

Article



Assessment of Air Pollution before, during and after the COVID-19 Pandemic Lockdown in Nanjing, China

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Abstract: A unique illness, the coronavirus disease 2019 (COVID-19), emerged in Wuhan, People's Republic of China, in December 2019. To reduce the spread of the virus, strict lockdown policies and control measures were put in place all over the world. Due to these enforced limitations, a drastic drop in air pollution and an improvement in air quality were observed. The present study used six air pollutants (PM10, PM2.5, SO2, NO2, CO and O3) to observe trends before, during and after the COVID-19 lockdown period in Nanjing, China. The data were divided into six phases: P1-P3, pre-lockdown (1 October-31 December 2019), lockdown (1 January-31 March 2020), after lockdown (1 April-30 June 2020), P4-P6: the same dates as the lockdown but during 2017, 2018 and 2019. The results indicate that compared with the pre-lockdown phase, the PM_{10} and $PM_{2.5}$ average concentrations decreased by -27.71% and -5.09%. Compared with the previous three years, 2017–2019, the reductions in PM_{10} and $PM_{2.5}$ were –37.99% and –33.56%, respectively. Among other pollutants, concentrations of SO₂ (-32.90%), NO₂ (-34.66%) and CO (-16.85%) also decreased during the lockdown, while the concentration of O_3 increased by approximately 25.45%. Moreover, compared with the pre- and during lockdown phases, PM₁₀, PM_{2.5} and NO₂ showed decreasing trends while SO_2 , CO and O_3 concentrations increased. These findings present a road map for upcoming studies and provide a new path for policymakers to create policies to improve air quality.

Keywords: COVID-19; lockdown; air pollution; air quality improvement; Nanjing; China

1. Introduction

A new type of virus, a novel coronavirus disease, was first identified at the end of December 2019 in the capital city of China's Hubei Province, Wuhan. The World Health Organization (WHO) officially called it the coronavirus disease 2019 (COVID-19) [1]. The initial symptoms of COVID-19 are similar to those of SARS and MERS [2]. After the first confirmed case, the number of infected people increased rapidly all over the country, and within just a few days, due to the spread of COVID-19, it turned into a national disaster [3,4]. At the end of June 2020, in 215 countries around the world, more than 10.6 million people had been infected and 514,315 people had died as a result of the spread of COVID-19. The WHO confirmed COVID-19 as worldwide public health emergency due to its large-scale spread and contagious effects [2]. The prevention and treatment of the virus' infection has become a significant task [5]. By early August 2020, more than 19.46 million confirmed cases of COVID-19 were observed in over 200 countries around the world, according to the WHO [4].



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To prevent the large-scale spread of COVID-19, the government of China imposed strict prevention and control policies such as social distancing, self-quarantine, traffic restrictions, community limitations and lockdowns for public health [6]. A lockdown was implemented in Wuhan and nearby affected areas, with travel limitations and restrictions on non-essential movement. Within a few days, in January 2020, the lockdown was in effect all over the country. This type of shutdown and strict policies have affected every aspect of life including the environment. These control measures and restrictions on human activity led to a reduction in local transport in cities and a considerable decline in industrial processes, contributing to a decrease in air pollution [3]. Compared to normal conditions, most cities have experienced a remarkable change and reduction in air pollution [7,8]. Many scholars have found a positive association between the reduction in air pollution and regular social activities during the COVID-19 pandemic in different regions and territories in China [9–12]. Owing to similar lockdown and control measures, the air quality has also improved in many countries and territories around the world [13]. A high number of deaths and an increasing number of cases of respiratory illness due to poor air quality have been reported [14]. Each year, 4.6 million people die from diseases and ailments related to poor air quality, according to the World Health Organization [15], with poor air quality resulting in more deaths compared to other environmental problems [16].

Overall, all around the world, an improvement in air quality has been observed due to the implementation of lockdown and shutdown policies [17,18]. For instance, according to Hanaoka and Masui (2020) [19], CO emissions decreased by 25% and by 6% in China and worldwide, respectively. In 366 urban areas across China, the concentrations of PM_{10} , PM_{2.5}, SO₂, NO₂ and CO were reduced, while O₃ showed increasing rates [20]. According to NASA [21], NO₂ emissions decreased by 30% in Central China. In the USA, a study using air quality data from 2017 to 2020 found that the concentrations of $PM_{2.5}$ and NO_2 decreased during the COVID-19 period. The study found a remarkable reduction in PM_{2.5} and NO₂ by 11% and 26%, respectively [22]. Furthermore, in the USA, concentrations of PM_{2.5}, NO₂ and CO decreased by 19%, 37% and 1.1%, respectively, while in China, concentrations of PM₁₀, PM_{2.5}, SO₂, CO and NO₂ were reduced by 27%, 39%, 18%, 18% and 38%, respectively [23]. Agarwal et al. [24] reported that nationwide lockdown and shutdown policies in India and China resulted in a significant improvement in air quality status. The results demonstrate that in India and China, concentrations of PM_{2.5} and NO₂ decreased by 65% and 66%, and 45% and 37%, respectively. Compared with the same window of time in 2019, the surface and tropospheric NO_2 declined by 20–30% in China [25]. According to Urrego and Urrego (2020) [26], fine particulate matter showed a declining trend in the 50 most polluted cities worldwide. In another study, Zambrano-Monserrate and Ruano (2020) [27] found that just after the implementation of lockdown, PM_{2.5} and NO₂ concentrations were reduced. However, during the COVID-19 period in North China, due to unfavorable atmospheric circumstances, the status of the 24 h average concentration of $PM_{2.5}$ exceeded 200 mg/m³ [28,29].

Satellite data and ground-based observations were used to determine the effect of different pollutants in Wuhan during China's Spring Festival in 2020 [30]. The authors of this study noticed a sudden decrease in different pollutants during the COVID-19 period compared with the pre-lockdown period. Griffin et al. [31] found similar results for NO₂, i.e., a reduction during COVID-19 in Ontario, Canada, by using the Tropospheric Monitoring Instrument (TROPOMI). Bauwens et al. [32] recorded a 40% decrease in NO₂ during the COVID-19 period from January 2020 to April 2020 in China, South Korea, Western Europe, and the USA using TROPOMI onboard Sentinel-5 Precursor and OMI on Aura. Lorente et al. [33] revealed that the concentration of NO₂ was highest during cold weekdays in February 2018 and lowest during Spring 2018 using satellite data. Solberg et al. [34] developed a generalized additive model (GAM) to find the relationships between various meteorological parameters and temporal metrics in different countries. The study observed a decrease in NO₂ concentrations in Eastern countries (Poland and Hungary) from April to June 2020. Wang et al. [35] studied the impact of lockdown on air pollutants using a

satellite data set. The authors found a significant decrease in the concentrations of the air pollutants during the lockdown. Goldberg et al. [36] reported that meteorological patterns have a major impact on air pollutants and observed a decrease in air pollutants in spring 2020 due to these meteorological variations. Li et al. [37] developed a regression model for predicting the mortality rate during COVID-19 and studied the impact of air quality on the mortality rate during COVID-19.

The present study estimated the levels of six air pollutants (i.e., PM₁₀, PM_{2.5}, SO₂, NO_2 , CO and O_3) in Nanjing, the capital city of Jiangsu Province, using data obtained from nine ground-based monitoring stations. This study determined the impact of the lockdown during COVID-19 on air pollution in Nanjing and compared the results with the previous 3 years to discover significant changes in air pollution. However, recent studies have shown that especially in urban areas and regions, forced limitations and lockdown measures contribute to improvements in air quality for limited time periods (e.g., [38]). Most of the studies used only a few air pollutants to assess the impacts of the COVID-19 lockdown on air quality [39]. Thus, studies assessing the impact of the COVID-19 lockdown on all six air pollutants before, during and after the lockdown period as well as a comparison of these air pollutants with the previous three years (2017–2019) for a deeper analysis, are lacking. Therefore, our study provides a more comprehensive analysis of this scenario, and the results show a remarkable decline in the selected pollutants during the lockdown period in comparison to the previous three years. The objectives of this study were (1) to examine the air pollutant concentrations before, during and after the lockdown period in Nanjing; (2) to explore and quantify the air-quality status due to the nationwide lockdown and strict limitations amid the lockdown phase; (3) to explore the air pollutant concentrations during the same window of time in the last three years. The current study provides credible and useful outcomes, and insights for the scientific community and policymakers on the impact of nationwide lockdowns on air pollution. Further, the study provides a roadmap for upgrading and improving Nanjing's air quality in the future.

2. Materials and Methods

2.1. Study Area

Nanjing, with its 2000 years of history, is the capital of Jiangsu Province and the economic hub of the Yangtze River Delta. Nanjing is one of the most important and rapidly developing cities in China, with a large population and well-developed industry and manufacturing sectors [40]. In recent years, Nanjing has been faced with extreme and severe air pollution owing to its rapid economic growth and non-stop energy consumption [41]. Nanjing lies between the geo-coordinates 31°14' to 32°37' and 118°22' to 119°14', and occupies an area of approximately 6596 km² with 11 districts that can be classified into three regions: urban, suburban and rural. Geographically, the city is located within the Yangtze River Delta. As of 2019, the population of Nanjing was approximately 8.34 million with a density of 8500 people/km² in the central area. The city experiences a subtropical monsoon climate with four distinct seasons. The annual average temperature ranges between 16 $^{\circ}$ C and 38 $^{\circ}$ C in the summer and is -8 $^{\circ}$ C in the winter, and the annual precipitation is approximately 1090 mm [42]. In China, Nanjing is one of four garden cities with a per capita green area of 13.7 km², although there are many large areas of industry and enterprise. The leading industries in Nanjing are electronics, automobiles, petrochemicals, and steel smelting. To improve and rectify these polluting sites and enterprises, the administration has taken a number of measures. Additionally, the city is bordered by highlands and mountains on three sides and by water on the other, which can result in the accumulation of air pollutants in urban areas.

Presently in Nanjing, there are nine monitoring stations operating and recording air pollutants. The locations of these stations are shown in Figure 1.

50°28'N

40°26'N

30°24'N

20°22'N

113°25'E



Aotizhongxin

Major Roads Water Body

Boundary Line

5 10

20 km

National Monitoring Sites

Legend

Figure 1. The geographical location and the air pollution monitoring stations in Nanjing.

2.2. Environmental Data and Study Period

TheYangtze

River Delta

40 • km

10 20

In order to investigate air quality in Nanjing, data on the daily average concentration for the six air pollutants, including particulate matter with a diameter of $\leq 10 \ \mu m \ (PM_{10})$, particulate matter with a diameter of $\leq 2.5 \ \mu m$ (PM_{2.5}), sulfur dioxide (SO₂), nitrogen dioxide (NO_2) , carbon monoxide (CO) and ozone (O_3) , were obtained from the Nanjing Environmental Monitoring Center, after being collected from the nine monitoring stations. The data for all concentrations had at least 347 daily values, which meets the annual concentration calculation criteria of the Ambient Air Quality Standards of China, which is 324 daily values. These nine monitoring stations were designed to signify areas with different characteristics and features according to the Technical Regulation for Selection of Ambient Air Quality Monitoring Stations of China. Among these nine national stations, Xianlin represents a cultural area, Pukou represents a suburban area, Caochangmen is an instructive and educational area, Xuanwuhu covers an environmental and ecological park area, Ruijinlu is connected with a residential and housing area, Zhonghuamen represents a transportation and traffic area, Maigaoqiao covers a commercial and industrial area, Aotizhongxin represents a built-up and new city area, and Shanxilu represents a commercial and market area. The Nanjing Environmental Monitoring Center provided the geographical location information for these monitoring sites. To assess the effect of the lockdown before, during and after the COVID-19 period, the data were divided into six periods in 2017–2020: P1-P3, before lockdown (1 October-31 December 2019), lockdown (1 January-31 March 2020), after lockdown (1 April–30 June 2020), and P4–P6, which include the same dates as the lockdown but in the previous three years (2017–2019).

2.3. Statistical Analysis and Data Visualization

Summary statistics were performed for different variables during the study period. The current study reports variations in pollutant concentrations before, during and after the

31°44'N

31°22'N

lockdown phases and compares the previous three years (2017–2019) with the same time frame as that of the lockdown. The net difference and percentage change in concentrations of the selected pollutants were also investigated. To better understand the impact of the nationwide lockdown on air pollution, this work also reports the temporal evolution in daily average concentrations of the pollutants before, during and after the lockdown periods. Meanwhile, violin plots were generated to represent the concentrations of selected air pollutants during the study period. To assess the relationships among air pollutants, linear regression analysis was performed for different air pollutants during the lockdown period. The current study area map was created with ArcGIS 10.2.2, while other plots were created with Python.

3. Results and Discussion

3.1. Changes in Different Pollutants before, during and after the Lockdown Phases

Changes in different pollutants (PM_{10} , $PM_{2.5}$, SO_2 , NO_2 , CO and O_3) before, during and after the lockdown periods are shown in Figure 2. Overall, an increasing trend in PM_{10} was observed before the lockdown phase. During lockdown, a diminishing trend in the concentration of PM_{10} was observed, and it continued to decrease after the lockdown phase with similar variabilities. The results suggest that the significant reduction in the concentration of PM_{10} could be due to the limited vehicular, industrial and construction activities. A remarkable reduction in vehicular and transportation activities could also decrease air pollution [43]. Before the lockdown phase, $PM_{2.5}$ demonstrated an increasing trend; at first, during lockdown it showed an increasing trend and later decreased, while after lockdown, the concentration of $PM_{2.5}$ decreased significantly. The results suggest that, overall, during the lockdown phase, $PM_{2.5}$ showed a constantly decreasing trend.



Figure 2. Temporal evolution of 24 h average concentrations of PM₁₀, PM_{2.5}, SO₂, NO₂, CO, and O₃ before, during and after the lockdown periods.

Before lockdown, SO_2 concentrations showed an increasing trend, while during and after lockdown, SO_2 concentrations decreased. The results suggest that the decrease in the concentration of SO_2 was due to the reduced thermal, transportation and industrial activities. The main sources of SO_2 are the burning of fuels such as coal and diesel used in thermal, transportation and industrial enterprises [44]. The stoppage of industrial, vehicular, and heating activities were responsible for the reduction in SO_2 emissions during the lockdown phase in China [10]. Moreover, before the lockdown phase, just as for PM,

a rapidly increasing trend in NO₂ was observed, while during lockdown, NO₂ showed a declining trend. After lockdown, NO₂ presented a substantial diminishing tendency.

Before the lockdown phase, CO demonstrated an increasing trend, while during the lockdown phase, within just a few days, CO showed an increasing trend, then a consistent decline. After lockdown, CO presented an increasing trend with some fluctuations compared with the lockdown phase. Furthermore, a significant decreasing trend in O_3 was observed before the lockdown phase, while during lockdown, O_3 showed an increasing tendency. A rapidly growing trend was observed after the lockdown phase owing to the enhancement of solar radiation in the summer. In the summer, emissions of isoprene and biomass burning are responsible for the increment in O_3 [45]. The results suggest that the decrease in all air pollutants during COVID-19 was due to the low level of traffic, decreased human mobility and the closure of all industrial and construction activities [46].

*3.2. Spatial Concentration Pattern of PM*₁₀

Owing to the COVID-19 pandemic, a lockdown was imposed in many countries to control and minimize the movements of people. In China, the lockdown was implemented in January 2020. This type of shutdown and strict control policies reduce the movement of people and vehicles and restrict industries, markets, universities and construction activities, among others, leading to a drastic change and substantial improvement in air quality in many countries and regions. Our results demonstrate that during the COVID-19 pandemic lockdown phase in China, Nanjing experienced a significant change in PM₁₀ and a reduction of approximately -27.71% compared with the pre-lockdown phase, due to the restricted traffic and shutdown of industries. Compared with the pre- and during lockdown phases, an approximately -23.65% reduction in PM₁₀ concentration was recorded. The average concentration of PM_{10} and the variations are shown in Figure 3 and Tables 1–3. The main sources of PM₁₀ concentrations are road dust and soil resuspension, agronomy, transportation and fugitive dust emissions generated by industrial and manufacturing activities [13]. During the COVID-19 lockdown in 2020, these activities diminished significantly, which resulted in a drastic drop and reduction in air quality, especially in cities that mostly experience heavy pollution due to transportation, manufacturing and industrial processes [47]. For instance, it was reported by Shakoor et al. (2020) [23] that an approximately 27% reduction in PM₁₀ concentration was found in China during the COVID-19 pandemic lockdown period. According to Bao and Zhang 2020 [10], during the COVID-19 pandemic, air pollution decreased by approximately 7.80% in 44 cities in northern China.

Our study shows, compared with 2019 (for the same time frame), the concentration of PM_{10} was significantly reduced (36.90%) during the COVID-19 lockdown period. As compared with the previous three years 2017–2019 (same dates of lockdown), a –37.99% decline in the concentration of PM_{10} was observed. According to Chen et al. (2020b) [20], the concentration of PM_{10} during the COVID-19 pandemic lockdown period decreased in comparison to the previous three years (2017–2019). The results show the variations between the lockdown and post-lockdown periods. During the lockdown period, the reduction in the concentration of PM_{10} was observed to be –9.02%. After the lockdown phase, compared to the last three years (2017–2019), a significant reduction in PM_{10} concentration was observed, –43.58%. The results suggest that an improvement in PM_{10} concentration and improvement in the concentration of PM_{10} lockdown. In summary, this significant reduction and improvement in the concentration of PM_{10} demonstrates that the COVID-19 pandemic lockdown had a remarkable impact on the reduction of PM_{10} concentrations in Nanjing, China.



Figure 3. Daily average concentrations of PM₁₀, PM_{2.5}, SO₂, NO₂, CO and O₃ in 2017, 2018, 2019, before, during and after lockdown.

Table 1. 24 h average concentration and variation of pollutants before, during and after lockdown in Nanjing. (Bold values show average maximum decrease).

Pollutants	before Lockdown	during Lockdown	Avg. before and during Lockdown	after Lockdown _	Variation (d before Lo	luring and ckdown)	Variation (after Lockdown and Avg. of before and during Lockdown)		
					Net %		Net	%	
PM ₁₀									
Maximum	355.76	170.79	263.28	111.45	-184.97	-51.99	-151.83	-57.67	
Average	83.47	60.34	71.91	54.9	-23.13	-27.71	-17.01	-23.65	
Minimum	30.43	13.22	21.83	15.4	-17.21	-56.56	-6.43	-29.44	
PM _{2.5}									
Maximum	107.18	134.64	120.91	47.58	27.46	25.62	-73.33	-60.65	
Average	42.64	40.47	41.56	27.67	-2.17	-5.09	-13.89	-33.41	
Minimum	10.96	8.95	9.96	7.61	-2.01	-18.34	-2.35	-23.56	
SO ₂									
Maximum	20.28	16.30	18.29	16.11	-3.98	-19.63	-2.18	-11.92	
Average	9.15	6.14	7.65	8.1	-3.01	-32.90	0.46	5.95	
Minimum	3.66	2.99	3.33	3.89	-0.67	-18.31	0.57	16.99	
NO ₂									
Maximum	103.23	74.34	88.79	61.92	-28.89	-27.99	-26.87	-30.26	
Average	52.86	34.54	43.70	33.78	-18.32	-34.66	-9.92	-22.70	
Minimum	13.56	12.52	13.04	12.55	-1.04	-7.67	-0.49	-3.76	
СО									
Maximum	1.58	1.61	1.60	1.27	0.03	1.90	-0.33	-20.38	
Average	0.89	0.74	0.82	0.84	-0.15	-16.85	0.03	3.07	
Minimum	0.40	0.35	0.38	0.59	-0.05	-12.50	0.22	57.33	
O ₃									
Maximum	115.28	97.05	106.17	165.61	-18.23	-15.81	59.45	55.99	
Average	45.97	57.67	51.82	89.18	11.7	25.45	37.36	72.10	
Minimum	5.72	8.02	6.87	32.55	2.3	40.21	25.68	373.80	

Pollutants	2017	2018	2019	Avg. of 2017–2019	2020	Varia (2020 an	ntion 1d 2019)	Variation (2020 and Avg. of 2017–2019)	
				2017 2017		Net	%	Net	%
PM ₁₀									
Maximum	237.96	304.96	194.38	245.77	170.79	-23.59	-12.14	-74.98	-30.51
Average	93.57	102.75	95.62	97.31	60.34	-35.28	-36.90	-36.97	-37.99
Minimum	27.05	16.35	25.60	23.00	13.22	-12.38	-48.36	-9.78	-42.52
PM _{2.5}									
Maximum	159.87	217.46	150.48	175.94	134.64	-15.84	-10.53	-41.30	-23.47
Average	55.30	65.36	62.08	60.91	40.47	-21.61	-34.81	-20.44	-33.56
Minimum	15.16	11.99	15.27	14.14	8.95	-6.32	-41.39	-5.19	-36.70
SO ₂									
Maximum	36.62	28.94	20.93	28.83	16.30	-4.63	-22.12	-12.53	-43.46
Average	19.24	13.39	10.92	14.52	6.14	-4.78	-43.77	-8.38	-57.70
Minimum	9.02	5.27	4.60	6.30	2.99	-1.61	-35.00	-3.31	-52.51
NO ₂									
Maximum	114.33	109.81	91.51	105.22	74.34	-17.17	-18.76	-30.88	-29.35
Average	52.57	53.17	47.55	51.10	34.54	-13.01	-27.36	-16.56	-32.40
Minimum	16.53	21.33	14.66	17.51	12.52	-2.14	-14.60	-4.99	-28.48
СО									
Maximum	2.26	1.97	1.55	1.93	1.61	0.06	3.87	-0.32	-16.44
Average	1.17	0.89	0.93	1.00	0.74	-0.19	-20.43	-0.26	-25.75
Minimum	0.63	0.44	0.37	0.48	0.35	-0.02	-5.41	-0.13	-27.08
O ₃									
Maximum	110.12	83.46	87.27	93.62	97.05	9.78	11.21	3.43	3.67
Average	60.15	50.50	45.76	52.14	57.67	11.91	26.03	5.53	10.61
Minimum	18.00	11.54	6.44	11.99	8.02	1.58	24.53	-3.97	-33.13

Table 2. 24 h average concentration and variation of pollutants during 2017–2020 (same dates of lockdown) in Nanjing. (Bold values show average maximum decrease).

Table 3. 24 h average concentration and variation of pollutants for the periods of 2017–2020 to after lockdown in Nanjing. (Bold values show average maximum decrease).

Pollutants	2017	2018	2019	Avg. of 2017–2019	during Lockdown (2020)	after Lockdown	Variation (after and during Lockdown)		Variation (after lockdown and Avg. of 2017–2019)	
							Net	%	Net	%
PM_{10}										
Maximum	237.96	304.96	194.38	245.77	170.79	111.45	-59.34	-34.74	-134.32	-54.65
Average	93.57	102.75	95.62	97.31	60.34	54.9	-5.44	-9.02	-42.41	-43.58
Minimum	27.05	16.35	25.60	23.00	13.22	15.4	2.18	16.49	-7.60	-33.04
PM _{2.5}										
Maximum	159.87	217.46	150.48	175.94	134.64	47.58	-87.06	-64.66	-128.36	-72.96
Average	55.30	65.36	62.08	60.91	40.47	27.67	-12.8	-31.63	-33.24	-54.57
Minimum	15.16	11.99	15.27	14.14	8.95	7.61	-1.34	-14.97	-6.53	-46.18
SO ₂										
Maximum	36.62	28.94	20.93	28.83	16.30	16.11	-0.19	-1.17	-12.72	-44.12
Average	19.24	13.39	10.92	14.52	6.14	8.1	1.96	31.92	-6.42	-44.20
Minimum	9.02	5.27	4.60	6.30	2.99	3.89	0.9	30.10	-2.41	-38.22
NO ₂										
Maximum	114.33	109.81	91.51	105.22	74.34	61.92	-12.42	-16.71	-43.30	-41.15
Average	52.57	53.17	47.55	51.10	34.54	33.78	-0.76	-2.20	-17.32	-33.89
Minimum	16.53	21.33	14.66	17.51	12.52	12.55	0.03	0.24	-4.96	-28.31
СО										
Maximum	2.26	1.97	1.55	1.93	1.61	1.27	-0.34	-21.12	-0.66	-34.08
Average	1.17	0.89	0.93	1.00	0.74	0.84	0.1	13.51	-0.16	-15.72
Minimum	0.63	0.44	0.37	0.48	0.35	0.59	0.24	68.57	0.11	22.92

Pollutants	2017	2018	2019	Avg. of 2017–2019	during Lockdown (2020)	after Lockdown -	Variation (after and during Lockdown)		Variation (after lockdown and Avg. of 2017–2019)	
							Net	%	Net	%
O3										
Maximum	110.12	83.46	87.27	93.62	97.05	165.61	68.56	70.64	71.99	76.90
Average	60.15	50.50	45.76	52.14	57.67	89.18	31.51	54.64	37.04	71.05
Minimum	18.00	11.54	6.44	11.99	8.02	32.55	24.53	305.86	20.56	171.40

Table 3. Cont.

3.3. Spatial Concentration Pattern of PM_{2.5}

Particulate matter, also known as PM2.5 with an aerodynamic diameter of 2.5 µm or less than 2.5 µm, is linked with numerous adverse human health effects, especially respiratory and cardiovascular infections. According to the Global Burden of Disease, particulate matter ($PM_{2.5}$) is the seventh and fourth main risk factor in the world and China, respectively [15,48]. During the COVID-19 lockdown phase in Nanjing, the PM_{2.5} concentration decreased by -5.09% compared with the pre-lockdown phase. Compared with PM_{10} , the reduction in the concentration of $PM_{2.5}$ was relatively lower. The average concentration of PM_{25} and variations are presented in Figure 3 and Tables 1–3. Further, compared with the pre- and during lockdown phases, Nanjing experienced a significant decline of -33.41% after the lockdown. Similar decreasing trends in the concentrations of PM_{2.5} in many cities across the world have been reported by Singh and Chauhan (2020) [8]. Vehicular emissions, industrial production and construction activities, among others, are the main sources of $PM_{2.5}$ concentrations [13]. The results suggest that during the COVID-19 lockdown, reduced human mobility and the stoppage of vehicular and industrial processes subsequently caused a considerable drop in fine particulate matter in the environment. Previously, Chen et al. (2020b) [20] also reported that during the COVID-19 period, PM_{2.5} declined in many areas and regions across China.

During the lockdown period a noteworthy improvement and reduction in the PM_{2.5} concentration (-34.81%) was found compared with 2019. The previous three years' (2017–2019) data showed a significant reduction in PM_{2.5} (-33.56%). The results indicate that the reduction ratio in 2020 was greater compared with 2017–2019 in Nanjing. A similar pattern of PM_{2.5} reduction was reported in the USA, using air-quality data between 2017 and 2020 and 2017 and 2019 in China, respectively [20,22]. In the Guangxi Region, compared with 2016–2019, during the lockdown period, an approximately -22.6% reduction in PM_{2.5} was observed as reported by Fu et al. (2020) [49]. However, the present study revealed that compared with the lockdown period, the concentration of PM_{2.5} reduced by up to -31.63%, and after lockdown it reached -54.57%. Overall, compared with the previous three years, the present study concludes that the lockdown and strict polices caused a notable reduction and improvement in air quality.

3.4. Spatial Concentration Pattern of SO₂

The present study shows that due to the nationwide lockdown, a significant improvement in SO₂ was observed. Compared with the pre- and during lockdown phases, SO₂ showed an increasing trend. The results demonstrate that compared with the pre-lockdown phase, an approximately -32.90% reduction in the SO₂ concentration was observed. However, compared with the pre- and during lockdown phases, SO₂ increased by 5.95% in Nanjing. This increment in SO₂ concentration can be attributed to coal burning, power plants and industrial activities after lockdown [13]. The average concentration of SO₂ and variations are presented in Figure 3 and Tables 1–3. The main sources of SO₂ are coal and diesel used in thermal power, burning of fuels, transport and industry [44]. Due to the COVID-19 lockdown, limited industrial, vehicular and heating activities were responsible for the reduction in SO₂ emissions. Previously in China, a similar pattern in SO₂ reduction was reported [10,12]. In addition, it is evident from Shakoor et al.'s (2020) [23] study, that compared with the pre-lockdown phase, SO_2 was reduced by 18% during the lockdown phase in China.

Moreover, compared to the year before (2019) with the same time frame, a sizable reduction and improvement in the concentration of SO_2 was observed, that is, up to -43.77% during the lockdown phase in Nanjing. A reduction in the SO₂ concentration during this period was greater compared with the pre-lockdown phase for the same time frame in Nanjing. Similar results have been reported by Bao and Zhang (2020) [10] and Islam et al. (2020) [39] in China and Bangladesh, respectively. These studies demonstrate that compared to 2019, the SO_2 concentration decreased. Further, our study also found that compared with the previous three years with the same time period (2017–2019), SO_2 showed a sharp decline of up to -57.70% during the lockdown phase. It is evident from the study by Chen et al. (2020b) [20] that concentrations of SO₂ were reduced compared with 2017–2019 in many areas across China. Nanjing experienced a considerable increasing trend in SO_2 up to 31.92% after the lockdown. However, in the previous three years, the concentration of SO₂ decreased by -44.20%. According to Fu et al. (2020) [49], SO₂ was found at its lowest level during the lockdown phase compared with the previous five years in the Guangxi Region, China. Overall, there was a decline in SO₂ concentration throughout the study period in Nanjing, except after the lockdown phase compared with the pre- and during lockdown phases.

3.5. Spatial Concentration Pattern of NO₂

The results witnessed during the lockdown phase, show that owing to the COVID-19 pandemic and post-lockdown, Nanjing experienced a significant reduction in NO₂ concentration. The average concentration of NO₂ and variations are shown in Figure 3 and Tables 1–3. The study revealed that compared with the pre-lockdown phase, a -34.66% reduction and improvement in NO₂ concentration was observed. During the lockdown phase, compared with pre- and during lockdown phases, the concentration of NO₂ decreased by -22.70%. The reduction in NO₂ concentration was greater during the lockdown phase. A similar pattern of results was observed by NASA (2020) [21], and NO₂ emissions decreased by 30% in Central China. Shakoor et al. (2020) [23] reported that during the lockdown phase, a 38% decline in NO₂ concentration was found in China. Another study revealed that during lockdown, there was a decline in NO₂ concentration over the Yangtze River Delta [9]. NO₂ is mainly emitted from vehicles, power plants, road traffic and industrial and manufacturing activities in urban areas and regions. Due to the nationwide lockdown, all of these sectors closed, which resulted in the decline in pollutants such as NO₂.

During the lockdown, Nanjing was found to experience a -27.36% drop in NO₂ concentration compared to the previous year, 2019. It was reported by Fu et al. (2020) [49] that NO₂ showed a declining trend during the lockdown phase compared with the previous 5 years. Compared to the 2019 measurements for the same dates, a 34.7% drop in the concentration of NO₂ was found in North China. Compared with 2019, the concentration of surface and tropospheric NO₂ decreased by up to 20–30% in China [25]. It is evident from the study by Chen et al. (2020b) [20] that in many areas across China, the concentration of NO₂ decreased during 2017–2019. According to Berman and Ebisu 2020 [22], between 2017 and 2020, NO₂ emissions decreased by -26% during the lockdown phase in the USA. Moreover, compared to the lockdown phase, the concentration of NO₂ declined by up to -2.20% after the lockdown. Compared to the previous three years, for the same time frame (2017–2019), a significant decline of -33.89% in NO₂ concentration was observed after the lockdown phase. In summary, a drastic change and improvement in the concentration of NO₂ showed that the lockdown and strict policies had a significant impact on changing and decreasing the NO₂ concentrations in Nanjing.

3.6. Spatial Concentration Pattern of CO

During the lockdown phase, due to the COVID-19 pandemic in Nanjing, like other pollutants, CO showed a decreasing trend, while after lockdown the CO concentration increased. The average concentration of CO and variations are depicted in Figure 3 and Tables 1–3. The present study shows that compared to the pre-lockdown phase, the concentration of CO decreased by -16.85% during the lockdown. The results suggest that it this was mainly due to the restrictions on transportation and vehicles in Nanjing, while compared with the pre- and during lockdown phases, CO increased by 3.07%. CO is emitted from vehicular sources, burning of agricultural waste, biofuel burning and combustion of fossil fuels [50]. During the lockdown period, all of these sectors were closed, which resulted in a significant improvement in the concentration of CO. It was previously reported that during the lockdown period in China, the concentration of CO was reduced by 18% [23]. These findings are very similar to our results. Another study reported by Hanaoka and Masui (2020) [19] revealed that due to the COVID-19 pandemic lockdown period, 25% and 6% reductions in CO concentrations were observed in China and globally, respectively. Meanwhile, during the nationwide lockdown phase in the USA, the concentration of CO was reduced by 1.1%, while in the megacity Delhi, India, compared with the pre-lockdown phase, CO decreased by 30.35% during the lockdown phase [23,51].

Moreover, our results demonstrate that compared to 2019 and using the same dates, the concentration of CO decreased by -20.43% during the lockdown phase, while compared with the previous three years and the same time frame, CO was reduced by up to -25.75%, which is greater than for 2019 in Nanjing. Chen et al. (2020b) [20] found that in many areas across China, the concentration of CO was reduced during the lockdown compared to the previous three years. Compared with the same period from 2016 to 2019, there was a decline in CO concentration of -18.6% during the lockdown in South China. During the lockdown phase, the CO concentration was at its lowest ratio compared to the previous 5 years, and the concentration of CO decreased by 14.5% [49]. Further, compared with the lockdown phase, CO showed an increasing trend of up to 13.51% after the lockdown, while in comparison to the previous three years, concentrations of CO decreased by an average of -15.72% in Nanjing. Overall, during the study period, Nanjing was found to experience a significant reduction in the concentration of CO, except after the lockdown phase.

3.7. Spatial Concentration Pattern of O_3

In our study, analysis of the O_3 concentration revealed that there was an increasing trend in the concentration of O_3 during and after the lockdown phases in Nanjing. The average concentration of O_3 and variations are shown in Figure 3 and Tables 1–3. O_3 is a minor contaminant that is emitted from sunlight and nitrogen oxides (NOx), and volatile organic compounds (VOCs) [52]. During the lockdown phase, the concentration of O_3 increased by 25.45% compared with the pre-lockdown phase, while compared with the pre- and during lockdown phases, O_3 continuously increased by 72.10% in Nanjing. The increment ratio for the concentration of O_3 was greater after the lockdown than during the lockdown due to the winter–summer transection. A similar observation was reported by Chen et al. (2020b) [20], who found that during the lockdown phase in China, the concentration of O_3 increased. According to Islam et al. (2020) [39], O_3 increased during the lockdown phase in Bangladesh, while Mahato et al. (2020) [51] found that O_3 showed an increasing trend during the lockdown phase in Delhi, India.

Moreover, compared to 2019, the concentration of O_3 increased by 26.03%. Compared with the previous three years, the O_3 concentration increased by 10.61% in Nanjing. Chen et al. (2020b) [20] reported that there was a rising trend in O_3 concentration during the lockdown phase in China. Further, compared with the lockdown phase, Nanjing experienced a remarkable increment in the concentration of O_3 after the lockdown with an average increment of 54.64%, while in comparison with the previous three years, 2017–2019, for the same period, the concentration of O_3 continuously increased by an average of 71.05% in Nanjing. This increment in O_3 concentration was greater compared with the lockdown phase in 2020. A drastic change and notable improvement in air quality were observed due to the implementation of the lockdown amid the COVID-19 pandemic, except for O_3 in Nanjing.

3.8. Correlation between Different Air Pollutants

The correlations between different air pollutant concentrations during the lockdown period in Nanjing are shown in Figure 4. The daily (24 h) average concentrations of PM_{10} and PM_{2.5} were highly correlated (r = 0.82) with SO₂ (r = 0.26). There was a significant positive correlation between PM_{10} and NO_2 (r = 0.41). The strong correlation between PM_{10} and PM_{25} suggests that it was due to their mutual pollution sources: vehicular and industrial emissions. The correlation analysis indicated that there was a strong correlation between PM_{10} and CO during the lockdown phase in Nanjing (r = 0.52). $PM_{2.5}$, SO_2 (r = 0.07) and NO₂ (r = 0.26) were highly correlated. This shows that PM_{2.5}, SO₂ and NO₂ had a certain homology, while after the chemical reactions occurred in the atmosphere, SO2 and NO2 produced small particles. Combustion of fossil fuels contaminated with sulfur compounds result in the existence of SO_2 in the atmosphere. The daily average concentrations of $PM_{2.5}$ and CO were significantly correlated (r = 0.51) during the lockdown phase. Moreover, the (24 h) average concentration of SO₂ was significantly correlated with the (24 h) average concentration of NO₂ (r = 0.38) and CO (r = 0.27). The concentration of NO₂ was strongly correlated with the CO concentration (r = 0.39) and O₃ (r = 0.23). The positive correlation between NO₂ and CO was due to the positive correlation between particulate matter (PM) and CO. It suggests that O_3 levels increased with the reduction in the other pollutants, especially NO₂ and CO.



Figure 4. Correlation between different air pollutants.

4. Conclusions

The capital of Jiangsu Province, Nanjing, is known for its extreme and severe pollution levels, and it is considered one of the most polluted cities in China and internationally. The COVID-19 pandemic lockdown and shutdown policies in different parts of the world have provided a great opportunity to study the impact of humans on the environment. Therefore, the results of this study may help us to understand how responsible we are for our air pollution problems and how to mitigate them. In the current study, the impact of the nationwide lockdown that was imposed in order to curb the rapid spread of COVID-19 in China, on the air quality of the capital city of Jiangsu Province, Nanjing, was evaluated based on six air pollutants. The results show that there was a significant reduction in

these pollutants, except for O_3 during the lockdown phase in Nanjing. Compared to the previous three years (2017–2019), the concentrations of PM_{10} and $PM_{2.5}$ were reduced by -37.99% and -33.56%, respectively, during the lockdown. Therefore, compared to the previous three years, PM_{10} and $PM_{2.5}$ concentrations decreased by -43.58% and -54.57%, respectively, after the lockdown. Moreover, a significant reduction in other pollutants, such as SO_2 , NO_2 and CO concentrations, were also observed during the lockdown phase. SO₂ and CO showed a tendency to increase after the lockdown phase in Nanjing. During the lockdown, an approximately 25-35% improvement in air quality was observed. This study provides useful information and outcomes for future studies and creates a new paradigm for regulatory authorities and policymakers to create policies for the improvement of air pollution. Other studies, as discussed in Section 1, have mainly focused on either air quality assessment and monitoring over the last few years or the comparison between before and current air pollutants; however, our study performed three types of comparisons, i.e., before, after, and current trends as well as a comparison with data on air pollutants from the last 3 years. Another major advantage of this study is that it considered all of the pollutants, while other studies have focused on only a few pollutants. This helps in policy recommendations for government with regard to how trends in air quality are changing after COVID-19, and it helps air quality and monitoring stations to take the necessary steps if air quality does not improve. Furthermore, the outcomes of the current study will encourage the Chinese administration to deliberate on how to decrease industrial and vehicular contamination to reform and improve air quality, which will help to maintain better public health in China. The current study can be further extended to other regions and countries by finding new correlation factors between air pollutants and meteorological indicators.

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