Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
How do pollutants change post-pandemic? Evidence from changes in five key pollutants in nine Chinese cities most affected by the COVID-19

Qiang Wang a,b,*, Xuan Yang a,b

a School of Economics and Management, China University of Petroleum (East China), Qingdao, Shandong, 266580, People’s Republic of China
b Institute for Energy Economics and Policy, China University of Petroleum (East China), Qingdao, Shandong, 266580, People’s Republic of China

ARTICLE INFO

Keywords:
Air pollution
Lockdown
Post pandemic period
Hysteresis
Rebound

ABSTRACT

Under the COVID-19 global pandemic, China has weakened the large-scale spread of the epidemic through lockdown and other measures. At the same time, with the recovery of social production activities, China has become the only country which achieves positive growth in 2020 in the major economies. It entered the post pandemic period. These measures improved the local environmental quality. However, whether this improvement can be sustained is also a problem that needs to be solved. So, this study investigated the changes of five air pollutants (PM2.5, PM10, NO2, SO2, and CO) in the nine cities most severely affected by the pandemic in China during the lockdown and post pandemic period. We emphasized that when analyzing the changes of environmental quality during the epidemic, we must consider not only the impact of the day and short-term changes but also the cumulative lag effect and sustainable development. Through a combination of qualitative and quantitative methods, it is found that the concentration of pollutants decreased significantly during the lockdown compared to the situation before the epidemic. PM10 and NO2 are falling most, which downs 39% and 46% respectively. During the lockdown period, the pollutant concentrations response to the pandemic has a lag of 3–7 days. More specifically, in the cities related to single pollutants, the impact on the pollutant shows a significant correlation when the measures are delayed for seven days. In the cities that are related to multiple pollutants, the correlation is usually highest in 3–5 days. This means that the impact of policy measures on the environment lasted for 3–5 days. Besides, Wuhan, Jingmen and Jingzhou have seen the most obvious improvement. However, this improvement did not last. In the post pandemic period, the pollutants rebounded, the growth rates of PM10 and NO2 reached 44% and 87% in September. When compared with the changes of pollutants concentration in the same period from 2017 to 2019, the decline rate has also been significantly slower, even higher than the average concentration of previous years. The research not only contributes to China’s economic “green recovery” plan during the post epidemic period, but also provides references for environmental governance during economic recovery in other countries.

1. Introduction

The COVID-19 pandemic poses a high risk to global health. As a country seriously affected by the pandemic, China has adopted a series of measures to stop the spread of the virus (Chen et al., 2020). Such as urban "lockdown" and traffic control, and they have been proven to be the most effective countermeasures (Flaxman et al., 2020; Oraby et al., 2021). But these measures also restricted industrial production and production activities (Shakoor et al., 2020; Verschuur et al., 2021). The concentration of air pollutants in cities is also affected. China has become the only country among the major economies that will achieve positive growth in 2020 (IMF, 2020; Wang and Zhang, 2021). China experienced three stages (before the pandemic, the lockdown period, and the economic recovery period). From the long-term development of the pandemic, it is a topic worth discussing to analyze the relationship between China’s response measures, human activity habits and changes of air pollutants in different COVID-19 periods. More importantly, this research can provide references for other countries’ air pollution control during the economic recovery.

Many reports indicate that the control measures taken to control the...
epidemic have improved the quality of the local environment (Balasubramaniam et al., 2020; Sulaymon et al., 2021; Wang and Li, 2021). Such as, MEP (2020) investigated that lockdown caused several industries to close down and stop production, which directly reduced pollutant emissions. At the same time, judging from changes in the air quality data between before and after the outbreak, NASA (2020), ESA (2020), and BIRA-IASB (2020) found that both ecological and environmental problems in many cities have indeed improved. Finland’s center for research on energy and clean air pointed out that during the lockdown, due to the closure of Chinese factories and travel restrictions, CO₂ emissions were reduced by nearly 25% (Brief, 2020). He et al. (2020) found that the short-term lockdown measures for COVID-19 have greatly improved the air quality in Chinese cities. Lian et al. (2020) found that the city lockdown has improved the air quality in Wuhan. Wang et al. (2020) showed that the concentration of pollutants also dropped sharply during the Hangzhou lockdown. Li et al. (2020) also found that the Yangtze river delta region’s emissions were greatly reduced during the lockdown of COVID-19. At the same time, similar phenomena have also appeared in other countries (Azuma et al., 2020; Berman and Elshis, 2020; Briz-Rodrón et al., 2021). Xu et al. (2020) found that the concentration of air pollutants decreased to varying degrees during the pandemic. The COVID-19 pandemic, short-term lockdown measures reduced the concentration of particulate pollutants by about half in large Indian cities (Mahato and Ghosh, 2020; Mahato et al., 2020; Singh and Chauhan, 2020). Abou El-Magd and Zanaty (2020) also proved that the lockdown has reduced the discharge of pollutants in Egypt. And the concentration of NO₂ in major Italian cities dropped significantly (Gualtieri et al., 2020; Kanniah et al. 2020) found that various environmental pollutant indicators decreased by summary data of the 2020 Malaysian pandemic. Chauhan and Singh (2020) studied PM2.5 and found that with the decreased human activity during the pandemic, the concentration of PM2.5 in the study area decreased. Such changes were also reported by Kerimray et al. (2020). To sum up, some literature shows that the control measures during the pandemic did cause the concentration of pollutants to decrease. However, after the lockdown measures are lifted, as social production activities resume, whether this improvement can be sustained is also an issue that needs to be resolved. Long-term analysis of air pollutant changes is lacking.

Based on the above analysis and related literature, we emphasize that when analyzing the changes of environmental quality during the pandemic, we must consider not only the impact of the day and short-term changes, but also the cumulative lag effect and sustainable development. The main purpose of this paper is to analyze the impact of the lockdown measures taken during different COVID-19 periods on pollutants. The paper focuses on the changes of pollutant concentrations in the three development stages of COVID-19. The change of pollutant concentration also reflects the duration of urban control measures. The nine cities (Wuhan, Xiaogan, Huanggang, Jingzhou, Ezhou, Xiangyang, Huangshi, Yichang, Jingmen) with the most severe epidemics in China were selected as the research objects. In addition, in order to eliminate the differences in climate and seasonal factors, a comparative analysis of the pollutant concentration in the same period from 2017 to 2019 was also conducted. The Spearman correlation function model was used to quantitatively analyze the lagging response of different pollutants in different cities to the measures. It is helpful to understand the best effective time for environmental improvement after the measures are implemented. The research not only helps to understand the environmental changes in China during the epidemic period, but also provides references for environmental governance in other countries when their economies recover.

The remainder of this paper is organized as follows: Section 2 shows the main research framework of this paper, and introduces the sources and methods of the data. Section 3 shows the calculation results. Section 4 discusses and analyzes the impact of different response measures and social activities on urban air pollutants in different stages of COVID-19. Section 5 concludes the key conclusions of this paper.

2. Methods and data

2.1. Research framework

In different periods of the pandemic, the control measures adopted by the government are different, and the resulting economic impact and social activities are also different. The most intuitive and most significant is the change in the concentration of air pollutants in the city. As shown in Fig. 1:

This paper is to study the correlation between the lockdown measures and the urban environment. The research indicator selected the COVID-19 daily newly confirmed cases to measure the development trend of the urban pandemic. It also more intuitively reflects the control effect of different control measures on the pandemic. The data were obtained from the official notices (Health Commission of Hubei Province, 2020), for the time from January 16, 2020, to September 31, 2020. Environmental quality is measured by the concentration of five common air pollutants in cities. They included PM2.5 (particles with a diameter ≤2.5 μm), PM10 (particles with a diameter ≤10 μm), SO₂ (sulfur dioxide), NO₂ (nitrogen dioxide), and CO (carbon monoxide). The data was obtained from the Ministry of Ecology and Environment of the People’s Republic of China (2020).

In fact, the effect of any policy measures on other things is not immediately obvious, but after a period of reaction and accumulation of practice. There is a lag (Ainslie et al., 2020; Courtemanche et al., 2020). Therefore, we set an average lag time for the cumulative lag effect of policy measures on the environment. This paper uses the moving average method to capture the moving average lagging response of environmental quality changes to the COVID-19 epidemic development.

This paper divides the entire research cycle into two stages: the first phase is the epidemic lockdown period. It is from January to March 2020. In order to control the movement of people and the spread of the pandemic, the government adopted measures such as “lockdown”. The city has suspended work and production, and social activities have decreased. The second stage is the lockdown lifting period (the post-pandemic period). It was from April to September 2020. Compared with the global pandemic trend, the government began to gradually abolish traffic control in cities. Economic production activities and traffic operations gradually returned to normal. It began to enter the post-pandemic period.

This paper uses a combination of qualitative and quantitative methods to study the dynamic impact of different control measures and social activities on different air pollutants and the heterogeneity between cities during different periods of the pandemic. Different representations to visualize changes in the concentration of different pollutants. Specifically, this paper uses the daily and monthly indicators of the concentration of five air pollutants from January to September 2020 to calculate the range of changes in pollutants during this period. Then we use Spearman’s correlation function to quantitatively analyze the relationship between different periods of COVID-19 and five major air pollutants. Finally, the regression model is used to fit the change trend of air pollutant concentration throughout the development stage of the pandemic.

2.2. Spearman correlation function model

We have used the Kolmogorov-Smirnov method and Shapiro-Wilk method to test the data for normality. The test result shows that the data does not obey a normal distribution. Considering the obvious deviation between the overall data set and the normal distribution (Croux and Dehon, 2010; Martins and Castro, 2020), the Spearman’s correlation function model was chosen.

It is a commonly used nonparametric statistical correlation analysis method (Xie and Zhu, 2020; Zar, 1972). The model does not require the
selection of raw data, related forms, or distribution types. It abandons
the traditional Pearson method, which requires data to be normally
distributed and linearly dependent. It is commonly used to measure the
strength of correlations between variables. Its versatility and robustness
are better than traditional Pearson statistical functions (Bonett and
Wright, 2000; Hauke and Kossowsk, 2011; Headrick, 2016). Zhang
et al. (2020) and Zhang et al. (2021) used Spearman correlations model
to calculate the correlation between air pollutants in major cities in
China during the pandemic. Bashir et al. (2020) used Spearman corre-
lation tests as an empirical methodology to observe environmental
pollutants’ correlation with COVID-19 in California. Therefore, it is
reasonable to use the Spearman correlation function model for the study
of the correlation of COVID-19 to environmental pollutants. In addition,
we used the nonlinear regression model to quantify the dynamic rela-
tionship between COVID-19 and pollutants in different cities. The spe-
cific analysis processes are shown in Fig. 2.

**Step 1:** Introduce sliding moving average function to address the
hysteresis effect of the COVID-19 daily newly confirmed cases on the
investigated environmental pollutants. The processing flow diagram is
shown in Fig. 3:

**Step 2:** Calculate the hysteresis effect and influence of the COVID-19
on air pollutants in different cities. The specific steps are as follows:

1. Pair analysis object, recorded as \( [(X_1, Y_1), (X_2, Y_2), \ldots, (X_n, Y_n)] \)

   where, \( X \) represents the COVID-19 daily newly confirmed cases under
different hysteresis effects. \( Y \) represents the daily concentration value of
five individual environmental pollutants (PM2.5, PM10, SO\(_2\), NO\(_2\), and
CO). \( n \) represents the number of samples.

2. Calculate the Spearman’s correlation coefficient \( R \). First, sort
\( X_i \) and \( Y_i \) separately, obtain the ranks of \( X \) and \( Y \), respectively,
and record them as \( [(T_1, S_1), (T_2, S_2), \ldots, (T_n, S_n)] \). Then, the result
can be calculated by the following models:
Environmental Research 197 (2021) 111108

Q. Wang and X. Yang

3. Empirical results

3.1. The impact of lockdown on the COVID-19

According to the statistical report of the Chinese Health Commission, the daily newly confirmed cases in 9 cities from January to September are listed as shown in Fig. 4 (After March 17th, the pandemic was under control, daily newly confirmed cases were zero, and with no obvious change. Therefore, the change curve in subsequent time is not fully displayed). The newly confirmed cases in these cities gradually and slowly increased from January 16.

On January 23, these nine cities had successively adopted "lockdown" measures to curb the spread of the pandemic. Wuhan officially closed at 10:00 on January 23. After, Ezhou and Huanggang also immediately implemented the "lockdown" initiative, suspended public transportation within the city, and strictly controlled residential travel. Then, Huanggang officially suspended the city’s public transportation from 24:00 on January 23 and also implemented the "lockdown" measure. Starting from January 24, Jingmen, Huangshi, Xiaogan, Yichang, Xiangyang, and Jingzhou have also implemented the "lockdown" initiative. These measures included the suspension of railway, high-speed, and ordinary highway traffic in the city, especially the suspension of public transportation such as buses and long-distance passenger transportation. Two weeks after implementing the "lockdown" traffic control measures, the daily newly cases began to decline gradually. Especially after entering March, most cities maintained zero growth, and the number of daily newly cases in Wuhan gradually decreased from three digits to single digits.

The above results indicate that temporary measures such as lockdown and traffic control during the pandemic have a significant inhibitory effect on the development of COVID-19 in the city.

3.2. The changes of air pollutants during lockdown period

3.2.1. The impact of lockdown on air pollutants

Up to March 17, 2020, the COVID-19 confirmed cases of these nine cities reached 63,452, accounting for 78% of the total cases in China. The daily increase reached up to 13,436. As shown in Table 1, the average concentration of PM2.5 (50ug/m³) exceeded the secondary air quality standard by 1.43 times, and the minimum value was 7ug/m³, which was detected for Wuhan on January 28. The maximum value appeared in Xiangyang, which was closed last, on January 23 (five days before the official traffic control measures) and reached 157ug/m³.

The average concentration of all indicators except for PM2.5 remained far below the limit of the secondary standard of GB 3095–2012. The average concentration of PM10 was 63ug/m³, and the highest concentration reached 159ug/m³, which was observed in Xiangyang on January 22. The lowest concentration occurred in Xiaogan and

Fig. 3. Hysteresis processing diagram.
Jingmen on February 28, which was one month after both cities implemented lockdown measures. The average concentration of SO_2 was 9 ug/m^3, the lowest value of 1 ug/m^3 was observed in Xiaogan on February 17. The average concentration of NO_2 was 18 ug/m^3, and the lowest level was observed in Xiaogan and Jingmen on February 15 (4 ug/m^3), while the highest level (75 ug/m^3) appeared before the Wuhan lockdown on January 20. The average concentration of CO was 1.05 mg/m^3. The lowest concentration (0.33 mg/m^3) was recorded in Yichang City, and the highest concentration (1.98 mg/m^3) was recorded in Huangshi.

(2) The changes of air pollutants compared the same period in 2019

Taking the pollutant data of the same period in 2019 as a control, this study conducted a comparative analysis of the pollutant content in 2020. As shown in Fig. 5, the five environmental pollutants in the 9 cities in 2019 and 2020 are clearly listed. Generally speaking, the concentration of pollutants in these nine cities has significantly decreased in 2020, and the overall air quality is generally better than the same period last year.

Fig. 5 a and Fig. 5 b shows the comparative data of PM10 and PM2.5 content in 9 cities, respectively. The main particulate pollutants (PM2.5 and PM10) are greatly reduced. The average change of PM2.5 remained relatively uniform, with an average decrease of 32%. The decline in cities ranged between 28% and 27%, and the largest decline (37%) was found for Wuhan (Fig. 5 a). PM10 showed a consistent trend with PM2.5, and the decrease was slightly stronger than PM2.5 for most cities, representing a 39% year-on-year decrease. The largest decrease (49%) was found in Jingmen.

Compared with the same period in 2019, among the main gaseous pollutants, the decreasing trend of NO_2 was the most significant. As shown in Fig. 5 d, the NO_2 concentration was significantly lower than during the same period the year before, representing an average decrease of 46%. However, compared with the expected concentration, the decrease of SO_2 and CO was smaller. As shown in Fig. 5 c and Fig. 5 e, these decreased by 2% on average. The concentration of SO_2 in the four cities of Ezhou, Xiangyang, Yichang, and Jingmen remained the same as during the same period of the preceding year, which ranged between (8 – 11) ug/m^3. The trend is dynamic and complementary with the same period last year. Especially, the concentration of SO_2 in Huanggang and Huangshi increased by 20% and 30%, respectively, compared with the preceding year, and the concentration of CO also increased by 10% and 21% year-on-year in these cities.

The improvement of environmental quality during the lockdown is due to the help of control measures. The purpose of these measures is to avoid crowd gathering and reduce the flow of residents. Restricting traffic operations has significantly reduced emissions from motor vehicles (Lian et al., 2020). Secondly, during the lockdown period, the home office is advocated. At the same time, construction activities and other industrial activities that emit pollutants are also under the closure policy (Rahman et al., 2021). It can be seen that the measures taken during the pandemic to prevent the spread of the disease also provide good help for environmental governance. On the other hand, many scholars have found that the closure of these industrial activities caused economic losses (Bashir et al., 2020; Goolsbee and Syverson, 2021; Verschuur et al., 2021). Commercial and economic activities were temporarily suspended during the epidemic, and socio-economic development was slow. But due to the reduced cohesive situation for work, the environment is benefitted (Bherwani et al., 2020). It also temporarily reduced specific air pollutant emissions. Therefore, during the blockade, not only
economic losses were caused, but also the local environmental quality was improved.

For example, Jingzhou’s emission reduction effect during the pandemic was remarkable, and the decline of various pollutants was at the forefront. Among them, the average concentration of NO\textsubscript{2} decreased strongly from 32\(\text{ug/m}^3\) in 2019 to 14\(\text{ug/m}^3\) in 2020, indicating an average decrease of 56% (Fig. 5 d). The lowest concentration of 4\(\text{ug/m}^3\) in the entire region was found on February 15 in Jingzhou. The concentration of SO\textsubscript{2} decreased from 10\(\text{ug/m}^3\) in 2019 to 7\(\text{ug/m}^3\) in 2020, indicating a decrease of 30% (Fig. 5 c). The concentration of CO also decreased by 12% (Fig. 5 c). The main reason for the significant improvement in the environment is that during the pandemic, the city took measures such as suspension of construction and transportation, motor vehicle control, and business suspension to control the spread of the pandemic. At the same time, measures such as controlling industrial pollution sources, limiting emissions and limiting production have further increased environmental supervision. In particular, the monitoring of medical waste, medical wastewater treatment and environmental pollutant discharge has further controlled the increase in air pollutants during the pandemic.

3.2.2. The hysteresis impact of COVID-19 on air pollutants

Due to changes in government control measures and human social activities, the impact of the pandemic on air pollutants is not direct, but has a lag effect (Ainslie et al., 2020; Courtemanche et al., 2020). Therefore, the daily newly cases are used as an indicator to measure the
development of the pandemic in the city. The moving average function and Spearman correlation function model were used to calculate the average hysteresis effect (lag 0, lag 3, lag 5, and lag 7) of the COVID-19 on the air pollutants. According to the results, when the test value remains below 0.05, a significant correlation can be considered to exist. As shown in Fig. 6, the COVID-19 daily newly confirmed cases were negatively correlated with the air pollutants. Moreover, the lag response to lockdown measures in different cities has obvious differences. In the three cities of Huanggang, Huangshi and Jingmen, there is only a single pollutant passed the computational test. This shows that the change in the concentration of only one pollutant in the three cities is significantly related to the pandemic. As shown in Fig. 6, in Huanggang, only CO changes in gaseous pollutants are directly related to pandemic, and after the seventh day, CO has the greatest correlation. On the contrary, in the two cities of Huangshi and Jingmen, the changes in PM10 in particulate pollutants are directly related to pandemic, and the correlation has gradually increased over time. This shows that during the lockdown period, the impact on the pollutant shows a significant correlation when the measures last for seven days. But the changes in gaseous pollutants are not significantly related to the pandemic.

The calculation results show that the changes of multiple environmental pollutants in cities, such as Wuhan, Xiaogan, Jingzhou, Ezhou, Xiangyang and Yichang are directly related to pandemic. For example, during the pandemic in Ezhou, the development of pandemic significantly impacted the concentrations of PM10, SO2, NO2 and CO. But different environmental pollutants have different reaction time to changes in pandemic situation. Such as, SO2 and NO2 in Yichang, PM10 and CO in Jingzhou, and NO2 in Xiangyang. The cumulative hysteresis effect is more significant after seven days. The correlation between other pollutants in other cities and COVID-19 generally shows another char-
characteristic, that is, first increase and then decrease. The correlation is usually highest in 3–5 days. This means that the impact of policy measures on the environment lasted for 3–5 days.

3.2.3. The dynamic relationship between COVID-19 and pollutants

To investigate the dynamic relationship, the indicator of which the change of environmental pollutants in each city is most affected by COVID-19 was selected, under the strongest hysteresis of COVID-19. A nonlinear regression equation was established (Table 2) to investigate the dynamic relationship between them.

Derivation of the functions in Table 2 can get the rate of change of the curves, as shown in Table 3. The reaction rate of particulate pollutants to the pandemic is greater than that of gaseous pollutants. More specifically, the coefficients of the function expressions for the rate of change of PM10 and PM2.5 are between \([-7, -0.6]\), and the coefficients of the function expressions for gaseous pollutants are between \([-0.38, 0.63]\).

![Fig. 5. (continued).](image)

![Fig. 6. Correlation and hysteresis of COVID-19 and environmental pollutants in different cities.](image)
3.3. The changes of air pollutants after lockdown

(1) Through the statistical analysis of the concentration of urban pollutants during the first phase (January–March), it is found that the air quality has improved significantly during the pandemic lockdown. Fig. 7 found that there was a dynamic relationship between COVID-19 and air pollutants with the development of the pandemic. In the early stage of the pandemic, air pollutants had a significant decrease in the city. After the lockdown is lifted, the concentration of pollutants in the city may rebound. Therefore, in order to further study the changes of air pollutant concentrations in cities, we analyzed the changes of air pollutant concentrations during the post pandemic period (April to September).

It can be seen from Fig. 8 that the concentration of air pollutants in the city began to increase in the second stage. Specifically, starting from April to June, the concentrations of the five pollutants in all cities showed an alternating growth rate. Although the concentration of air pollutants has remained declining, it is far lower than the first phase. Especially, from August, the concentration of air pollutants in all cities began to increase, indicating that the concentration of pollutants in cities rebounded after the lockdown is lifted. Among them, the major particulate pollutants (PM2.5 and PM10) rebounded most obviously.

The growth rate in September has even reached more than 40% in some cities (Ezhou 53%, Huanggang 45%, Huangshi 55%, Jingmen 50%, Wuhan 43%, Xiangyang 61%, Xiaogan 58%, and Yichang 50%), showing a retaliatory rebound. The main gaseous pollutants also rebounded to varying degrees. Among them, the concentration of NO2 in Xiangyang increased by 87% and S02 of Jingzhou rebounded by 133% in September.

(2) Since Secretary Xi Jinping put forward the environmental development concept of “Green trees and green mountains are golden mountains and silver mountains” in 2017, cities have begun to fully implement environmental quality improvement plans, and air pollutant concentrations have begun to decline year by year. However, Fig. 8 shows that with the pandemic under control, the concentration of air pollutants in the city did not continue to decline as everyone predicted, but began to increase. This phenomenon is a retaliatory rebound after the pandemic. Therefore, in order to better demonstrate the impact of COVID-19 on urban air pollutants after the pandemic, we have selected historical data from 2017 to 2019 for the comparison. The descriptive statistics of pollutant concentration values (2017–2019) are shown in Table 4.

The part “a” of Fig. 9 shows that the average change rate of the pandemic period of the first phase (1–3 months) and the second phase (4–9 months) relative to the previous three years. And we further calculated the difference between the change rate of the two periods, namely the rebound rate. For comparison, part b of Fig. 9 increases the rebound rate between the two periods of 2017–2019. It can be seen from Fig. 9 that the overall air pollutant concentration of 2020 has dropped compared to the average of 2017–2019. However, the average decline rate of pollutants at the post pandemic period (April to September) has been greatly reduced compared to the pandemic period (January to March). As shown the part b of Fig. 9, fluctuations between these two periods of time each year are common. Since Secretary Xi put forward...
Fig. 7. The dynamic relationship between COVID-19 and pollutants.

(a) 

PM10, PM2.5 and SO2

(b) 

NO2 and CO

Q. Wang and X. Yang
Table 3
The rate of change of the curve.

| City      | Function |
|-----------|----------|
| Wuhan     | $T_{\text{PM2.5}} = -3.387 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (22) |
| Wuhan     | $T_{\text{PM10}} = -6.917 \times \frac{X_{\text{PM10}}}{X_{\text{PM10}}}$ (23) |
| Xiaogan   | $T_{\text{NO2}} = -0.599 \times \frac{X_{\text{NO2}}}{X_{\text{NO2}}}$ (24) |
| Xiaogan   | $T_{\text{CO}} = -0.024 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (25) |
| Huanggang | $T_{\text{CO}} = -0.011 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (26) |
| Jingzhou  | $T_{\text{PM2.5}} = -0.605 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (27) |
| Jingzhou  | $T_{\text{NO2}} = -0.2014 \times \frac{X_{\text{NO2}}}{X_{\text{NO2}}}$ (28) |
| Jingzhou  | $T_{\text{CO}} = -0.099 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (29) |
| Ezhou     | $T_{\text{PM2.5}} = -0.777 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (30) |
| Ezhou     | $T_{\text{NO2}} = -0.105 \times \frac{X_{\text{NO2}}}{X_{\text{NO2}}}$ (31) |
| Ezhou     | $T_{\text{CO}} = -0.297 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (32) |
| Xiangyang | $T_{\text{NO2}} = -0.005 \times \frac{X_{\text{NO2}}}{X_{\text{NO2}}}$ (33) |
| Xiangyang | $T_{\text{PM2.5}} = -0.279 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (34) |
| Xiangyang | $T_{\text{CO}} = -0.016 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (35) |
| Huangshi  | $T_{\text{PM2.5}} = -0.933 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (36) |
| Yichang   | $T_{\text{NO2}} = -0.032 \times \frac{X_{\text{NO2}}}{X_{\text{NO2}}}$ (37) |
| Yichang   | $T_{\text{CO}} = -0.150 \times \frac{X_{\text{CO}}}{X_{\text{CO}}}$ (38) |
| Jingmen   | $T_{\text{PM2.5}} = -0.954 \times \frac{X_{\text{PM2.5}}}{X_{\text{PM2.5}}}$ (39) |

Table 4
Statistics of environmental pollutants monthly concentration (2017–2019).

| Indicators      | Year | Mean | Min | Max |
|-----------------|------|------|-----|-----|
| PM2.5 concentration (ug/ m$^3$) | 2017 | 54   | 21  | 135 |
|                 | 2018 | 45   | 16  | 130 |
|                 | 2019 | 48   | 19  | 148 |
| PM10 concentration (ug/ m$^3$)   | 2017 | 85   | 42  | 160 |
|                 | 2018 | 71   | 33  | 149 |
|                 | 2019 | 77   | 42  | 176 |
| SO2 monthly concentration (ug/ m$^3$) | 2017 | 14   | 4   | 29  |
|                 | 2018 | 11   | 5   | 20  |
|                 | 2019 | 10   | 4   | 18  |
| NO2 monthly concentration (ug/ m$^3$) | 2017 | 36   | 11  | 71  |
|                 | 2018 | 30   | 7   | 54  |
|                 | 2019 | 31   | 8   | 63  |
| CO monthly concentration (mg/ m$^3$) | 2017 | 1.17 | 0.78 | 2.92 |
|                 | 2018 | 0.97 | 0.57 | 1.36 |
|                 | 2019 | 0.91 | 0.40 | 1.49 |

the concept of environmental development in 2017, the volatility rate in the first three years has remained between –4% and 18%. However, compared with the average of the previous three years, the relative concentration of pollutants in the second phase of 2020 generally increased compared to the first phase, with an average rebound of 10%–31%. For example, the PM2.5 concentration in Wuhan and Xiangyang rebounded by 25% and 23% respectively during the post pandemic period. The PM10 concentration in Huangshi rebounded by 25%. The SO2 concentration in Huanggang area rebounded by 41%. In particular, the NO2 concentration in Xiaogan rebounded by 40%, while the difference in the average growth rate in 2017–2019 years was only 12%. The volatility in 2020 has increased by 18% over the previous three years.

4. Discussion and analyze

The previous chapters analyzed the impact of COVID-19 on urban air pollutants from the pandemic period to post pandemic period. In summary, next, we will further discuss the impact of COVID-19 on air pollutants from the overall development period of the pandemic and each stage.

(1) As shown in Table 2 and Fig. 7: the impact of COVID-19 on air pollutants is dynamic, and it shows phased characteristics throughout the development of COVID-19. In this study, a non-linear regression model is established to find the most significant relationship between local air pollutants and pandemic. In the early stage of the pandemic, in order to control the spread of the pandemic, the city adopted measures such as lockdown and traffic control. These caused most industries to stop production. And various transportation trips have been cancelled. Therefore, the emission of air pollutants has been greatly reduced, which has a major impact on environmental quality. When the pandemic weakened, as the lockdown measures were lifted, residents gradually resumed production and consumption. Emissions of air pollutants have also increased slowly relative to the period of the pandemic. However, as shown in Fig. 8, as the pandemic was gradually brought under control, the concentration of air pollutants began to rebound. This is related to the government’s incentive policy in the post pandemic period: enterprises quickly resume production. Residents’ enthusiasm for consumption increased under various subsidies. Also, the weather became warmer and traffic resumed. All these make the pollution worse.

(2) During the COVID-19 pandemic, the concentration of air pollutants generally decreases, with NO2 and PM10 decreasing the most, and SO2 and CO decreasing the least. And, research has found that the impact of COVID-19 on air pollutants is negatively correlated. Moreover, the response of pollutants to the pandemic is not timely, but has a certain lag. As shown in Fig. 6, usually 3–7 days after COVID-19 changes, then there is a significant correlation between local pollutants and the development of the pandemic. Specifically, the types of pollutants directly related to COVID-19 in each city are different. It can be divided into two kinds: one is a city where only a single pollutant is related to the pandemic. Such as Huanggang, Huangshi and Jingmen. In the remaining cities, there are 2–4 pollutant changes related to the pandemic, such as Wuhan, Xiaogan, Jingzhou, Ezhou, Xiangyang and Yichang.

In the cities with a correlation to a single pollutant, the development of the COVID-19 pandemic mainly affected PM10. The reason is that the urban traffic emissions, agricultural emissions in rural areas, and the emissions from fuel heating all affect PM10 in the air (van Pinxteren et al., 2019). Among them, Huangshi and Jingmen decreased the most. Mostly, Huangshi rapidly decreased from 95μg/m$^3$ in 2019 to 57μg/m$^3$ in 2020, representing an average decrease of 39%. The average decrease in Jingmen reached 49%, which represents the lowest concentration among all cities on February 28 (Fig. 6). This is because Jingmen depends strongly on industry for economic development, is a petrochemical manufacturing base in Hubei Province, and Jingmen’s industrial zone surrounds the city center and produces large emissions. Therefore, specific measures such as work stoppages and traffic control measures during the pandemic period are important for pollutant reductions. The effect of emissions was remarkable. In cities with multiple pollutants correlations, the main particulate pollutants directly affected by the pandemic are similar to those with single pollutant correlations, mainly PM10. At the same time, gaseous pollutants represented by NO2 also have a significant correlation with the pandemic situation. NO2 is a
brown-red toxic gas at high temperatures (Cui et al., 2019), and anthropogenic sources are mainly vehicle exhausts and exhaust emissions from industrial facilities (Lorente et al., 2019). In Jingzhou, Yichang, and Wuhan, NO$_2$ concentrations decreased the most, with 56%, 52%, and 49%, respectively. Since January 23, these cities have gradually closed factories and enterprises, restricted traffic, and cleaned streets (Wang and Su, 2020), all of which resulted in a significant decrease of NO$_2$ emissions. The average concentration of NO$_2$ in Jingzhou decreased rapidly from 32 ug/m$^3$ in 2019 to 14 ug/m$^3$ in 2020.

(3) With the gradual control of the pandemic, the concentration of pollutants in the city began to rebound in the post-pandemic period. Since the Chinese government gradually lifted the lockdown of the city in April, production and economic activities gradually returned to normal, and the concentration of pollutants in the city began to increase and decrease alternately. Among

Fig. 8. The range of changes in air pollutant concentrations from January to September 2020.
them, the concentration of gaseous pollutants first increased from April. The increased amount of medical waste is usually incinerated or processed through industrial kilns (in the short term), the sharp increase in incineration disposal may further deteriorate the environment (Rume and Islam, 2020; Wang and Wang, 2020). In particular, the research object is the most severely affected city in China, so more medical waste was accumulated and processed during the period (Tripathi et al., 2020; Yang et al., 2021). Since August, the growth rate of pollutants in all cities has changed from negative to positive. As the first country in the world to effectively control the pandemic, China’s economy has gradually recovered. According to data released by the National Bureau of Statistics, various economic indicators of industry, retail and investment improved in August, and industry and construction showed significant growth. The industrial added value of manufacturing and mining activities increased by 5.6% year-on-year in August (National Bureau of Statistics, 2020). Therefore, in the post-pandemic period, high-energy-consuming
Fig. 8. (continued).

Fig. 9. The year-on-year changes in air pollutants in 2020, 2017–2019 (a: The changes in air pollutants concentrations in 2020 and the 2017–2019 average; b: Comparison of the two-stage rebound value in 2020 and 2017–2019).
industries, especially mining, transportation, and electric heating production and supply are the first to recover and develop, which makes the decline of air pollutants gradually slow down or even rebound. Moreover, with the advent of the graduation season in August and September, social mobility has increased and the concentration of pollutants has further increased. As shown in Fig. 8 a and Fig. 8 b, the growth rate of major particulate pollutants in all cities increased significantly in September. The concentration of PM2.5 in Xiangyang increased by 60.9% from August. The concentration of PM10 in Xiaogan increased by 44.1% from the previous month. At the same time, it is worth noting that the gaseous pollutant (NO2), which declined the most during the pandemic lockdown, also increased significantly in the post-pandemic period. Among them, the concentration of NO2 in Xiangyang increased by 87% in September.

Compared with the same period in 2017–2019 years, the decline in the second phase of 2020 is significantly reduced. Some cities and pollutants whose air pollutant concentration dropped more during the pandemic lockdown have rebounded in the post-pandemic period. For example, during the pandemic lockdown, the PM2.5 concentration in Wuhan and Huangshi decreased by more than 37% compared with the previous three years. But they are also rebounded by 25% and 17% respectively after the “lockdown”. So, in the post pandemic period, it dropped by only 12% and 21% compared with the previous three years. Especially for NO2, within six months after the epidemic was unblocked, the concentration of this pollutant in all cities rebounded by 22%–40% compared with the first stage. However, the difference in pollutant change rates between 2017 and 2019 is only ~15%–21%. It can be said that after the pandemic lockdown was lifted under control, not only did the air pollutants in cities not continue to decline due to the reduction in economic and living activities during the pandemic lockdown, but there was a large-scale rebound.

5. Conclusion

This paper selects the nine cities with the worst pandemic situation in China as the research objects, and takes the development of the COVID-19 pandemic as the mainline. Through a combination of qualitative and quantitative methods, we have studied the correlation between lockdown measures and pollutants, and analyzed the changes in urban air quality at different stages of the pandemic. The conclusions as follow:

Firstly, the impact of COVID-19 on urban air pollutants is different in different periods. Through the regression equation and the pollutant concentration change curve, it can be found that the range of pollutant concentration changes is huge in the early and post pandemic periods. This is because of the short-term changes in urban management systems and people’s lifestyles during different periods. This also proves that government intervention and management will have an impact on pollutants in the short term.

Next, in the pandemic, due to the implementation of prevention and control measures, the intensity of human activities and pollution emissions have decreased. So, during the lockdown period, the concentration of pollutants decreased significantly. PM10 and NO2 are falling most, which downs 39% and 46% respectively. Wuhan, Jingmen and Jingzhou have seen the most obvious improvement. In addition, the pollutant concentration response to the pandemic has a lag of 3–7 days. More specifically, in the cities related to single pollutants, the impact on the pollutant shows a significant correlation when the measures lasted for seven days. In the cities that are related to multiple pollutants, the correlation is usually highest in 3–5 days. This means that the impact of policy measures on the environment lasted for 3–5 days.

Last but not least, in the post pandemic period, the concentration of air pollutants has rebounded to varying degrees. Especially since August, the pandemic crisis in China has been gradually lifted, and the overall situation has become stable and controlled. With the steady recovery of production demand, and the gradual recovery of energy, industry and manufacturing. The concentration of pollutants rebounded. The growth rates of PM10 and NO2 reached 44% and 87% in September. When compared with the changes of pollutants concentration in the same period from 2017 to 2019, the decline rate has also been significantly slower, even higher than the average concentration of previous years. In particular, some cities and pollutants, which dropped the most during the pandemic, also rebounded most significantly. In the six months after the COVID-19 was unblocked, the rate of decline of NO2 in all cities rebounded by 22%–40% compared to the lockdown period. The PM10 also rebounded by an average of 15%. All in all, the improvement of urban air quality during the pandemic lockdown did not continue, and the process of environmental governance in the post pandemic period has slowed down compared with previous years.

This paper analyzes the changes in environmental pollutants during and after the epidemic is blocked. The focus is on the relationship between lockdown measures and pollutants. The research not only helps to understand the environmental changes in China during the epidemic period, but also provides references for environmental governance in other countries when their economies recover. In the future, we hope to build a comprehensive evaluation model to further study the comprehensive impact of other parameters on air quality, such as geographic conditions and environmental factors. Further analysis of differences in different cities may also be an interesting research direction.

Author contribution statement

Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Supervision, Writing- Reviewing and Editing.Xuan Yang: Methodology, Software, Data curation, Investigation Writing- Original draft, Writing- Reviewing and Editing.

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.

Acknowledgement

The authors would like to thank the editor and these anonymous reviewers for their helpful and constructive comments that greatly contributed to improving the final version of the manuscript. This work is supported by National Natural Science Foundation of China (Grant No. 71874203), and Natural Science Foundation of Shandong Province, China (Grant No. ZR2018MG016).

References

Abou El-Magd, I., Zanaty, N., 2020. Impacts of short-term lockdown during COVID-19 on air quality in Egypt. Egypt. J. Rem. Sens. Space Sci. https://doi.org/10.1016/j.ejrs.2020.10.001. In press.
Ainslie, K.E., et al., 2020. Evidence of initial success for China exiting COVID-19 social distancing policy after achieving containment. Wellcome Open Res. 5.
Azuma, K., et al., 2020. Impact of climate and ambient air pollution on the epidemic growth during COVID-19 outbreak in Japan. Environ. Res. 190, 110042.
Balasubramaniam, D., et al., 2020. Assessing the Impact of Lockdown in US, Italy and France– what Are the Changes in Air Quality? Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp. 1–11.
Banerjee, M.F., et al., 2020. Correlation between environmental pollution indicators and COVID-19 pandemic: a brief study in Californian context. Environ. Res. 187, 109652.
Berman, J.D., Ebisu, K., 2020. Changes in U.S. air pollution during the COVID-19 pandemic. Sci. Total Environ. 739, 139864.
Bherwani, H., et al., 2020. Valuation of air pollution externalities: comparative assessment of economic damage and emission reduction under COVID-19 lockdown. Air Qual. Atmos. Health 13, 683–694.
BIRASJ, 2020. TROPOMI Observes the Impact of the Corona Virus on Air Quality in China, vol. 2020.
Bonett, D.G., Wright, T.A., 2000. Sample size requirements for estimating Pearson, Kendall and Spearman correlations. Psychometrika 65, 23–28.

Brief, C., 2020. Finland’s Center for Research on Energy and Clean Air, vol. 2020.

Briz-Redin, Á., et al., 2021. Changes in air pollution during COVID-19 lockdown in Spain: a multi-city study. J. Environ. Sci. 101, 16–26.

Chauhan, A., Singh, K.P., 2020. Decline in PM2.5 concentrations over major cities around the world associated with COVID-19. Environ. Res. 187, 109634.

Chen, S., et al., 2020. COVID-19 control in China during mass population movements at New Year. Lancet 395, 764–766.

Coccia, M., 2020. Two Mechanisms for Accelerated Diffusion of COVID-19 Outbreaks in Regions with High Intensity of Population and Polluting Industrialization: the Air Pollution-To-Human and Human-To-Human Transmission Dynamics medRxiv. 2020.04.06.20055657.

Courtemanche, C., et al., 2020. Strong social distancing measures in the United States reduced the COVID-19 growth rate. Health Aff. 39, 1237–1246.

Croux, C., Dehon, C., 2010. Influence functions of the Spearman and Kendall correlation measures. Stat. Methods Appl. 19, 497–515.

Cui, Y., et al., 2019. Spatiotemporal dynamics of nitrogen dioxide pollution and urban development: satellite observations over China, 2005–2016. Resour. Conserv. Recycl. 142, 59–68.

ESA, 2020. COVID-19: Nitrogen Dioxide over China, vol. 2020.

Flaxman, S., et al., 2020. Estimating the effects of non-pharmaceutical interventions on COVID-19 in Europe. Nature 584, 257–261.

Goolsbee, A., Syverson, C., 2021. Fear, lockdown, and diversion: comparing drivers of pandemic economic decline 2020. J. Publ. Econ. 193, 104311.

Guaitieri, G., et al., 2020. Quantifying road traffic impact on air quality in urban areas: a Covid19-induced lockdown analysis in Italy. Environ. Pollut. 267, 115682.

Hauke, J., Kossowski, T., 2011. Comparison of values of Pearson’s and Spearman’s correlation coefficients on the same sets of data. Quaest. Geogr. 30, 87–93.

He, G., et al., 2020. The short-term impacts of COVID-19 lockdown on urban air pollution in China. Nat. Sustain. 3, 1005–1011.

Headrick, T.C., 2016. A note on the relationship between the Pearson product-moment and the spearman rank-based coefficients of correlation. Open J. Stat. 6, 1025–1027.

Kanniah, K.D., et al., 2020. COVID-19’s Impact on the Atmospheric Environment in the Southeast Asia Region. Science of The Total Environment, 139658.

Kerimray, A., et al., 2020. Assessing Air Quality Changes in Large Cities during COVID-19 Lockdowns: the Impacts of Traffic-free Urban Conditions in Almaty, Kazakhstan, vol. 730. Science of The Total Environment, p. 139179.

Li, L., et al., 2020. Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. Sci. Total Environ. 732, 139282.

Lian, X., et al., 2020. Impact of city lockdown on the air quality of COVID-19-hit of polluted Indian cities due to lockdown amid SARS-CoV-2. Environ. Res. 187, 109835.

Mahato, S., Ghosh, K.G., 2020. Short-term exposure to ambient air quality of the most polluted Indian cities due to lockdown amid SARS-CoV-2. Environ. Res. 188, 109835.

Mahato, S., et al., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 139086.

Martins, F.F., Castro, H., 2020. Raw material depletion and scenario assessment in European Union - a circular economy approach. Energy Rep. 6, 417–422.

Mep, 2020. Regional Air Quality Has Improved Significantly, but Air Pollution Prevention Still Has a Long Way to Go. Ministry of Environmental Protection of China.

NASAs Airborne Nitrogen Dioxide Plummets over China. Vol. vol. 2020, 2020.

National Bureau of Statistics, The National Economy Continued to Recover Stably in August. 2020.

Oraby, T., et al., 2021. Modeling the effect of lockdown timing as a COVID-19 control measure in countries with differing social contacts. Sci. Rep. 11, 3354.

Rahman, M.S., et al., 2021. How air quality and COVID-19 transmission change under different lockdown scenarios? A case from Dhaka city, Bangladesh. Sci. Total Environ. 762, 143161.

Rume, T., Islam, S.M.D.-U., 2020. Environmental effects of COVID-19 pandemic and potential strategies of sustainability. Heliyon 6, e04965.

Shahoor, A., et al., 2020. Fluctuations in environmental pollutants and air quality during the lockdown in the USA and China: two sides of COVID-19 pandemic. Air Qual. Atmos. Health 13, 1335–1342.

Singh, R.P., Chauhan, A., 2020. Impact of lockdown on air quality in India during COVID-19 pandemic. Air Qual. Atmos. Health 13, 921–928.

Stewart, P.F., et al., 2014. Reliability, factorial validity, and interrelationships of five commonly used change of direction speed tests. Scand. J. Med. Sci. Sports 24, 500–506.

Sulaymon, I.D., et al., 2021. COVID-19 pandemic in Wuhan: ambient air quality and the relationships between criteria air pollutants and meteorological variables before, during, and after lockdown. Atmos. Res. 250, 105362.

The Ministry of Ecology and environment of the people’s Republic of China. 2020, 2020.

Tripathi, A., et al., 2020. Challenges, opportunities and progress in solid waste management during COVID-19 pandemic. Case Stud. Chem. Environ. Eng. 2, 100060.

van Pinxteren, D., et al., 2019. Quantifying impact and sources of trans-boundary PM10 in eastern Germany. Geophys. Res. Abstr. 21.

Verschuur, J., et al., 2021. Observed impacts of the COVID-19 pandemic on global trade. Nat. Human Behav.

Wang, L., et al., 2020. Unexpected rise of ozone in urban and rural areas, and sulfur dioxide in rural areas during the coronavirus city lockdown in Hangzhou, China: implications for air quality. Environ. Chem. Lett. 18, 1713–1723.

Wang, Q., Li, S., 2021. Nonlinear Impact of COVID-19 on Pollution – Evidence from Wuhan, vol. 65. Sustainable Cities and Society, New York, Milan, Madrid, Bandra, London, Tokyo and Mexico City. p. 102629.

Wang, Q., Su, M., 2020. A Preliminary Assessment of the Impact of COVID-19 on Environment–A Case Study of China. Science of the Total Environment, p. 138915.

Wang, Q., Wang, S., 2020. Preventing carbon emission relativity rebound post-COVID-19 requires expanding free trade and improving energy efficiency. Sci. Total Environ. 746, 141158.

Wang, Q., Zhang, F., 2021. What does the China’s economic recovery after COVID-19 pandemic mean for the economic growth and energy consumption of other countries? J. Clean. Prod. 295, 126265.

Xie, J., Zhu, Y., 2020. Association between ambient temperature and COVID-19 infection in 122 cities from China. Sci. Total Environ. 724, 138201.

Xu, F., et al., 2020. Air Quality Index, Indicatory Air Pollutants and Impact of COVID-19 Event on the Air Quality Near Central China. Aerosol and Air Quality Research, p. 20.

Yang, L., et al., 2021. Emergency response to the explosive growth of health care wastes during COVID-19 pandemic in Wuhan, China. Resour. Conserv. Recycl. 164, 105074.

Zar, J.H., 1972. Significance testing of the Spearman rank correlation coefficient. J. Am. Stat. Assoc. 67, 578–580.

Zhang, X., et al., 2021. Associations between air pollution and COVID-19 epidemic during quarantine period in China. Environ. Pollut. 268, 115897.

Zhang, Z., et al., 2020. Effects of meteorological conditions and air pollution on COVID-19 transmission: evidence from 219 Chinese cities. Sci. Total Environ. 741, 140244.