Journal of Environmental Engineering and Landscape Management
ISSN 1648–6897 / eISSN 1822-4199
2023 Volume 31 Issue 3: 219–231
https://doi.org/10.3846/jeelm.2023.19472

IMPACT OF THE COVID-19 LOCKDOWN ON AIR POLLUTION IN AN INDUSTRIAL CITY IN NORTHEASTERN CHINA

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Received 27 December 2022; accepted 05 June 2023

Highlights

- The effects of lockdown measures on air quality were explored in this paper.
- $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO decreased, but O_3 increased relative to pre-lockdown period.
- Responses of air pollutants to lockdown were more sensitive in downtown areas than those in the suburbs.
- Reduction in anthropogenic emissions can achieve substantial air quality improvement.

Abstract. Many studies in China investigated how the lockdown following the coronavirus disease 2019 substantially affected air quality; however, few were conducted in Northeastern China. Here, the changes in six criteria air pollutants, including particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3), were investigated in Shenyang from January to May 2015–2020. Compared with the pre-lockdown, the mass concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO during the lockdown decreased by 40.3% to 48.6%, indicating a positive impact of lockdown policies on reducing pollutant emissions. The responses of $PM_{2.5}$, PM_{10}, and CO to the lockdown measures in downtown areas were more sensitive than in the suburbs. However, the O_3 concentration showed the opposite trend, attributed to the drop in NO_x and particulate matters. Compared to the same period in 2015–2019, the proportion of days with good air quality increased from 63.2% to 77.2% during the lockdown and Shenyang experienced no severe pollution. Our results suggest that reducing human activities can improve air quality; however, coordinated control policies of O_3, $PM_{2.5}$, and NO_2 are imperative.

Keywords: novel coronavirus, air quality index, spatiotemporal distribution, lockdown, particulate matter, nitrogen dioxide, carbon monoxide, sulfur dioxide, ozone.

Online supplementary material: Supporting information for this paper is available as online supplementary material at https://doi.org/10.3846/jau.2023.19472

Introduction

In late December 2019, the first case of the novel coronavirus (COVID-19) was detected in Wuhan, Hubei Province, China (Harapan et al., 2020; X. Huang et al., 2020). Subsequently, COVID-19 has spread globally owing to its high propagation rates among humans (World Health Organization, 2020). To contain the transmission of COVID-19, national and region-wide lockdown measures have been strictly imposed in various countries, including restrictions on human mobility and public transportation and closure of industries and public areas (Huang & Li, 2022; Jia et al., 2023; Sekar et al., 2023; J. Wang et al., 2023; Q. Zhang et al., 2023). The COVID-19 lockdown has adversely impacted human life and socio-economic growth (Hammad et al., 2023; Han et al., 2023; Vadiati et al., 2023). However, this also provided a "quasi-natural" experiment to explore the impacts of human activities on air quality. This provides valuable insights for the post-epidemic establishment of environmental policies.

Many studies have investigated the changes in air quality during the COVID-19 outbreak based on ground-level observations, satellite-based observations, and model simulations across the world (Bao & Zhang, 2020; He et al., 2020; X. Huang et al., 2020; Le et al., 2020; L. Li

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et al., 2020; Liu et al., 2020; Singh et al., 2020; Wang & Zhang, 2020; P. Wang et al., 2020a; Y. Wang et al., 2020b; Xu et al., 2020; Y. Zhao et al., 2020; H. Zheng et al., 2020; Zhu et al., 2020; Adam et al., 2021; Cai et al., 2021; Chu et al., 2021; Sbai et al., 2021; Song et al., 2021; H. Wang et al., 2021a; M. Wang et al., 2021b; B. Zheng et al., 2021; Cao et al., 2022; Cooper et al., 2022; Huang & Li, 2022; K. Li et al., 2022; Mamtimin et al., 2022; Zeng & Wang, 2022; Bagherinia et al., 2023; Gao et al., 2023; Jia et al., 2023; Pushpawela et al., 2023; Ren et al., 2023; Sekar et al., 2023; J. Wang et al., 2023; Wang & Ge, 2023; Wong et al., 2023; J. Yang et al., 2023; Q. Zhang et al., 2023). Most studies report an improvement in air quality and a significant reduction in $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2 during the lockdown compared to pre-lockdown periods and/or previous years, suggesting a significant correlation between anthropogenic activities and air pollution (Bao & Zhang, 2020; He et al., 2020; Huang & Li, 2022; K. Li et al., 2022; Mamtimin et al., 2022; Zeng & Wang, 2022; Bagherinia et al., 2023; Gao et al., 2023; Jia et al., 2023; Pushpawela et al., 2023; Ren et al., 2023; Sekar et al., 2023; J. Wang et al., 2023; Wang & Ge, 2023; Wong et al., 2023; J. Yang et al., 2023; Q. Zhang et al., 2023). However, several studies have found that the lockdown measures do not significantly prevent air pollution (Le et al., 2020; P. Wang et al., 2020a; Z. Chen et al., 2021; Mo et al., 2021; Song et al., 2021; Luo et al., 2022; Q. Ma et al., 2023; L. Wang et al., 2024). For example, an increased concentration of O_3 was observed in several regions during the lockdown, which would offset the benefit of a decrease in other air pollutants (Le et al., 2020; L. Wang et al., 2020c; Q. Ma et al., 2023). Several studies have also found non-significant changes or even increases in SO_2 and $PM_{2.5}$ accompanied by severe haze events (Z. Chen et al., 2021; Mo et al., 2021; Song et al., 2021; L. Wang et al., 2024). The variations in air pollutant concentrations in different cities during the lockdown period can be attributed to differences in geographical location, city development, economic structure, meteorological conditions, and topographical factors (L. Li et al., 2020; Sharma et al., 2020; P. Wang et al., 2020a; Mo et al., 2021; Yao et al., 2021). Therefore, investigating the changes in air quality during the lockdowns in different cities and regions is necessary.

Severe air pollution poses a significant threat to human health in China. Stringent home-based quarantine measures provide an unexpected opportunity to evaluate the efficiency of national air pollution control policies. Previous studies have concentrated on changes in air quality during the COVID-19 lockdown to study the relationships between anthropogenic emissions and air pollution (Bao & Zhang, 2020; He et al., 2020; X. Huang et al., 2020; L. Li et al., 2020; P. Wang et al., 2020a; Y. Wang et al., 2020b; Zhu et al., 2020; Cai et al., 2021; H. Wang et al., 2021a; M. Wang et al., 2021b; Dong et al., 2022; K. Li et al., 2022; Zeng & Wang, 2022; Gao et al., 2023; Guo et al., 2023; Jia et al., 2023; Ren et al., 2023; Wang & Ge, 2023). However, most of these studies have concentrated on changes in air pollutant concentrations at large spatial scales or in highly developed regions, such as the North China Plain, Yangtze River Delta, and Pearl River Delta; few studies have been conducted in cities in Northeastern China (J. Wang et al., 2023).

Shenyang is the largest city and a heavy industrial base (including the petrochemical industry and iron and steel smelting) in Northeastern China (H. Yang et al., 2020; C. Huang et al., 2021; Y. Ma et al., 2021). Along with economic development, industrialization, and urbanization, air pollution in Shenyang has become increasingly severe owing to an increase in energy consumption (Y. Ma et al., 2021). Meanwhile, Shenyang has a long heating period and high air pollutant emissions during winter (Y. Ma et al., 2021). In early 2020, Shenyang experienced a COVID-19 outbreak and implemented strict control measures during the lockdown period. However, few studies have been published on the impact of the COVID-19 lockdown on air quality in Shenyang.

To address this shortage, Shenyang was selected as an example in this study to explore changes in six criteria pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) during COVID-19. The hourly air quality monitoring data of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 at nine ambient air quality monitoring stations in Shenyang from January to May 2015–2020 were obtained. The nine monitoring stations were distributed in different areas of Shenyang, covering the downtown areas and suburbs (Figure 1). Our primary objectives were as follows: 1) to examine the temporal variations in six criteria pollutants during the COVID-19 period; 2) to investigate differences in the changes in six criteria pollutants in response to the COVID-19 lockdown measures between the downtown areas and suburbs; and 3) to examine the impact of the imposed lockdown on air quality. Our results contribute to understand the impact of the lockdown on air quality and provide policy suggestions for controlling air pollution in the post-epidemic era.

1. Material and methods

1.1. Study site

Shenyang (41°48′11.75″ N, 123°25′31.18″ E), located in the middle of Liaoning Province and south of Northeast China, is a crucial traffic center and economic hinterland in Northeastern China (Figure 1).

The topography of Shenyang primarily includes plains and hills, with a hilly area situated in the southeast and northeast and a plain area situated in the west. The region is characterized by a temperate monsoon climate with a mean annual temperature of 6.2–9.7 °C. The temperature changes rapidly in spring and autumn over a short duration, with a windy spring and sunny autumn. The mean annual precipitation is 600–800 mm and is concentrated in the summer.

1.2. Lockdown period division

According to the requests of Order No. 1 and Order No. 9 issued by the Prevention and Control Headquarters of

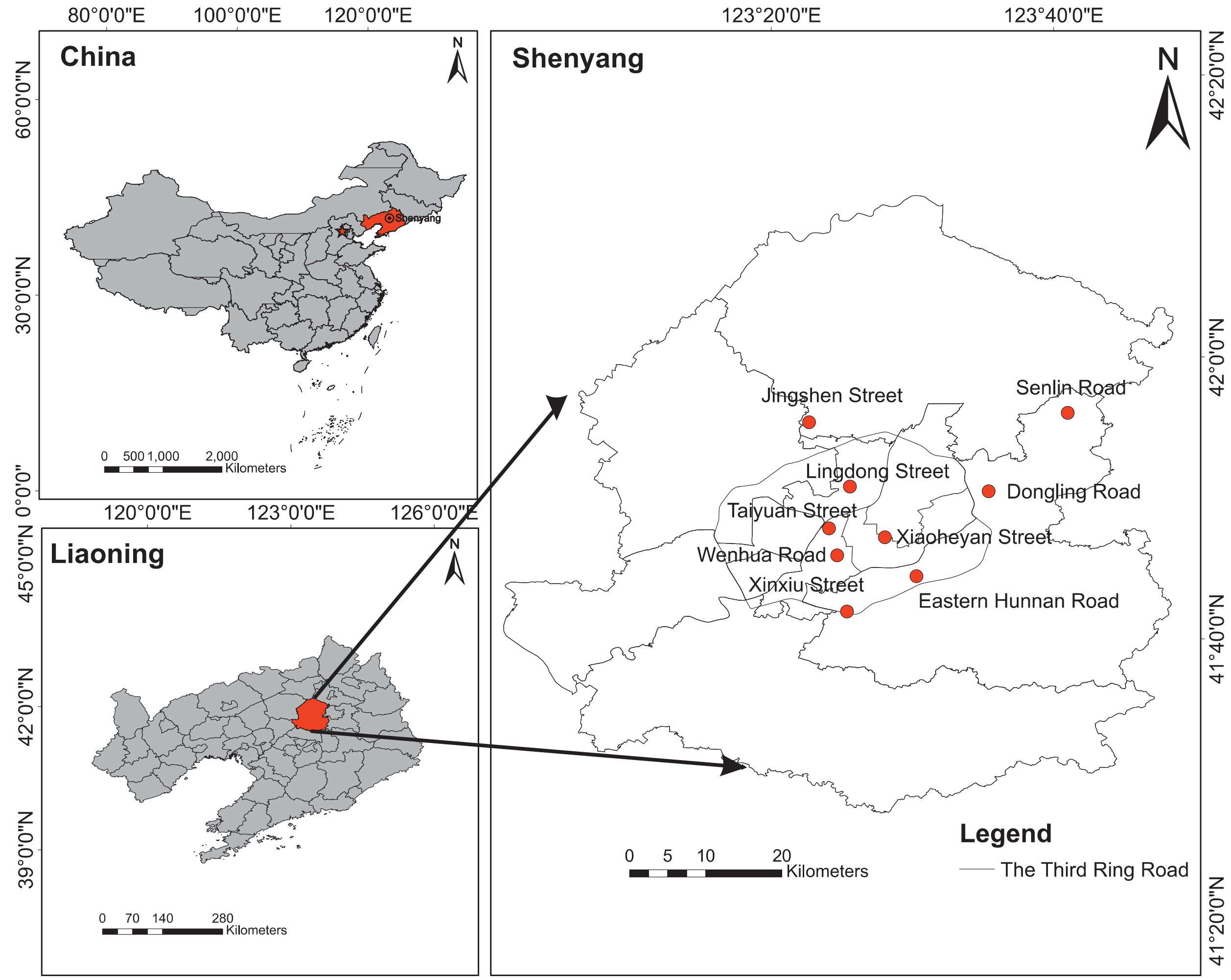

Figure 1. Geographical location and distribution of ambient air quality monitoring stations in Shenyang. The black line represents the Third Ring Road of Shenyang. Areas within the black line is defined as the downtown area, and areas outside the black line represent the suburbs

COVID-19 in Shenyang, emergency response procedures were enacted, and individuals had to stay home from January 26, 2020. From March 22, 2020, social production and the daily life were fully restored. To understand the changes in air quality, this study divided the entire period into three stages: before the lockdown (January 1 to 25, 2020), during the lockdown (January 26 to March 22, 2020), and after the lockdown (March 23 to May 31, 2020).

1.3. Data sources

Three categories of data were used in this study, including air quality data, meteorological data, and socio-economic background data. For air quality data, real-time hourly monitoring data of six criteria pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) and the air quality index (AQI) were obtained from nine ambient air quality monitoring stations in Shenyang from January to May 2015 to 2020 (Table S1). All data were collected from the National Environmental Monitoring Platform (https://air.cnemc.cn:18007/), which provides open access to the public. Figure 1 shows the names and geographical locations of the monitoring stations. Daily meteorological data for Shenyang from January to May 2020, including precipitation (P, mm), temperature (T, °C), and wind velocity (WV, m s^{-1}), were collected from the National Oceanic and Atmospheric Administration of America (NOAA; https://www.ncdc.noaa.gov/). The relative humidity (RH, %) data were obtained from the website (http://rp5.ru/Weather).

Socio-economic background data includes population migration data, passenger volume, number of tourists and total amount of pollutants emission in this study. Population migration data were collected from the Baidu Qianxi (https://qianxi.baidu.com/) and Auto-Navi migration datasets (https://trp.autonavi.com/migrate/page.do), which were obtained from the mapping apps of Baidu and AutoNavi that record personal real-time locations through mobile phones. These datasets were considered to accurately reflect population movements at the city level, which are correlated with air pollution levels (M. Wang et al., 2021b; Wang & Ge, 2023; Q. Zhang et al., 2023). Therefore, the within-city migration (WM) index was employed to measure the intensity of epidemic-induced human mobility restrictions (M. Wang et al., 2021b). According to data availability, the WM index of Shenyang between January 1 and May 8, 2020, and between January 12 and March 28, 2019, was obtained from the Baidu Qianxi dataset. The in-migration (IM) and out-migration (OM) indices of Shenyang between January 1 and May 31, 2019, and 2020 were obtained from the AutoNavi migration dataset. The data of passenger volume, number of tourists and total amount of pollutants emission were collected from Shenyang Statistical Yearbook (2015–2020).

1.4. Data analysis

AQI is a dimensionless index that quantitatively describes air quality. A higher AQI value indicates more severe air pollution. The AQI can be divided into six sets based on its value: excellent (0–50), good (51–100), light pollution (101–150), moderate pollution (151–200), heavy pollution (201–300), and severe pollution (>300) (Table 1).

Air quality data were processed using SPSS 26.0. Differences in air pollutant concentrations between different periods and years were tested using a one-way analysis of variance (ANOVA) and independent t-tests. The spatial patterns of the air quality data were analyzed and mapped using the Kriging interpolation method in ArcGIS 10.3. Pearson's correlation coefficient values were calculated for the relationships between the six criteria pollutants and meteorological data. Statistical significance was defined as $P < 0.05$.

2. Results and discussion

2.1. Temporal changes in air pollutant concentrations in different periods of COVID-19

In this study, the temporal changes in the mass concentrations of six criteria air pollutants in Shenyang during different periods of COVID-19 were analyzed. Before the lockdown, the mass concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3 were 100.2 μg m^{-3}, 130.5 μg m^{-3}, 1.6 mg m^{-3}, 32.4 μg m^{-3}, 59.4 μg m^{-3}, and 27.8 μg m^{-3}, respectively (Figure 2). Particulate matter ($PM_{2.5}$ and PM_{10}) was the major pollutant during this period. The concentration of $PM_{2.5}$ and PM_{10} in the period exceeded corresponding Chinese Ambient Air Quality Grade I standard (CAAQS Grade I) (35 and 50 μg m^{-3}), while daily mean concentrations of the other four pollutants did not exceed CAAQS Grade I in most of this period (Table S3).

Concurrent changes in air pollutant concentrations were observed in Shenyang during the lockdown (Figures 2, 3, and 4).

Among these six criteria air pollutants, $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO showed a significant decreasing trend ($P < 0.05$; Figure 2), which was consistent with other studies (Bao & Zhang, 2020; He et al., 2020; Huang & Li, 2022; K. Li et al., 2022; Mamtimin et al., 2022; Zeng & Wang, 2022; Bagherinia et al., 2023; Gao et al., 2023; Jia et al.,

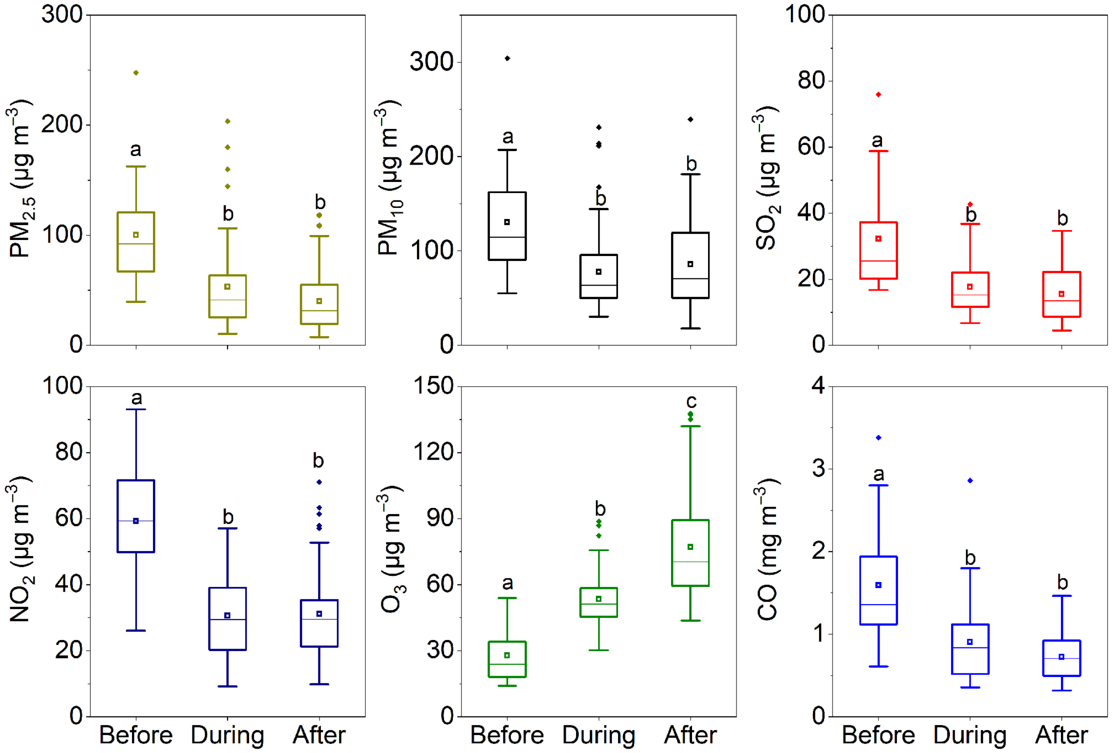

Figure 2. Changes in mass concentrations of six criteria air pollutants in different periods of COVID-19. The fine line and square, lower and upper edges, and error bar outside the boxes represent median and mean values, 25th and 75th, and < 25th and > 75th percentiles of all data, respectively. Different letters indicate significant differences among different periods (one-way ANOVA, $P < 0.05$)

2023; Pushpawela et al., 2023; Ren et al., 2023; Sekar et al., 2023; J. Wang et al., 2023; Wang & Ge, 2023; Wong et al., 2023; J. Yang et al., 2023; Q. Zhang et al., 2023). Compared with the pre-lockdown period, the mass concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO decreased by 46.7%, 40.3%, 48.6%, 45.6%, and 43.2%, respectively, with absolute values of 53.4 $\mu g\ m^{-3}$, 77.9 $\mu g\ m^{-3}$, 30.5 $\mu g\ m^{-3}$, 17.6 $\mu g\ m^{-3}$, and 0.9 $mg\ m^{-3}$, respectively (Figure 2). This suggested that the enforced lockdown as a response to COVID-19 significantly and positively impacted air quality, which is attributed to mandatory traffic restrictions and industry shutdowns (Liu et al., 2020; B. Zheng et al., 2021; Liang et al., 2023; Pushpawela et al., 2023; Wang & Ge, 2023; J. Yang et al., 2023; Q. Zhang et al., 2023). However, $PM_{2.5}$ and PM_{10} concentrations still exceeded CAAQS Grade I (Figure 2, Table S3), indicating the existence of other background sources contributing to air pollution, even with reductions in human activities (Filonchyk & Peterson, 2020). Shenyang was still in the heating period during the lockdown. In order to ensure the lives of residents, the heating and electric power industries which are closely related to the residents were not shutdown.

Among these five air pollutants, NO_2, which is primarily emitted by vehicle activities, decreased significantly, with a maximum decrease of 48.6% (Figure 2), which was consistent with previous studies in Jinan (54%; K. Li et al., 2022), Shanghai (50%; Q. Ma et al., 2023), the Beijing-Tianjin-Hebei region (65%; Ren et al., 2023), India (51%; Sekar et al., 2023), and Sri Lanka (82%; Pushpawela et al., 2023), etc. The most significant decrease in NO_2 was strongly associated with substantial restrictions on local traffic (Li & Lasenby, 2023; Llaguno-Munitxa & Bou-Zeid, 2023; Sekar et al., 2023; J. Wang et al., 2023). According to the migration data of Shenyang in different periods, we also found that the IM, OM, and WM

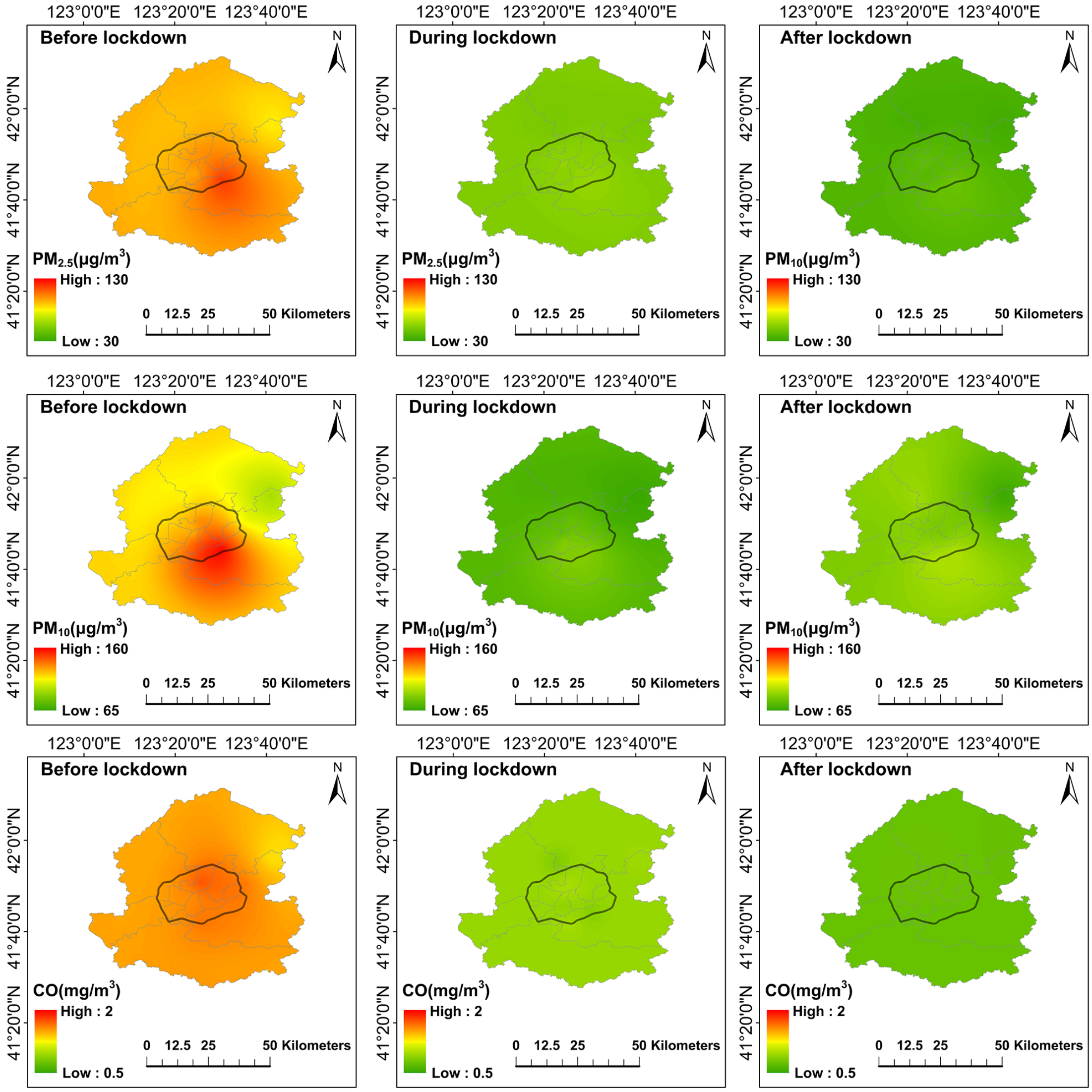

Figure 3. Spatial patterns for $PM_{2.5}$, PM_{10}, and CO mass concentrations before, during, and after the lockdown. The black line represents the Third Ring Road of Shenyang. Areas within the black line is defined as the downtown area, and areas outside the black line represent the suburbs

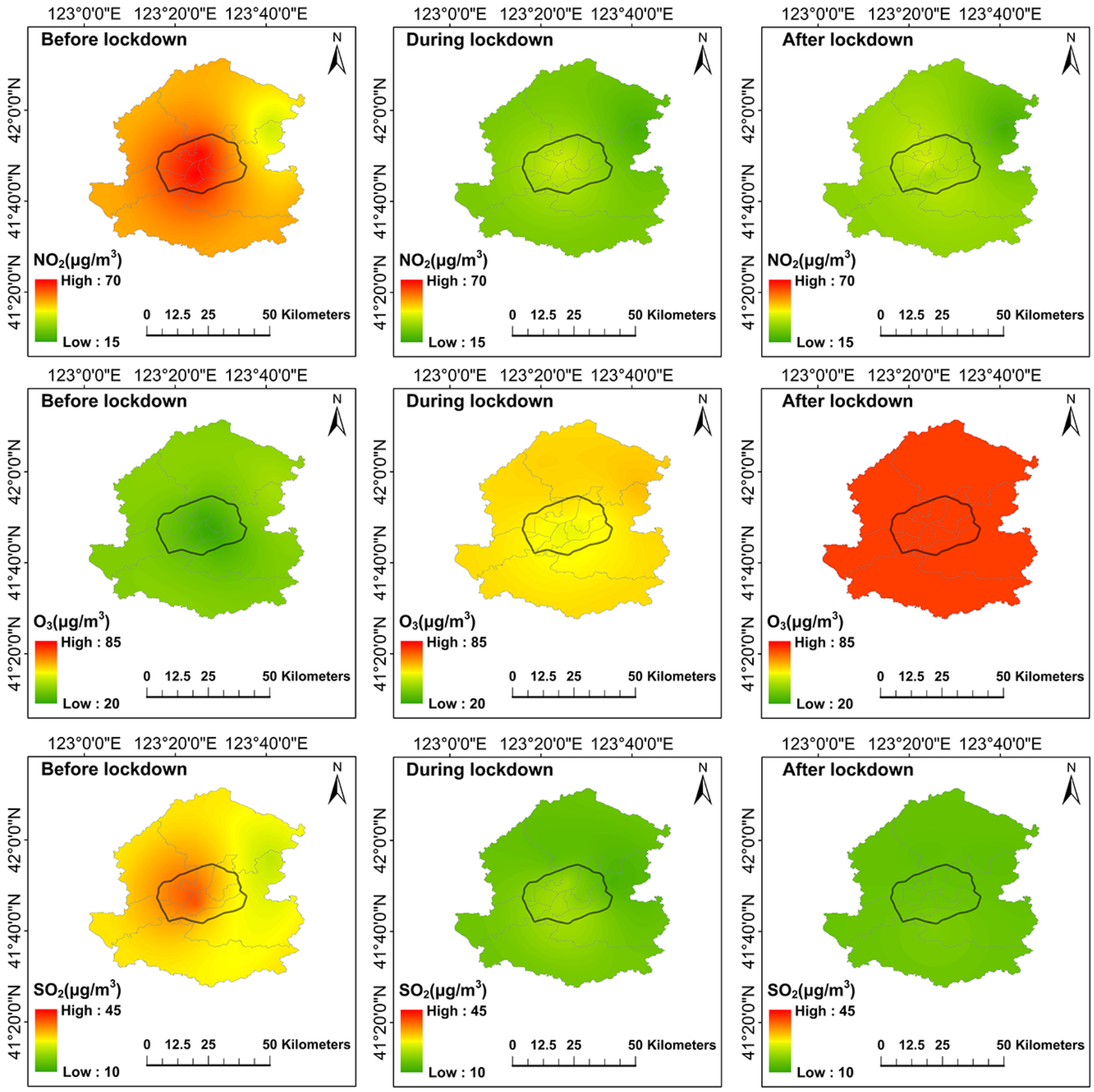

Figure 4. Spatial patterns for NO_2, O_3, and SO_2 mass concentrations before, during, and after the lockdown. The black line represents the Third Ring Road of Shenyang. Areas within the black line is defined as the downtown area, and areas outside the black line represent the suburbs

indices during the lockdown decreased compared to pre-lockdown (Figure S1), indicating that the level of vehicle activity in Shenyang was reduced, accompanied by strict traffic restrictions and home-based quarantine policies.

However, contrary to the above trend, the mass concentration of O_3 during the lockdown was significantly higher than that before the lockdown ($P < 0.05$; Figure 2) and increased by 92.0%, consistent with previous studies in Jinan (K. Li et al., 2022), Urumqi (Mamtimin et al., 2022), Shanghai (Q. Ma et al., 2023), Lanzhou (J. Yang et al., 2023), Beijing-Tianjin-Hebei region (Ren et al., 2023), London (Zhang & Stevenson, 2022), Sri Lanka (Pushpawela et al., 2023), etc. O_3 is a secondary pollutant whose chemical formation depends on nitrogen oxides (NO_x), volatile organic compounds (VOCs), and solar radiation. We also found that the mass concentration of O_3 was negatively correlated with that of NO_2 and PMs (Figure 5).

During the lockdown, the decrease in NO_2 emissions owing to strict traffic restrictions weakened the titration effect of NO_x on O_3, thereby increasing its mass concentration of O_3 (Grange et al., 2021; Sbai et al., 2021; Yin et al., 2021; K. Li et al., 2022; Pushpawela et al., 2023). In addition, a decline in the mass concentration of $PM_{2.5}$ led to an increase in solar radiation and, therefore, enhanced the photochemical production of O_3 (Sicard et al., 2020; Y. Wang et al., 2020d; Gao et al., 2023; Wang & Ge, 2023). Meanwhile, low $PM_{2.5}$ levels also reduce the loss of hydroperoxyl radicals, enhancing O_3 generation via the peroxy radical pathway (K. Li et al., 2019; Sicard et al., 2020).

Since March 23, 2020, COVID-19 has eased significantly, and social production and daily life have resumed. However, the mass concentrations of $PM_{2.5}$, SO_2, and CO showed a downward trend after the lockdown (Figures 2, 3, and 4). This is because the process of resuming social production and daily life is gradual (Cai et al., 2021; J. Yang et al., 2023; Zhang et al., 2023). From the migration data, we also found that the number of individuals traveling across and within the city gradually returned

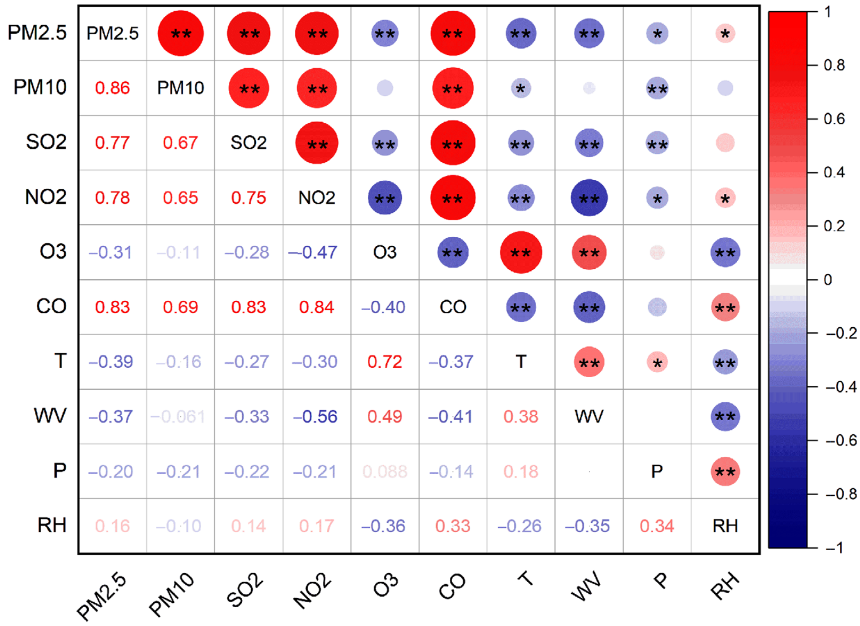

Figure 5. Correlations between six criteria air pollutants and meteorological factors based on daily data from January to May 2020 (*: $P < 0.05$; **: $P < 0.01$)

to pre-lockdown levels (Figure S1). NO_2 and PM_{10} concentrations increased slightly, which may be attributed to the increase in traffic volume and the occurrence of dust events in spring. Notably, O_3 concentration still increased significantly after the lockdown, which is consistent with the results of studies conducted in Nanjing (Hasnain et al., 2021). We speculated that the increase in solar radiation and temperature accelerated photochemical reactions, resulting in an increase in O_3 concentration (Xu et al., 2020; Hasnain et al., 2021; J. Wang et al., 2023).

2.2. Comparison of the air quality between the lockdown period in 2020 and the same period from 2015 to 2019

Compared to the same period in 2015–2019, the mass concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO decreased significantly by 19.9%, 27.9%, 31.5%, 72.6%, and 13.9%, respectively ($P < 0.05$; Figure 6).

We found that the three migration indices during the lockdown were lower than those during the same

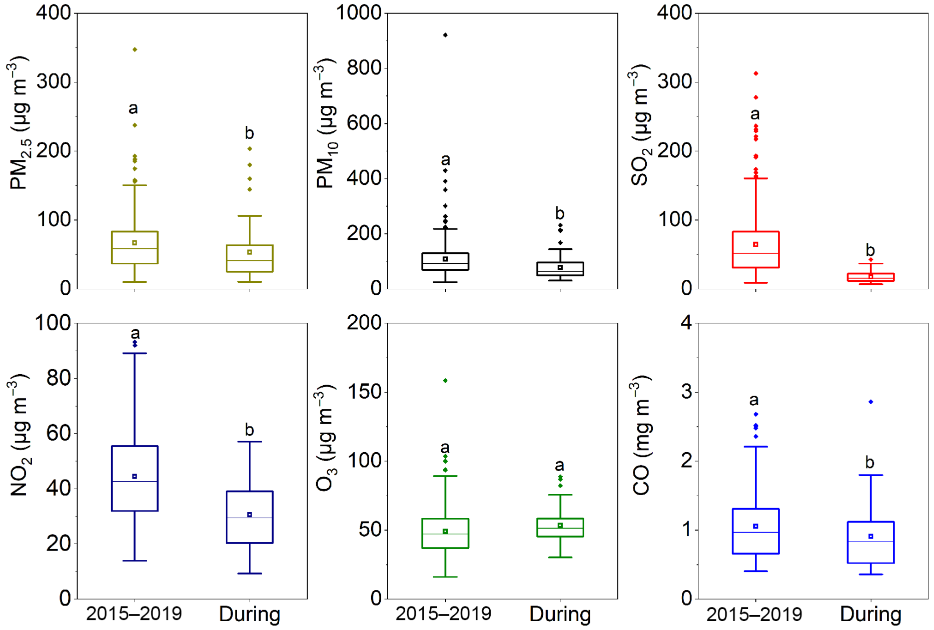

Figure 6. Comparison in mass concentrations of six criteria air pollutants between the lockdown period of COVID-19 and the same period in 2015–2019. The fine line and square, lower and upper edges, and error bar outside the boxes represent median and mean values, 25th and 75th, and < 25th and > 75th percentiles of all data, respectively. Different letters indicate significant differences between the lockdown period of COVID-19 and the same period in 2015–2019 (independent t-test, $P < 0.05$)

Table 1. Air quality in Shenyang during the lockdown and the same period from 2015 to 2019

AQI	Classification of air quality	2015–2019 (day)	During the lockdown (day)	Percentage of the whole period	
				2015–2019	During the lockdown
0–50	Excellent	5	12	8.8%	21.1%
51–100	Good	31	32	54.4%	56.1%
101–150	Light pollution	14	9	24.6%	15.8%
151–200	Moderate pollution	4	1	7.0%	1.8%
201–300	Heavy pollution	2	3	3.5%	5.3%
> 300	Serious pollution	1	0	1.8%	0.0%

period in 2015–2019 (Figure S1). Furthermore, through an analysis of Shenyang Statistical Yearbook (2015–2020), we found that the passenger volume, number of tourists, and total amount of pollutant emissions in Shenyang decreased significantly from 2015 to 2020 (Table S2). These results indicate a reduction in human activities owing to the lockdown policies, which led to a reduction in pollutant emissions.

The air quality indices during the lockdown (January 26 to March 22, 2020) and during the same period in 2015–2019 were also analyzed. The AQI decreased significantly by 19.2% (from 97.3 to 78.6) compared to the same period in 2015–2019 ($P < 0.05$), which is consistent with other studies (Bao & Zhang, 2020; He et al., 2020; Song et al., 2021; Zeng & Wang, 2022; J. Yang et al., 2023; Q. Zhang et al., 2023). This indicates that air quality improved significantly owing to lockdown measures. During the lockdown, there were 44 days of good air quality, 6 days more than the same period in 2015–2019. The overall proportion of good air quality days increased from 63.2% to 77.2% (Table 1). Meanwhile, the number of days of light pollution, moderate pollution, and severe pollution decreased by 7 days compared to the same period in 2015–2019, and the overall proportion of pollution days decreased from 36.9% to 22.9% (Table 1).

Moreover, Shenyang experienced no severe pollution during the lockdown. Our results indicate that strict lockdown policies during the lockdown improved air quality in Shenyang. This can be attributed to restricted traffic levels and industrial production, thereby reducing pollutant emissions from anthropogenic activities (He et al., 2020; Adam et al., 2021; Sbai et al., 2021; Li & Lasenby, 2023; Llaguno-Munitxa & Bou-Zeid, 2023; Sekar et al., 2023; Q. Zhang et al., 2023).

2.3. Spatial distribution of air pollutant concentrations during the lockdown

The spatial patterns of the six criteria air pollutants in Shenyang were analyzed using the Kriging interpolation method (Kumar et al., 2022). The spatial patterns of different pollutants varied, and different areas were not equally affected by different pollutants. Before the lockdown, the mass concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 in the downtown areas tended to be higher than those in the suburbs (Figures 3 and 4), which is consistent with previous studies in Hangzhou and Lanzhou (L. Wang et al., 2020c; J. Yang et al., 2023).

The population is centralized in the downtown areas of Shenyang, with higher heating demand, traffic volumes, and industrial intensity than those in the suburbs, resulting in higher pollutant concentrations (L. Wang et al., 2020c; Y. Ma et al., 2021; Liang et al., 2023; Q. Ma et al., 2023; J. Yang et al., 2023). However, the spatial pattern of O_3 followed the opposite trend, indicating that the mass concentration was higher in the suburbs than in the downtown areas. O_3 is primarily generated by the photochemical reactions of VOCs and NO_x under ultraviolet radiation (Xiao et al., 2018). In the downtown areas, high NO_x concentrations limit the formation of O_3. Conversely, strong solar radiation in the suburbs would promote O_3 formation (Sbai et al., 2021). In addition, with high vegetation coverage in the suburbs, biogenic VOCs (BVOCs) released by plants promote an increase in O_3 concentration (Kulkarni et al., 2013; Z. Wang et al., 2015; Allison, 2020).

During the lockdown, the overall concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO decreased. However, different decreasing amplitudes were observed in different areas, with smaller reductions in $PM_{2.5}$, PM_{10}, and CO in the suburbs than in the downtown areas (Figure S2). This suggests that the responses of $PM_{2.5}$, PM_{10}, and CO to changes in the lockdown measures were more sensitive in the downtown areas than in the suburbs (Q. Ma et al., 2023). Jia et al. (2023) also found that $PM_{2.5}$ in densely populated and economically developed areas declined substantially during the lockdown. In contrast, O_3 showed an increasing trend due to the reduction of $PM_{2.5}$ and NO_2. Moreover, the increasing amplitude of O_3 was smaller in the suburbs than in downtown areas. This may be attributed to the high sensitivity of $PM_{2.5}$ and NO_2 in the downtown areas to restrictions on human activities (Q. Ma et al., 2023).

2.4. Correlations between air pollutants and meteorological factors

Air quality is influenced by meteorological conditions, of which precipitation, air temperature, relative humidity, and wind speed are crucial factors (He et al., 2020; Sharma et al., 2020). The correlations between air pollutants and meteorological factors were analyzed in our study. $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO were significantly negatively correlated with temperature, wind velocity, and precipitation (Figure 5).

A higher temperature leads to a higher boundary layer height, which favors the diffusion and dilution of surface air pollutants; therefore, the concentrations of these five pollutants decrease (Y. Chen et al., 2020; J. Wang et al., 2023). Strong winds can enhance the horizontal migration and diffusion of pollutants, resulting in the decrease of pollutant concentrations (Rupakheti et al., 2021; Y. Wang et al., 2022). Precipitation can reduce the concentration of air pollutants through the scavenging process (S. Zhao et al., 2016; Guo et al., 2023).

In contrast, the O_3 concentration was significantly positively correlated with temperature and wind velocity (Figure 5), which can be attributed to a reduction in the concentrations of aerosols and NO_x. In addition, high temperatures promote photochemical reactions and increase the emissions of BVOCs, leading to an increase in the O_3 concentration (H. Zhang et al., 2015; Coates et al., 2016; H. Zhao et al., 2018; Y. Ma et al., 2021). A significant negative correlation was observed between O_3 and relative humidity (Figure 5). Previous studies have demonstrated that high relative humidity can promote the formation of aerosols, leading to higher $PM_{2.5}$ concentration, which reduces the rate of photochemical reactions and inhibits the formation of O_3 (Mo et al., 2021; Gao et al., 2023; Wang & Ge, 2023).

3. Limitations and future research directions

Our results demonstrated the positive impact of the COVID-19 lockdown on air quality. However, this study has several limitations. The limitations of this study are described below, and future research directions are proposed. First, our study only investigated the effect of human activity reduction on air pollutant concentrations and air quality during a single lockdown period. Previous studies have suggested differences in the degree of air quality improvement in multiple lockdowns due to various seasons and lockdown levels (Mamtimin et al., 2022; Q. Ma et al., 2023; J. Yang et al., 2023). Thus, quantifying the importance of seasonal factors in future studies and considering them when developing pollutant control policies is necessary. Second, our study was based on ground-based observations from nine continuous air quality monitoring stations in Shenyang, which are insufficient for determining the spatial distribution of air pollutants in an area. Therefore, future studies should use multi-source data, such as satellite observations and remote sensing, to explore the spatial variations in air pollutant concentrations affected by the lockdown (Mamtimin et al., 2022; Q. Ma et al., 2023). Third, future studies on the quantitative relationship between human activities and changes in air quality should be strengthened, which will be more conducive to the formulation of future air pollution control policies and the evaluation of economic costs. In addition, further studies are required to explore strategies for the synergistic reduction of O_3, NO_2, $PM_{2.5}$, and VOCs.

Conclusions

The lockdown measures implemented during the COVID-19 pandemic provided a unique "quasi-natural" experiment for investigating the complex relationship between anthropogenic activities and air quality. To improve our understanding of how the COVID-19 lockdown affected air quality, this study evaluated the impact of the lockdown on the air quality in Shenyang. Our results suggest that the mass concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO decreased significantly during the lockdown, which was attributed to the mandatory traffic restrictions and industry shutdowns. The responses of changes in $PM_{2.5}$, PM_{10}, and CO to lockdown measures in the downtown areas were more sensitive than those in the suburbs. In contrast, O_3 concentration increased significantly during and after the lockdown. This may be due to the attenuated titration effect of NO_x on O_3 and the reduction in $PM_{2.5}$. Compared with the air quality during the same period in 2015–2019, the proportion of excellent and good air quality days increased significantly. In addition, the proportion of light, moderate, heavy, and severe pollution days gradually decreased. These results demonstrate the positive impact of lockdown measures on air quality and the potential benefits of reducing traffic and industrial activity. Overall, our study provides valuable empirical evidence on the impact of COVID-19 and the associated lockdown measures on air quality and pollutant concentrations in Shenyang, which can guide the establishment of air pollution control policies in the post-epidemic era.

Acknowledgements

This work was supported by Liaoning Province Doctoral Scientific Research Initiation Fund Project (2021-BS-288), Science and Technology Program of Shenyang-Fushun Reform and Innovation Demonstration District (2021JH08), and the Doctoral Scientific Research Foundation of Shenyang Institute of Technology (LX201905).

Author contributions

X. W. conceived and designed the experiment. X. W., Y. W., Y. Z., M. T., X. Wu., and Y. Zhang. collected data. X. W. analyzed the data. X. W., F. G., J. S., X. Wei., X. Y., and X. Q. wrote the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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