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Original Research

Spatiotemporal Variations of Air Pollutants before and after the COVID-19 Pandemic in Chengdu

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Abstract

The pandemic of coronavirus disease 2019 (COVID-19, caused by the SARS-CoV-2 virus) had severe health, social, and economic impacts across the globe. However, the reduction in air pollution resulting from travel restrictions emerged as a beacon of hope. This study focused on Chengdu, China, using a generalized additive model and time series analysis to assess air quality changes during the lockdown. The research revealed a notable decrease in the Air Quality Index, nitrogen dioxide (NO_2), and particulate matter concentrations, with NO_2 showing the most pronounced response to reduced emissions from control measures. However, Chengdu experienced a relatively smaller decline in air pollution compared to other major Chinese cities. After the implementation of Class B measures in response to COVID-19, air pollutant concentrations in Chengdu significantly increased in February and March 2023 compared to the same period in 2022 and model-predicted values, despite little difference in annual average levels between the two years. The study suggested that the topography of the Sichuan Basin, with unique meteorological conditions such as temperature inversions and humidity anomalies, hindered pollutant dispersion and potentially reduced the likelihood of airborne virus transmission.

Keywords: COVID-19, air pollution, generalized additive models, time series model, basin

Introduction

The main categories of air pollutants are gaseous pollutants and particulate pollutants. The major air pollutants include particulate matter ≤ 2.5 μm ($PM_{2.5}$), particulate matter ≤ 10 μm (PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide (CO) [1, 2]. Although natural events, such as volcanic eruptions and forest fires, can release various pollutants into the environment, anthropogenic emissions are the primary source of pollutants in the ambient atmosphere [3]. Air pollutants are well recognized for contributing to ill health [4, 5]. According to World Health Organization (WHO) estimates, in 2019, environmental (outdoor) air pollution resulted in 4.2 million premature deaths globally, with 99% of the world's population living in areas that did not meet the air quality guidelines set by the WHO [6]. China is presently experiencing a pivotal

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phase in the management of environmental air pollution, whereby its diverse policies and measures aimed at reducing environmental emissions represent significant policy challenges in addressing the lingering health ramifications at both regional and global scales [7].

In December 2019, the outbreak of the SARS-CoV-2 virus (which causes coronavirus disease 2019 [COVID-19]) began in Wuhan, China. The epidemic was severe; therefore, most countries imposed city-wide lockdowns and introduced quarantine measures to reduce virus transmission. Given that human activity is a prominent contributor to the emission of major pollutants into the atmosphere, it was anticipated that the implementation of lockdown measures would result in a reduction of atmospheric concentrations of these pollutants. Chengdu, the capital city of Sichuan Province, China, is located at the bottom of the Sichuan Basin and has a permanent population of over 21 million, representing a typical megacity. What were the significant differences in the concentrations of air pollutants resulting from the COVID-19 lockdown in Chengdu? Considering the progressive reduction in the severity and mortality of COVID-19, coupled with the augmented levels of vaccination coverage, COVID-19 was managed as a Category B infectious disease in China on 8 January 2023, putting it in the same category as HIV and bird flu. Considering the economic cost of the pandemic, there was a need for reasonable measures to promote economic recovery during the post-COVID-19 period, which in turn might affect environmental contaminants.

In this study, we collected data on air pollutant concentrations in Chengdu from 2014 to 2024. We studied the impact of urban blockade policies on changes in air pollutant concentrations and used a time series model to predict these concentrations. Our study aimed to determine the relationship between air pollutants and COVID-19 before and after the pandemic in Chengdu, with the hope of providing a scientific basis for effective air quality management and public health protection in the future.

Materials and Methods

Daily COVID-19 cases in Chengdu were relatively sparse during the early epidemic period. To ensure adequate statistical power and reliability for the time-series analysis, daily COVID-19 cases at the Sichuan provincial level (covering Chengdu) were used as a proxy indicator. The validity of this substitution was verified by Spearman correlation analysis, which showed a strong positive correlation between daily COVID-19 cases in Chengdu and Sichuan Province (rs = 0.788, P<0.01). To validate robustness at the city scale, supplementary analyses were performed using actual daily cases in Chengdu. Data on COVID-19 cases were obtained from the official website of the Health Commission of Sichuan Province. Air quality data, including daily concentrations of AQI, $PM_{2.5}$, PM_{10}, and NO_2, were collected from the National Urban Air Quality Real-time Publishing Platform of China Environmental Monitoring Center. Monthly air quality data for Sichuan Province were calculated using the area-weighted average of individual prefecture-level cities.

The COVID-19 case data represent rare events and follow a Poisson distribution; therefore, a Poisson generalized additive model (GAM) approach was used to investigate the associations between daily mean air pollutant concentrations and cases of COVID-19. The models were fitted using R software (version 4.3.1) with the “mgcv” package. The model framework was as follows:

$$\mathrm{Log}[E(Yt)] = \alpha + \beta \cdot X(t\text{-}T) + s(\mathrm{time}, df) + s(WS,df) + \mathrm{Vacation} + \mathrm{Mobility} + \mathrm{Intervention}$$

In this formula, E(Yt) is the expected number of daily COVID-19 cases on day t, and α is the intercept. β is the pollutant regression coefficient, and X(t-T) denotes pollutant concentration at lag T. s(·) represents smoothing functions with specified degrees of freedom (df): s(time,df) controls the long-term temporal trend, and s(WS,df) adjusts for the daily mean wind speed (m/s). Vacation is a binary holiday dummy variable. Mobility is the Baidu migration-based population mobility index, indexed to 1.0 on January 1, 2020. Intervention is an ordinal policy variable (0 = no intervention for January 1-23, 1 = moderate control for February 26-29 under Level II response, 2 = strict lockdown for January 24-February 25 under Level I response). The lag effects of air pollutants from lag 0 to lag 7 were evaluated. Relative risk (RR) and its 95% confidence interval (CI) were calculated to quantify the changes in COVID-19 cases associated with a per-unit increment in pollutant concentration, accounting for sampling variability.

Our study employed time series modeling to predict air pollution concentrations under a non-epidemic scenario. We gathered and preprocessed the data, selected suitable models (including autoregressive integrated moving average (ARIMA), seasonal autoregressive integrated moving average (SARIMA), and exponential smoothing), trained and validated the selected model, and conducted forecasting with confidence intervals. Using the time series model, we forecasted the concentration levels of air pollutants in Chengdu for each month in 2020 under a non-epidemic scenario. Subsequently, leveraging the air pollutant concentrations in Chengdu over three epidemic years, we projected the concentrations for 2023. A comprehensive comparison was conducted between expected and actual air quality values from both absolute and relative perspectives. Model diagnostics, including a residual autocorrelation test and a stationarity check, were implemented for all candidate time-series models (ARIMA/SARIMA/exponential smoothing). The final optimal model was selected based on AIC, BIC and residual white noise test criteria.

Results and Discussion

In Sichuan Province, China, the first COVID-19 case was diagnosed on January 21, 2020, and the number of new cases peaked on January 30 (35 new cases were confirmed on that day). Subsequently, the number of cases gradually declined, approaching 0 after February 28 (Fig. 1). During this period, there were 538 COVID-19 cases, among which 150 cases were reported in Chengdu. The daily average Air Quality Index (AQI) and $PM_{2.5}$, PM_{10}, and NO_2 concentrations exhibited a similar trend, in which they all declined significantly after January 22 (Fig. 1).

Spearman correlation analysis was first employed to explore the crude associations between air quality indicators and daily new COVID-19 cases. As presented in Table 1, significant negative correlations were observed between COVID-19 incidence and air quality parameters, including AQI (r = −0.746), PM_{10} (r = −0.828), $PM_{2.5}$ (r = −0.675), and NO_2 (r = −0.459), whereas no significant correlations were detected for other confounding variables.

GAMs were subsequently utilized to evaluate the short-term lag effects (0-7 days) of air pollutants on daily COVID-19 cases, with rigorous adjustments for long-term temporal trends, public holidays, wind speed, population mobility, and epidemic intervention intensity. After full multivariate adjustment, distinct lag responses were identified across different air pollutants (Fig. 2). Specifically, NO_2 exhibited a significant negative association with daily COVID-19 cases at a 5-day lag (RR = 0.9725, 95% CI: 0.9510-0.9945, $P<0.05$). Similarly, PM_{10} showed a statistically significant negative lag effect at a 5-day lag (RR = 0.9891, 95% CI: 0.9801–0.9981, $P<0.05$). In contrast, neither AQI nor $PM_{2.5}$ displayed any significant association with COVID-19 incidence across all lag days (0-7 days, all $P>0.05$). Collectively, these analytical results indicated that, after controlling for meteorological factors, temporal trends, and human activity-related confounding factors, only 5-day-lagged PM_{10} and NO_2 were independently and negatively associated with daily new COVID-19 cases, while AQI and $PM_{2.5}$ had no statistically significant short-term lag effects

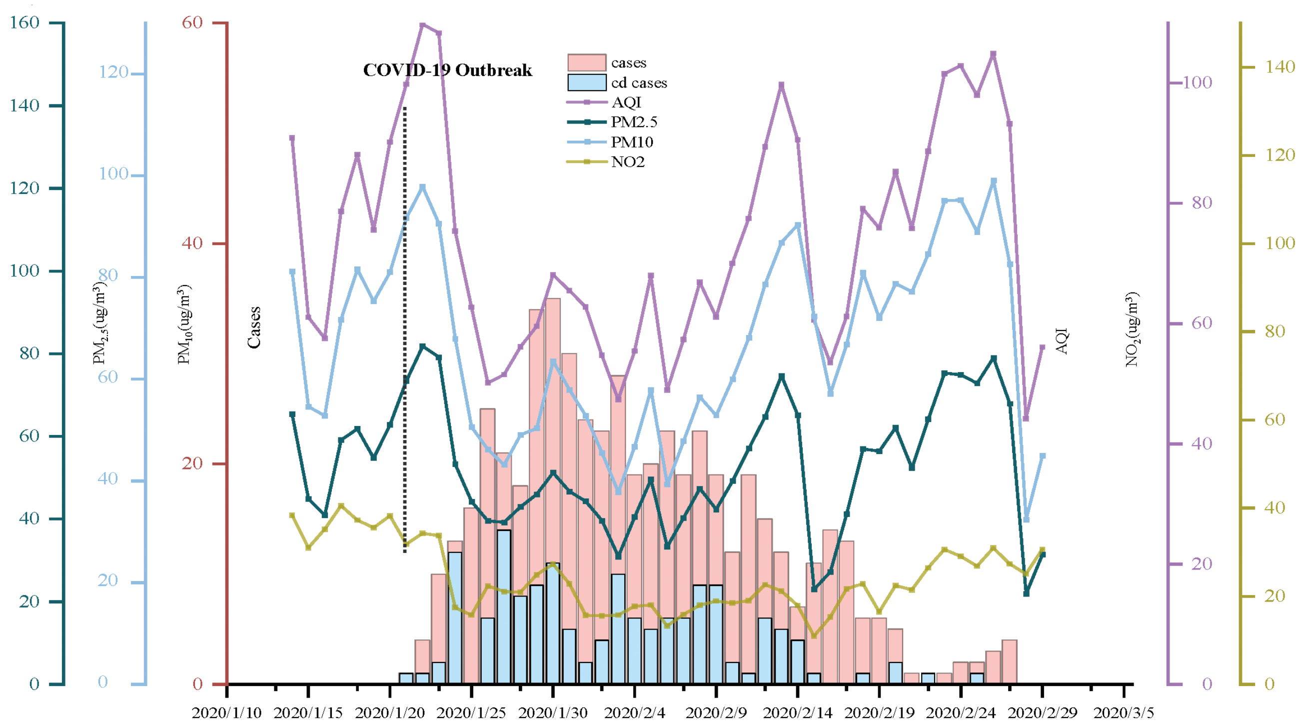

Fig. 1. Trends of daily air pollutant concentrations and COVID-19 cases.

Table 1. Correlation between air pollutants and new COVID-19 cases (**P<0.01).

	AQI	CO	NO_2	O_3	SO_2	$PM_{2.5}$	PM_{10}
rs(same-day)	−0.746**	0.041	−0.459**	−0.264	−0.238	−0.675**	−0.828**
rs(5-day lag)	−0.289	/	−0.028	/	/	−0.161	-0.442**

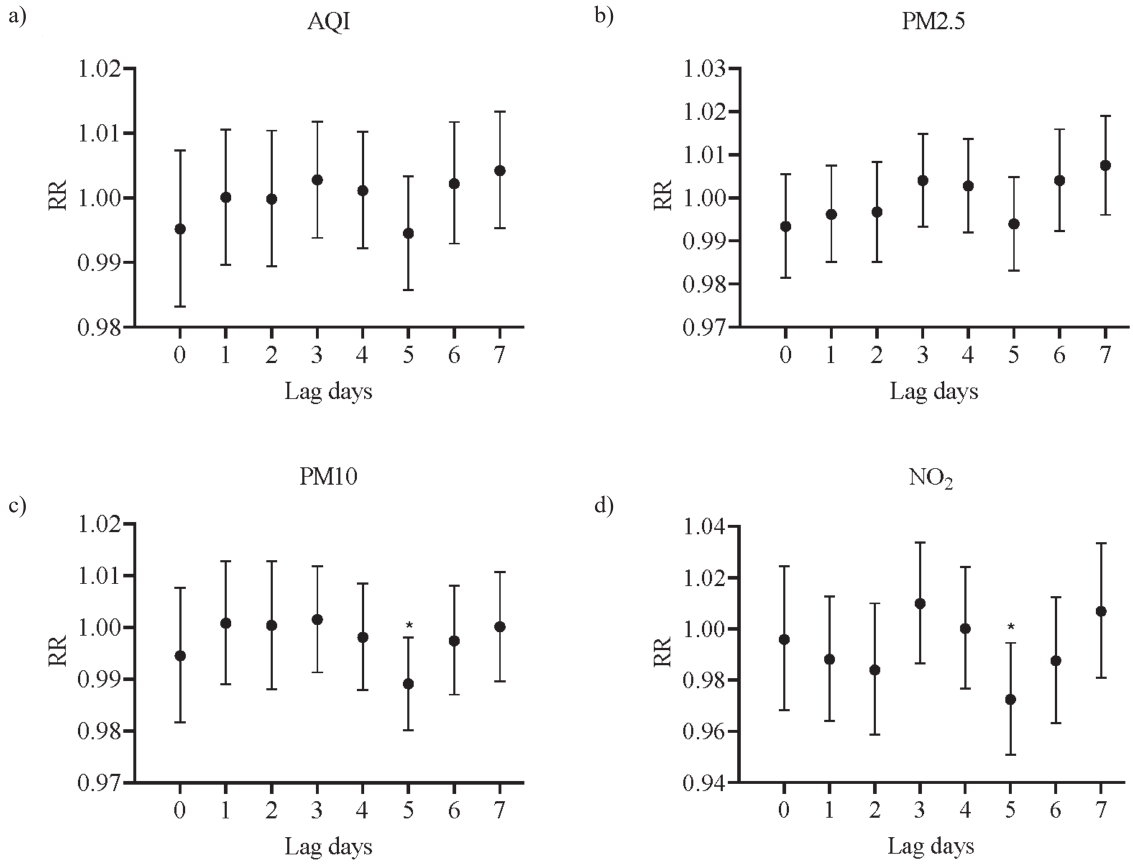

Fig. 2. Air pollutant concentrations and confirmed COVID-19 cases, January-February 2020.

on COVID-19 transmission during the study period. To further verify the spatial robustness of the above associations, supplementary analyses were performed based on urban-scale observational data from Chengdu City, with a total of 150 confirmed COVID-19 cases recorded during the study period. Using the identical fully adjusted Poisson generalized additive model framework, we evaluated the short-term lag effects of air pollutants at the municipal level. The results demonstrated that $PM_{2.5}$ was significantly negatively correlated with daily COVID-19 cases at a 3-day lag (RR = 0.9895, 95% CI: 0.9800-0.9991, $P<0.05$). No statistically significant associations were observed for AQI, NO_2, and PM_{10} across all lags from 0 to 7 days. Notably, consistent negative lag trends were still detectable for particulate pollutants at the urban level. The lowest RR value of PM10 was observed at a 5-day lag (RR = 0.9944, 95% CI: 0.9862-1.0026), which was consistent with the lagged pattern observed in the provincial-level analysis. For NO_2, the minimum RR value occurred at a 2-day lag (RR = 0.9935, 95% CI: 0.9864-1.0007), reflecting a potential marginal protective trend at the city scale.

Chengdu was under lockdown measures throughout January and February 2020. As shown in Fig. 3, the observed AQI and the concentrations of PM_{10}, $PM_{2.5}$, and NO_2 in January and February 2020 exceeded both the levels recorded during the same period in 2019 and the concentrations predicted for 2020 using the time series model. For the AQI (Fig. 3a)), if the epidemic had not occurred, the AQI distribution in Chengdu during 2020 closely resembled that of 2019, exhibiting the highest values in January followed by a progressive decrease and fluctuation, culminating in a minimum in September, followed by a modest upward trend. The overall trend of AQI resembled the approximate shape of an irregular letter "W". The observed average AQI for 2020 was 78.25, which was slightly higher than the predicted value of 71.25.

As depicted in Fig. 3b) and c), if an outbreak had not occurred, the distribution of PM_{10} and $PM_{2.5}$ in Chengdu in 2020 mirrored that of preceding years. Their concentrations peaked early in the year, gradually decreased, reached a minimum in September, and subsequently increased, showing a trend of being high at both the start and end of the year and low in the middle, with an irregular "V"-shaped distribution. The observed average PM_{10} value was 63.92 μg/m³, while the predicted value was 54.71 μg/m³, meaning that the actual value was approximately 16.83% higher than the predicted value. Similar findings were obtained for $PM_{2.5}$, where the measured value (40.83 μg/m³) exceeded the predicted value (34.64 μg/m³) by 17.87%. As depicted in Fig. 3d), in the hypothetical scenario where the epidemic had not occurred, the NO_2 levels in Chengdu during 2020 peaked in January, experienced

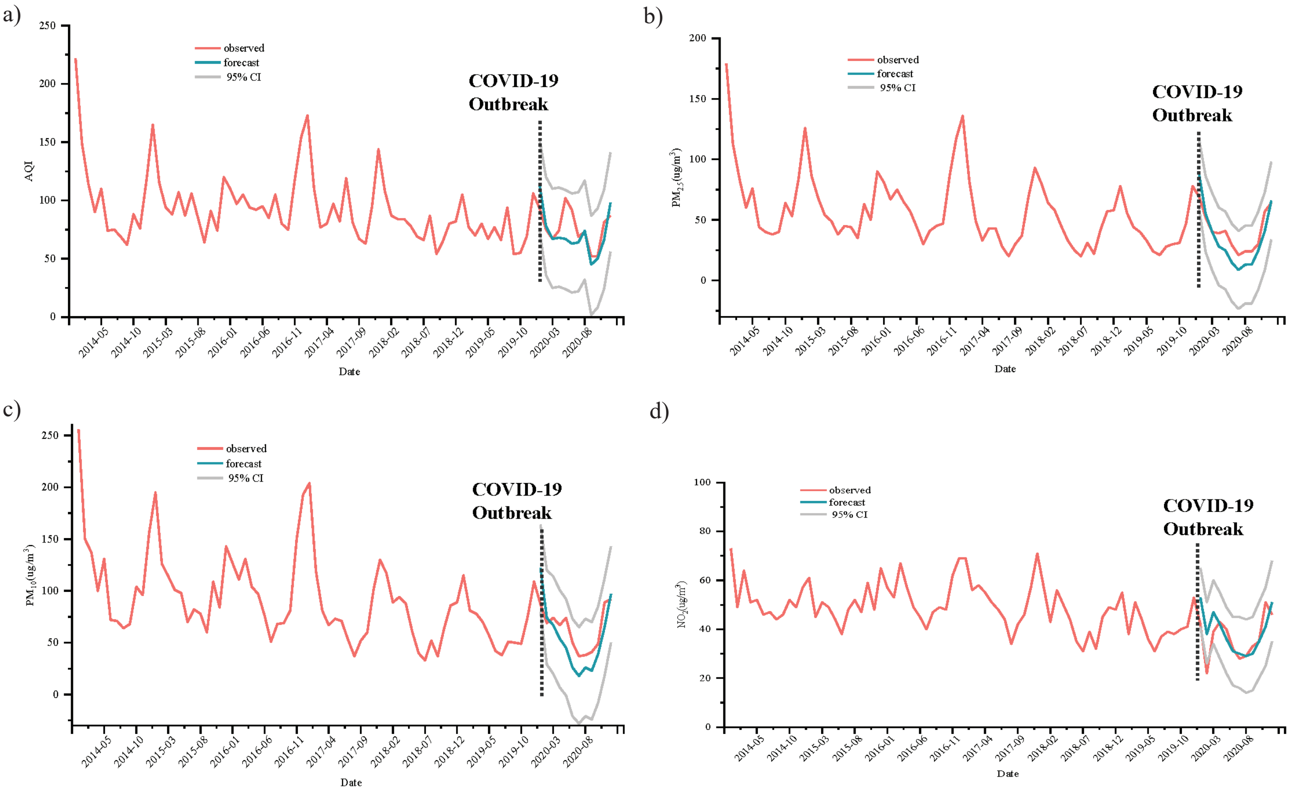

Fig. 3. The effects of the COVID-19 outbreak on air pollutants according to time-series models.

a substantial decrease in February, rose again in March, followed by a continuous decline until reaching a nadir in August, and subsequently increased again. The mean NO_2 concentration in 2020 (36.67 µg/m³) notably lagged that of 2019 (41.92 µg/m³) and fell below the predicted value (38.57 µg/m³).

COVID-19 was treated as a Category B disease in China on 8 January 2023. Based on the above policy, we further investigated the trends in the variations of all pollutant parameters. As illustrated in Fig. 4, the measured AQI and the PM_{10}, $PM_{2.5}$, and NO_2 concentrations in February and March 2023 surpassed both the levels observed during the corresponding period in 2022 and the concentrations forecast for 2023 by the time series model. As shown in Fig. 4a), between February 2023 and January 2024, the AQI exhibited a fluctuating pattern, with the observed average value peaking at 79.08, marginally surpassing both the average AQI during the three-year epidemic period of 76.67 and the predicted value of 77.48 derived from the time series model for the corresponding period. As illustrated in Fig. 4b) and c), the measured concentrations of PM_{10} and $PM_{2.5}$ demonstrated robust agreement with the predicted values, with annual average concentrations being closely aligned. In February 2023, the observed levels of PM_{10} and $PM_{2.5}$ surpassed the predicted values, exhibiting an increase compared with the corresponding period in 2022. Notably, during December 2023 and January 2024, the measured concentrations of PM_{10} and $PM_{2.5}$ exceeded the predicted values. The trend of NO_2 closely mirrored that of PM_{10} and $PM_{2.5}$, with measured concentrations surpassing the predicted values in February 2023 and January 2024 yet remaining near the annual average (Fig. 4d)).

The COVID-19 pandemic had severe health, social and economic impacts. However, the reduction in air pollution resulting from lockdown measures could be regarded as a benefit of the COVID-19 pandemic. Chengdu is located in the western part of the Sichuan Basin, characterized by dense urban development, high population density, strong economic development, and energy production heavily reliant on fossil fuels [8, 9]. These factors contribute to substantial emissions of primary pollutants in the region, resulting in persistently high aerosol optical thickness levels [10, 11]. Consequently, the Sichuan Basin is recognized as one of the four regions in China with the most severe air pollution, particularly during the winter season [12, 13]. In line with findings from other regions in China [14, 15], following the onset of the COVID-19 outbreak, the number of confirmed COVID-19 cases in Sichuan exhibited an initial increase, followed by a subsequent decline. Population mobility was also an important contributor to the COVID-19 pandemic [16]. As the Spring Festival approached, there was a continuous increase in the flow of Spring Festival travel, leading to a surge in the migration index, reaching its peak on January 21, 2020. Wuhan implemented a lockdown on January 23, 2020, which was followed by work stoppages, travel restrictions, and traffic controls in Sichuan Province. This reduction in travel demand

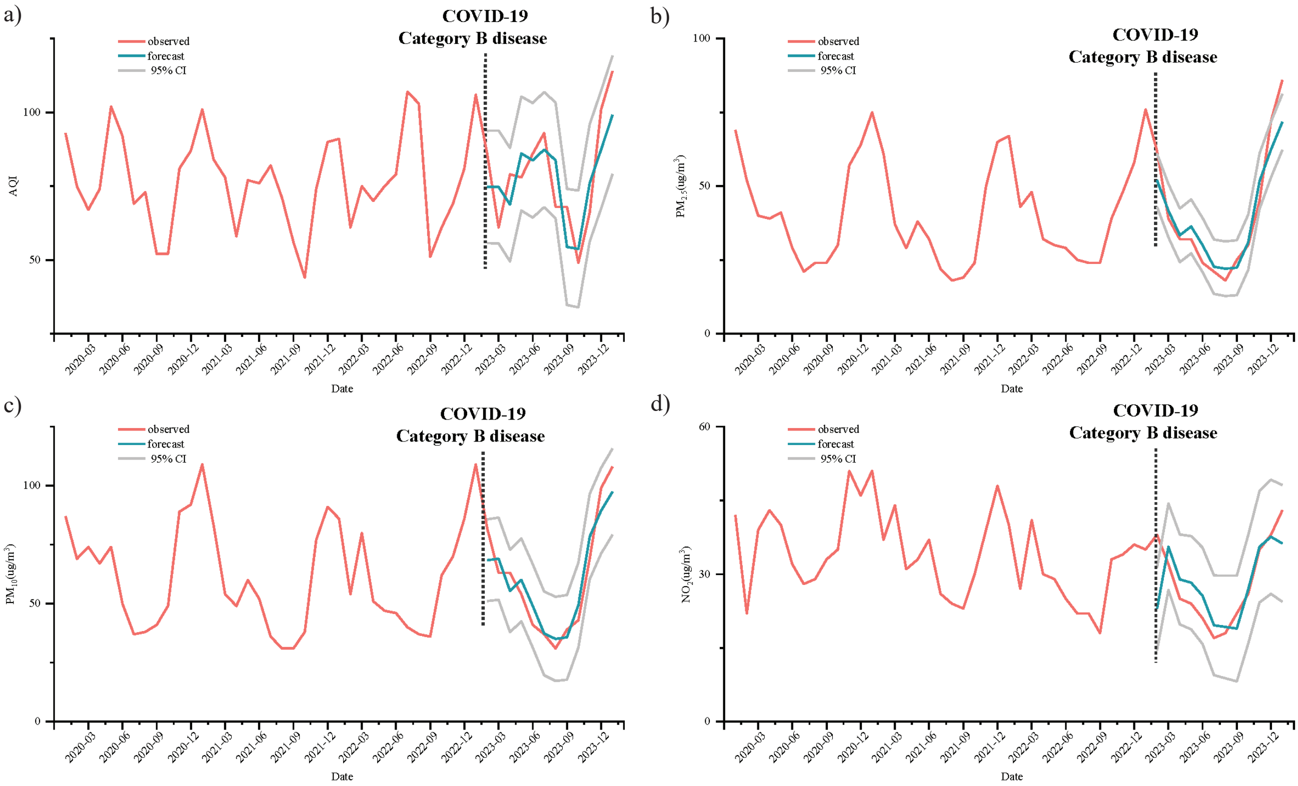

Fig. 4. Air pollutant levels post COVID-19 as a Category B disease in time-series models.

had a noticeable impact on air quality, as depicted in Fig. 1, where the AQI and the concentrations of NO_2, $PM_{2.5}$ and PM_{10} showed significant decreases. Among these pollutants, NO_2 is primarily emitted from traffic sources and exhibits the most pronounced response to reduced emissions resulting from control measures [17]. Consequently, the mass concentration of NO_2 remained consistently low until the gradual lifting of restrictions in late February. These changes highlighted the effectiveness of the implemented measures in curbing traffic-related emissions and improving air quality during the lockdown period.

Since the onset of the COVID-19 pandemic, numerous environmental health and public health experts globally have undertaken research on the correlation between air pollution and the transmission of COVID-19. The findings of most of these studies consistently converge on a singular conclusion: heightened levels of air pollutants correspond to an increased susceptibility to contracting the novel coronavirus, exacerbated symptomatology post-infection, elevated likelihood of experiencing mild to severe manifestations, and potentially fatal outcomes [18-20]. To our surprise, we found negative relationships between the AQI, NO_2, $PM_{2.5}$, PM_{10}, and daily confirmed COVID-19 case counts in Sichuan (Table 1). We could explain these results as follows. Although a correlation exists between air pollutants and the transmission of the novel coronavirus, their association is considered indirect [21, 22]. The primary modes of transmission of the novel coronavirus are respiratory droplets and close contact, primarily influenced by human behaviors. The increased transmission of the novel coronavirus in areas with higher air pollutant levels is not primarily attributed to direct interactions between the virus and pollutants [23, 24]. Air pollution might indirectly contribute to the transmission dynamics by compromising respiratory health and immune responses, thereby heightening people's susceptibility to respiratory infections, including SARS-CoV-2 infection [25-28]. The topography of a basin can influence the rate of sedimentation and the dispersion path of pollutants [29, 30]. This can facilitate the settling of certain pollutants to the ground or their confinement to specific areas within the basin, rather than allowing them to disperse into the air easily. Such mechanisms might potentially decrease the likelihood of airborne transmission of viruses.

The AQI serves as a classification index that simplifies the assessment of air pollution levels by aggregating data on routinely monitored air pollutant concentrations into a single conceptual index [31]. It provides a representation of the overall air pollution level and the corresponding air quality status. Surprisingly, the AQI index for 2020 did not exhibit significant deviations from that for 2019, with a modest decline of 7.69% observed during January and February compared with that in the same period in 2019. $PM_{2.5}$, originating mainly from industrial sources, serves as a representative pollutant, while PM_{10} encompasses both fine particles ($PM_{2.5}$) and coarse particles ($PM_{2.5}$-PM_{10}) [32]. Compared with 2019, the concentration of PM_{10} in 2020 showed a decrease of 7.48%, with a more substantial reduction of 20.41% during the lockdown period in January and February 2020, compared with that in the same period in 2019. In 2020, the concentration of $PM_{2.5}$ was 3.92% lower than that in 2019, and during January and February, it exhibited a decrease of 9.70% compared with that in the corresponding period in 2019. However, the decline in PM_{10} and $PM_{2.5}$ concentrations was not as pronounced as that of NO_2. Notably, despite the strict traffic and mobility restrictions implemented during the lockdown period that should have reduced particulate matter emissions, the observed concentrations of $PM_{2.5}$ and PM_{10} remained higher than the model-predicted levels. This phenomenon may be attributed to the unique terrain of the Sichuan Basin and unfavorable winter meteorological conditions, including stable atmospheric stratification, shallow boundary layer height, weak horizontal wind speed, and poor air diffusion capacity, which greatly limited pollutant dilution and offset the benefits of emission reductions. This mechanism has been well-documented in previous studies: Li et al. [33] found that the closed topography of the Sichuan Basin significantly hindered the horizontal and vertical diffusion of pollutants, leading to the sustained accumulation of particulate matter in winter even under reduced emissions; Wang et al. [34] further confirmed that adverse winter meteorological conditions in southwestern China could completely offset the air quality benefits brought by emission reduction measures.

From 2023 onwards, there were no significant changes in the concentrations of PM_{10} and $PM_{2.5}$ compared with those in 2020, although a slight increase was observed in January and February. Wang et al. [35] developed a model to investigate the influence of COVID-19 on air quality across 325 cities in China. The results of their study indicated that in the cities under lockdown measures during 2020, there was a notable decrease in the AQI of 12.2%. Moreover, the concentrations of $PM_{2.5}$ and PM_{10} exhibited reductions of 13.1% and 15.3%, respectively. Liu et al. [36] conducted a study in the four major cities of the Yangtze River Delta, namely Shanghai, Hangzhou, Nanjing, and Hefei. Their findings revealed a substantial reduction in the $PM_{2.5}$ levels, ranging from 37% to 55%, during the lockdown period. The decrease in air pollution in Chengdu was comparatively less significant than that in the other cities. We speculate that this discrepancy may be attributed to two aspects: on the one hand, the unique topographic constraints of the Sichuan Basin; on the other hand, with the government's accumulated experience in SARS-CoV-2 prevention and control, large-scale production suspensions were not implemented, which limited the pandemic's impact on PM_{10} and $PM_{2.5}$ concentrations.

NO_2 is a prominent pollutant emitted from transport sources, and its control and mitigation effects are particularly noticeable [37]. As Chengdu has the highest car ownership rate in China, its air quality would be very sensitive to changes in NO_2 concentrations caused by the COVID-19 lockdown and subsequent easing measures. The observed outcomes were in line with expectations: Following the onset of the COVID-19 outbreak, the NO_2 concentration in 2020 exhibited a notable decrease (12.52%) compared with that in 2019. Specifically, during January and February, the concentration experienced a remarkable reduction of 31.18% compared with that in the corresponding period in 2019, and was lower than the NO_2 concentration observed during the same period from 2014 to 2019 and surpassed the projections of the time series model. Similarly, in January and February 2023, the concentrations exceeded the levels observed in 2020 and surpassed the predictions of the time series model.

Model diagnostic tests confirmed that the established SARIMA models were reliable for simulating conventional seasonal variations of air pollutants under normal meteorological conditions. However, these linear time-series models have inherent limitations in capturing basin-specific extreme winter meteorological events, such as abrupt temperature inversion and persistent stagnant atmospheric conditions with poor diffusion capacity [38]. This structural deficiency leads to systematic underestimation of particulate matter concentrations during severe pollution episodes, which further explains the consistent deviation between model-predicted values and actual observed pollutant levels during pollution-prone periods.

Conclusions

Our study shed light on the impact of the COVID-19 pandemic on air quality in Chengdu, China. The lockdown measures implemented in response to the pandemic resulted in a significant decrease in AQI and NO_2, $PM_{2.5}$, and PM_{10} concentrations. Notably, NO_2, which is predominantly emitted by transportation sources, exhibited the most pronounced response to the reduced emissions resulting from control measures. However, the magnitude of the changes in air pollution during the COVID-19 pandemic in Chengdu was relatively small compared with that of other major Chinese cities. We surmised that the topography of the Sichuan Basin might have played a role in air pollution dynamics, potentially reducing the likelihood of airborne transmission of the virus. Given the observational ecological design, causal interpretation is not supported. Further research is needed to fully understand the complex relationship between air pollution and SARS-CoV-2 transmission under the joint influence of emission changes, topography, and critical meteorological conditions.

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Conflict of Interest

The authors declare no conflict of interest.

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