | The pre-epidemic era | The post-epidemic era |
|-------------------|------------------------------------|----------------------|-----------------------|
|                   | Workdays  | Weekends  | Diff (%) | Workdays  | Weekends  | Diff (%) | Workdays  | Weekends  | Diff (%) |
| Al                | 3201.76    | 3520.65   | 10       | 3434.61  | 3350.59   | −3       | 2983.68   | 2927.51   | −2       |
| Ca                | 116.25     | 364.26    | 213      | 340.36   | 320.02    | −6       | 162.61    | 160.82    | −2       |
| Fe                | 167.92     | 367.73    | 119      | 525.82   | 496.72    | −6       | 347.63    | 353.02    | −1       |
| Si                | 492.66     | 1347.38   | 174      | 737.65   | 665.17    | −10      | 571.90    | 578.53    | 2        |
| S                 | 2846.04    | 1646.29   | −42      | 2213.86  | 2094.98   | −5       | 1626.38   | 1656.12   | 1        |
| K                 | 845.03     | 814.34    | −3       | 664.79   | 647.90    | −3       | 439.36    | 436.02    | 2        |
| Cr                | 2.19       | 1.84      | −16      | 3.77     | 3.35      | −11      | 1.97      | 2.12      | −1       |
| Mn                | 8.13       | 13.72     | 69       | 27.91    | 26.80     | −4       | 22.91     | 23.52     | 7        |
| Ni                | 0.74       | 1.20      | 63       | 1.35     | 1.27      | −6       | 0.97      | 0.92      | 3        |
| Cu                | 82.22      | 89.81     | 9        | 39.35    | 37.14     | −6       | 36.11     | 34.62     | −5       |
| Zn                | 39.03      | 32.75     | −16      | 105.70   | 99.99     | −5       | 81.43     | 82.62     | −4       |
| As                | 5.34       | 3.51      | −34      | 7.44     | 6.67      | −10      | 3.69      | 3.69      | 1        |
| Se                | 3.88       | 1.26      | −33      | 1.78     | 1.69      | −5       | 1.27      | 1.25      | 0        |
| Ag                | 3.81       | 4.18      | 10       | 3.80     | 3.70      | −2       | 3.08      | 2.95      | −2       |
| Cd                | 7.55       | 7.79      | 3        | 8.54     | 8.38      | −2       | 6.80      | 6.96      | −4       |
| Ba                | 16.63      | 27.42     | 65       | 35.18    | 35.44     | 1        | 20.40     | 20.36     | 2        |
| Au                | 1.96       | 2.33      | 18       | 2.46     | 2.47      | 1        | 0.61      | 0.62      | 0        |
| Hg                | 1.73       | 2.19      | 27       | 2.44     | 2.41      | −1       | 0.52      | 0.51      | 2        |
| Pb                | 17.02      | 12.58     | −26      | 16.24    | 15.09     | −7       | 18.19     | 18.01     | 0        |
| NO$_3^-$           | 27.40      | 19.78     | −28      | 3.27     | 3.19      | −2       | 5.55      | 5.68      | 2        |
| NH$_4^+$           | 8.38       | 9.64      | 15       | 2.81     | 2.79      | −1       | 3.91      | 4.06      | 4        |
| SO$_2^-$           | 7.28       | 4.46      | −39      | 3.34     | 3.17      | −5       | 3.70      | 3.75      | 1        |
| Na$^{+}$           | 0.18       | 0.17      | −5       | 0.11     | 0.11      | −3       | 0.12      | 0.12      | 0        |
| K$^+$              | 0.84       | 0.65      | −23      | 0.16     | 0.15      | −4       | 0.27      | 0.28      | 3        |
| Mg$^{2+}$          | 0.29       | 0.24      | −17      | 0.08     | 0.09      | 8        | 0.08      | 0.09      | 2        |
| Cl$^-$             | 0.62       | 0.67      | 8        | 0.04     | 0.03      | −19      | 0.81      | 0.82      | 1        |
| ($\Delta$Diff) indicates the relative changes over weekends deduced from the GAM model. Unit: ng·m$^{-3}$ for trace elements and μg·m$^{-3}$ for water-soluble ions.)

Fig. 3. Weekly scaling factors for PM$_{2.5}$ from the GAM model during the same period in 2017–2019 and COVID-19 lockdown period in 2020 (a), and the pre-and post-epidemic eras (b). (WDS: Workdays, WES: Weekends).
3.3. Source apportionment

Source apportionment analysis of the chemical components in PM$_{2.5}$ was conducted with the PMP model, and six categories of pollution sources were identified as the best solution, including (1) biomass burning, (2) secondary aerosols, (3) ferrous metal smelting, (4) soil dust, (5) coal combustion, and (6) nonferrous metal smelting (Fig.A5).

Biomass burning. This source was characterized by water-soluble ion K’, with low contributions of Na’. K’ has been extensively used as a suitable tracer of biomass-burning aerosols (Dall’Osto et al., 2013; Tao et al., 2013). Although large-scale biomass burning has been strictly prohibited in Chengdu’s urban and suburb areas since 2009, air pollutants generated by biomass burning in the vast rural areas are still detected by our monitoring station after long-distance transportation (Tao et al., 2014). This factor accounted for 7.4% (5.9 μg m$^{-3}$), 21.4% (6.2 μg m$^{-3}$) and 3.3% (0.6 μg m$^{-3}$) of the PM$_{2.5}$ mass concentration in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era, respectively.

Secondary aerosols. This source was typically characterized by high contributions of NO$_3^-$, NH$_4^+$, NO$_2$ is mainly formed via NO$_x$ oxidation, which is largely generated from anthropogenic activities, such as coal combustion, vehicle exhaust, and even biomass burning. This source accounted for 63.0% (14.0 μg m$^{-3}$), 65.7% (16.4 μg m$^{-3}$) and 69.6% (12.7 μg m$^{-3}$) of the PM$_{2.5}$ mass concentration in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era, respectively.

Ferrous metal smelting. This factor was distinguished by high levels of Cr, As, Zn and Mn. These elements are typically released in the ferrous metal smelting process. Elements Cr, Mn and Zn are mainly emitted by metallurgical industries such as chrome plating and steel production (Chang et al., 2018; Cui et al., 2019b), while element As mostly originates from coal combustion during ore smelting (Wang et al., 2018). This factor accounted for 2.2% (0.5 μg m$^{-3}$), 1.3% (0.3 μg m$^{-3}$) and 3.4% (1.6 μg m$^{-3}$) of the PM$_{2.5}$ mass concentration in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era, respectively.

Soil dust. This source was primarily characterized by crustal elements (such as Ca and Fe). This mixed source is similar to the results reported for Shanghai (Chang et al., 2018), London (Visser et al., 2015) and Beijing (Cui et al., 2019b). Fe is mainly associated with non-exhaust emissions because the particles produced by brake abrasion are typically characterized by high Fe concentration (Chang et al., 2018; Dall’Osto et al., 2013). Ca is acknowledged as the most abundant element in the upper continental crust, and their atmospheric origin is usually attributed to release from construction, or road dust. This source accounted for 4.9% (1.1 μg m$^{-3}$), 1.9% (0.5 μg m$^{-3}$) and 3.6% (0.7 μg m$^{-3}$) of the PM$_{2.5}$ mass concentration in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era, respectively.

Nonferrous metal smelting (Cu and Au). This source was characterized by nonferrous elements Cu, As, Ag, and Cd. Heavy metal elements Au, Ag and Cd are important associated elements in Cu and Zn ores. In fact, the three most common non-ferrous metal smelting forms in China include Cu and Zn smelting (Chang et al., 2018); thus, the associated elements such as Cu, Ag, Cd are inevitably vaporized and released into the atmosphere in the non-ferrous smelting process. This source accounted for 13.8% (3.5 μg m$^{-3}$), 9.7% (4.3 μg m$^{-3}$) and 11.6% (1.7 μg m$^{-3}$) of the PM$_{2.5}$ mass concentration in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era, respectively.

In general, the contributions of those six major emission sources to PM$_{2.5}$ changed greatly during these three periods (Fig. 4). Compared to the pre-epidemic era, due to the strict shutdown policy during the COVID-19 lockdown period, the contributions of soil dust, nonferrous metal smelting and ferrous metal smelting to PM$_{2.5}$ decreased by 3.1%, 2.9% and 0.9%, respectively. In contrast, the contributions of biomass burning and secondary aerosols to PM$_{2.5}$ increased by 13.9% and 2.7%, respectively.

In the post-epidemic era, the contributions of anthropogenic sources to PM$_{2.5}$ have recovered but remain lower than those in the pre-epidemic era. For example, the contribution of coal combustion to PM$_{2.5}$ declined from 8.7% in the pre-epidemic era to 6.5% in the post-epidemic era. The effect of coal emission reduction could be attributed to air pollution prevention activities, especially measures “involving the consumption of electricity instead of coal” and “natural gas instead of coal” (Kong et al., 2020). The implementation of these measures has led to a reduction in the number of coal-consuming industries from 18 in the pre-epidemic era to 6 in the post-epidemic era, and coal consumption has become more concentrated and efficient, which is more beneficial to the management of air pollutants coal combustion emissions.

![Chart](chart.png)

**Fig. 4.** Comparison of the source contributions in the pre-epidemic era, the COVID-19 lockdown period and the post-epidemic era.
emissions comprise another important source of PM$_{2.5}$ in the urban atmosphere. In the post-epidemic era, the contribution of soil dust to PM$_{2.5}$ have decreased by approximately 1.3%. Considering the negative impact of this pandemic on the real estate industry, this reduction could be associated with the decrease in the real estate construction area in the Chengdu urban district. According to the Chengdu Statistical Yearbook, the annual real estate construction area increased in the pre-epidemic era, and the construction area reached 206 km$^2$ in 2019 but reached 191 km$^2$ in 2020, a decrease of 7.4%. Nonferrous and ferrous metal smelting emissions could be classified as industrial production sources, and the contributions of non-ferrous metal smelting decreased by 2.2%, while the fraction of ferrous metal smelting emissions conversely increased by 1.2%, in the post-epidemic era.

It should be noted that in the post-epidemic era, emissions of the secondary aerosol source to PM$_{2.5}$ increased by 6.6%, indicating a more intensive secondary pollution process in Chengdu urban areas. In the post-epidemic era, the concentrations of PM$_{2.5}$ and gaseous precursor NO$_2$ decreased by 5.3% and 12.1%, respectively, while the O$_3$ concentration conversely increased by 10.0%. Li et al. (2019a) found that the increase in O$_3$ could be driven by the decrease in PM$_{2.5}$ because PM$_{2.5}$ scavenges hydroperoxyl (HO$_2$) and NO$_3$ radicals that could otherwise generate O$_3$. Moreover, numerous results have indicated that O$_3$ might play a crucial role in the transformation of NO$_2$ into NO$_3$ via photochemical pathways (Fan et al., 2022; Kong et al., 2020; Li et al., 2021). Thus, with decreasing PM$_{2.5}$ concentration, the O$_3$ concentration could increase, resulting in NO$_3$ formation capacity enhancement during secondary air pollution formation. Similar results also were obtained in Beijing after the COVID-19 lockdown (Li et al., 2021).

3.4. Holiday effects

The concentrations of PM$_{2.5}$ and its chemical components may be affected by meteorological factors. In our study, the meteorological factors (e.g., temperature, air pressure, wind direction, wind speed and precipitation) during all holidays are basically accordant in the pre- and post-epidemic eras, except for the QMF and MAF (Table A5). Thus, the main driver of PM$_{2.5}$ and its chemical components during the holidays might be the other factors rather than the meteorological factors.

In the post-epidemic era, PM$_{2.5}$ concentrations during the holidays dropped substantially (except for the DBF holiday), which means that the positive holiday effect was greatly enhanced. PM$_{2.5}$ concentrations during the SF, QMF, DBF, MAF, and ND holidays in the pre-epidemic era were 76.1 ± 52.3 μg m$^{-3}$, 50.4 ± 15.9 μg m$^{-3}$, 33.9 ± 16.8 μg m$^{-3}$, 30.7 ± 13.5 μg m$^{-3}$ and 32.4 ± 18.1 μg m$^{-3}$ (Fig. 5a), respectively. However, in the post-epidemic era, they were 61.8 ± 47.0 μg m$^{-3}$, 33.7 ± 16.6 μg m$^{-3}$, 39.6 ± 20.5 μg m$^{-3}$, 18.3 ± 11.7 μg m$^{-3}$ and 27.5 ± 14.6 μg m$^{-3}$, respectively. In comparison, PM$_{2.5}$ concentrations during the SF, QMF, MAF, and ND holidays in the post-epidemic era were significantly lower than those in the pre-epidemic era ($p < 0.001$ or $p < 0.01$). Conversely, in the post-epidemic era, PM$_{2.5}$ concentration increased significantly over the DBF holiday ($p < 0.01$), exhibiting an evident negative holiday effect.

The scaling factors for PM$_{2.5}$ on all holidays dropped from ~26.7% - 27.3% in the pre-epidemic era to ~86.8% to ~11.7% in the post-epidemic era, with the scaling factors lower by 57.9% on SF holiday, 42.8% on QMF holiday, 78.7% on MAF holiday and 31.5% on ND holiday, while higher by 15.0% on DBF holiday, respectively (Fig. 5b).

Generally, air pollutants exhibit lower concentrations during holidays and higher concentrations during non-holiday periods, and this holiday effect usually results from changes in human activities, e.g., lifestyle, urbanization, and traditional culture patterns (Chen et al., 2019; Hua et al., 2021; Tan et al., 2019). In the post-epidemic era, the positive holiday effect was greatly enhanced due to the significant decrease in PM$_{2.5}$ concentrations over the SF, QMF, MAF, and ND holidays, this shift could be deduced from the changing habits of urban residents during these holidays. On the one hand, the traffic index during the QMF, MAF, ND, and SF holidays fell by 3.7%, 3.7%, 1.9% and 2.9%, respectively, in the post-epidemic era, while the emissions from soil dust during these holidays simultaneously reduced by 69.5%, 47.5%, 45.0% and 55.8%, respectively, in the post-epidemic era. Furthermore, the migration index (Sum of in-migration index and out-migration index) during the SF holiday in Chengdu in 2021 (16.2) was approximately 35% lower than that in 2019 (24.8), further confirming the significant decrease in traffic volume in the post-epidemic era (https://qianxi.baidu.com/#/2022chunyun). Thus, the evident drop in Chengdu’s traffic volume over these holidays in the post-epidemic era resulted in a significantly reduction in traffic vehicles emissions during these holidays.

On the other hand, the reduced traffic volume over the holidays in the post-epidemic era indicated that urban residents were more willing to stay at home rather than travel for outdoor activities, which led to a significant reduction of firework-burning activities during the SF holiday and tomb-sweeping activities during the QMF holiday. For example, to celebrate the SF, high-profile firework events usually occurred at midnight on the first day of SF (Cui et al., 2019b; Ji et al., 2018; Kong et al., 2015). Nevertheless, firework ignition emits a large number of fine particles comprising organic/elemental carbon, NO$_2$, SO$_2$, NH$_4$, K$^+$, Cl$^-$, and various metal elements, e.g., Cu, K, Ba, and Pb (Tian et al., 2014). Chemical components in PM$_{2.5}$ linked to the firework-burning activities presented an evident increase during the SF holiday in the...
pre-epidemic era, with concentrations increased by 161.6% for K, 637.5% for Ba, 103.4% for Pb, and 235.5% for K* (Table A5). However, during the SF holiday in the post-epidemic era, although the concentrations of these components have increased, their values remain lower than those in the pre-epidemic era. In addition, as shown in Fig. A6, the near real-time peaks of Pb, Cu, Ba, K, and Cl- during the firework events in the post-epidemic era were significantly lower than those in the pre-epidemic era. As a result, lower fireworks activities significantly reduced the peak PM2.5 concentration and significantly improved the urban air quality during the SF holiday in the post-epidemic era.

The QMF is another traditional Chinese festival when people commemorate their ancestors by tomb-sweeping. However, tomb-sweeping activities are often accompanied by firework ignition and ancestor money (Mingbi in Chinese) burning (https://m.news.cctv.com/2021/03/31/ARTIpe2NRXecCm2nQVwr1Sdf210331.shtml). As a result, during the QMF holiday in the pre-epidemic era, the products linked to biomass burning and firework burning in PM2.5 increased substantially (Table A6). For example, the concentrations of PM2.5, K, Ba, Pb, NO3-, NH4+ and SO42- during the QMF holiday in the pre-epidemic era reached 50.8±17.0 μg m⁻³, 917.7±360.9 ng m⁻³, 42.7±20.4 ng m⁻³, 43.2±15.6 ng m⁻³, 10.1±5.1 μg m⁻³, 6.6±2.1 μg m⁻³ and 9.1±5.6 μg m⁻³, respectively. However, in comparison, the concentrations of chemical components associated with biomass burning presented strong reductions on the QMF holiday in the post-epidemic era, with concentrations declining by 35.4% for PM2.5, 64.0% for K, 61.9% for Ba, 56.0% for Pb, 14.4% for NO3-, 50.5% for NH4+ and 56.1% for SO42-, respectively. Additionally, the concentrations of Ca, Fe and Si decreased significantly by 65.7%, 47.4% and 63.1%, respectively, during the QMF holiday in the post-epidemic era. Therefore, the significant decrease in PM2.5 during the QMF holiday could be attributed to the fewer tomb-sweeping activities in the post-epidemic era.

Notably, a stronger negative effect was detected during the DBF holiday in the post-epidemic era, with significantly higher PM2.5 concentrations than those in the pre-epidemic era (P < 0.01). The increased S, SO42- and NH4+ in PM2.5 during the DBF holiday was the primary driver for the elevated PM2.5 levels. Compared to the DBF holiday in the pre-epidemic era, most chemical components in PM2.5 decreased during the DBF holiday in the post-epidemic era (Table A7); in contrast, the concentrations of S, SO42- and NH4+ significantly increased by 0.9 μg m⁻³ (P < 0.001), 3.6 μg m⁻³ (P < 0.001) and 1.8 μg m⁻³ (P < 0.001), respectively.

This particular phenomenon may be due to the unique traditional cultural practices during the DBF holiday. The DBF is one of the oldest Chinese holidays and has been widely celebrated throughout the Asia Pacific since 300 BCE. On this day, people usually show respect to Qu Yuan by eating zongzi, rowing dragon boats, warding off evil spirits and lighting Xionghuang (Zhang et al., 2011). “Sulfur incense” is prepared from sulfur and wood bran powders, that emit a unique aroma when lit and can be used as a snake or insect repellent (https://zhidao.baidu.com/question/7535844990508103240.html). During the DBF holiday, “Xionghuang” is typically added to wine or water and used as an antiseptic and disinfection throughout the house. Moreover, the practice of hugging and lighting “Sulfur incense” at homes is also widespread and has been practiced for thousands of years. As a result, large amounts of sulfides are present in both “Realgar wine” and “Sulfur incense” contain, which can be released into the atmosphere via density celebrations during the DBF holiday and lead to a rapid increase in PM2.5. The increased behavior in the post-epidemic era has worsened the urban air quality to some extent; however, this behavior also represents the strong wishes of Chinese people for an early end to the COVID-19 epidemic.

3.5. Occasional COVID-19 events effect

There were no PM2.5 reductions in Chengdu during two local COVID-19 epidemic events due to the influence of severe secondary pollution processes (Fig. A7). The PM2.5 concentrations before, during and after the first local epidemic event in 2020 (from the 7th to the 31st of December) were 55.0±11.1 μg m⁻³, 82.1±16.5 μg m⁻³ and 80.2±19.4 μg m⁻³, respectively. There was no significant difference in the PM2.5 concentration between the EP (epidemic period) and the NP (normal periods). However, the PM2.5 concentration before, during and after the local epidemic event in 2021 (from the 2nd to the 23rd of November) reached 30.3±8.2 μg m⁻³, 60.1±11.5 μg m⁻³ and 55.5±11.4 μg m⁻³, respectively. The PM2.5 concentration was significantly higher during the EP than that during the NP (P < 0.01).

The main reason for these unexpected results could be the secondary pollution during these two local epidemic events. As mentioned above, Chengdu is located between two mountains, and this unique geographical condition is not conducive to the dispersion of air pollutants, especially during the winter. Stagnant meteorological conditions in winter are a major contributor to nighttime PM2.5 accumulation (Hu et al., 2021). Due to the surface radiation cooling after sunset, an air temperature inversion layer forms, limiting vertical PM2.5 diffusion and promoting PM2.5 accumulation (Hu et al., 2021; Li et al., 2017c). For example, because of the stagnant meteorological conditions during the first local epidemic event, Chengdu experienced an extremely polluted period lasting 6 days (from the 23rd to the December 28, 2020). During this heavily polluted period, the highest daily average PM2.5 concentration was 241.1 μg m⁻³, while the concentration of SNO3-, SO42- and NH4+ reached 100.6 μg m⁻³, accounting for 41.5% of the PM2.5 concentration. As shown in Fig. A8, the PM2.5 concentration tended to continuous growth with an average growth rate of 0.95 μg m⁻³·h⁻¹ over this pollution period. On December 26, 2020, the PM2.5 experienced explosive growth from 140.8 μg m⁻³ at 5:00 p.m. to 231.1 μg m⁻³ at 9:00 p.m., with a nighttime accumulation rate of 18.1 μg m⁻³·h⁻¹. In contrast, the highest PM2.5 accumulation rate during the daytime was 11.2 μg m⁻³·h⁻¹ (from 239.7 μg m⁻³ at 1:00 p.m. to 284.1 μg m⁻³ at 4:00 p.m. on December 27, 2020). Overall, the growth rate of PM2.5 at nighttime was much higher than that during the daytime within these two pollution periods.

4. Conclusions

With the use of high-resolution concentration datasets of PM2.5 and its chemical components from 2017 to 2021 in Chengdu, Southwest China, we conducted an empirical study of the short- and long-term effects of the COVID-19 epidemic on PM2.5 variations in a large city. Overall, the urban PM2.5 concentrations in the pre-epidemic era, COVID-19 lockdown period and post-epidemic era reached 46.3 μg m⁻³, 49.5 μg m⁻³ and 42.9 μg m⁻³, respectively. Compared to the same periods in 2018 and 2019, the COVID-19 lockdown policy resulted in a significant reduction in the PM2.5 concentration, with a greater decline in element concentrations than that in water-soluble ion concentrations (especially SNA ions); thus, the positive effect of emission reduction was partially offset by the secondary pollution process. Emissions originating from industry and soil dust all decreased during the COVID-19 lockdown period and post-epidemic era, but it should be noted that the contribution of secondary pollution progresses increased in the post-epidemic era.

The extreme reductions in anthropogenic emissions during the COVID-19 lockdown period resulted in a smoother daily variation in PM2.5, significantly sharpening the peak and delaying the timing of the valley value. In the post-epidemic era, although the form of the daily variation of PM2.5 remain unchanged, the timing of both peak and valley values was also delayed by about 1 h. Most importantly, we found that the workday and holiday effects of PM2.5 in the post-epidemic era changed as a result of the shift in the habitual behavior patterns of urban
residents. For example, in the pre- and post-epidemic eras, PM_{2.5} concentration on weekdays was significantly higher than that during weekends, indicating an obvious weekday effect. However, in the post-epidemic era, the reduced willingness of urban residents to travel during weekends resulted in a significant reduction in weekend PM_{2.5} concentration. Thus, the weekday effect was more pronounced in the post-epidemic era. In the post-epidemic era, the positive effects of holidays were reinforced due to the reduction in human activities during holidays. Specifically, the reduction in firework burning and tomb-sweeping activities led to a significant decrease in the PM_{2.5} concentration during the SF holidays and QMF holidays. However, the increased consumption of “Realgar wine” and “Sulfur incense” elevated the PM_{2.5} concentration during the DBF holiday in the post-epidemic era, resulting in a negative DBF holiday effect. Finally, there occurred no decrease in the PM_{2.5} concentration during the two observed local COVID-19 outbreak events due to the stronger influence of secondary pollution processes.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability
Data will be made available on request.

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Appendix A. Supplementary data
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