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## Did the COVID-19 lockdown affect air quality? Evidence from Viet Nam

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## **ADB Working Paper Series**

### **DID THE COVID-19 LOCKDOWN AFFECT AIR QUALITY? EVIDENCE FROM VIET NAM**

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Nghia Thi Thu Nguyen,  
Tran Thi Ngan, and  
Chun Yee Wong

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**Asian Development Bank Institute**

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**Abstract**

Against the backdrop of the COVID-19 pandemic, most countries implemented a partial or full lockdown as a preventive measure. Although lockdown caused an economic contraction, it unexpectedly improved the environment, especially air pollution. This paper quantifies the impact of the lockdown on air quality by utilizing the air quality data and the lockdown periods in 11 cities and provinces in Viet Nam in 2022 and 2021. Our main empirical framework examines how lockdown measures affected air quality across different locations in Viet Nam during this period. To address the heterogenous effects of lockdown, we conducted a subsample analysis on locations. Utilizing a linear model with time- and location-fixed effects, our analysis revealed that implementing an extra day of lockdown resulted in a decrease of 1.018 ppm in the CO level, while a stricter full lockdown for an additional day led to a drop of 1.369 ppm. These findings remained consistent even when examining the subsamples by location.

**Keywords:** COVID-19 pandemic, lockdown, air quality, Viet Nam

**JEL Classification:** H00, O13, Q53

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# 1. INTRODUCTION

In the realm of environmental factors influencing mortality rates, air pollution stands as a prominent concern. A comprehensive examination of data derived from the 2015 Global Burden of Disease study reveals that ambient PM<sub>2.5</sub> emerges as a key contributor to global mortality, accounting for a staggering 4.2 million deaths (Cohen, A. J. et al. 2017). A substantial majority, nearly 60%, of these fatalities unfolded in East and South Asia, encompassing countries such as Bangladesh, the People's Republic of China (PRC), India, and those within the Persian Gulf region, where PM<sub>2.5</sub> concentrations surpassed recommended levels by over 10 times. Notably, Viet Nam experienced a particularly severe situation, with PM<sub>2.5</sub> concentration surpassing standard levels by five to seven times, according to the World Air Quality Report of 2022 (IQAir 2022).

In early 2020, the World Health Organization (WHO) declared the coronavirus disease (COVID-19) a pandemic. In response, many countries implemented a partial or full lockdown as a preventive measure against COVID-19. Despite the adverse impact of these lockdowns on national economies, they proved to be an effective means of curbing the global spread of the coronavirus infection. Strikingly, the extensive limitations on human and business activities during the lockdowns yielded an unexpected but noteworthy consequence: the lockdowns effectively reduced air pollution worldwide. Chauhan and Singh (2020) observed a decline in concentrations of air pollution in major cities globally, including New York, Los Angeles, Rome, Dubai, Delhi, and Beijing, due to the lockdown measures. Venter et al. (2020) conducted an extensive analysis using data from a network of over 10,000 air quality stations in 34 countries, leveraging Google and Apple mobility data to examine the hypothesis that COVID-19 lockdowns led to a decline in tropospheric and ground-level air pollution concentrations. Their findings revealed that the lockdown events resulted in a 60% reduction in the concentration of nitrogen dioxide (NO<sub>2</sub>) and a 31% reduction in fine particulate matter (PM<sub>2.5</sub>). Lenzen et al. (2020) employed an input–output model for 38 regions worldwide and identified a decrease in global greenhouse gases, PM<sub>2.5</sub> (mass concentration of particles with diameters of 2.5 mm), and air pollutants by 4.6%, 3.8%, and 2.9%, respectively.

Several studies focused on a country-specific context rather than on a global scale. Wang, Liu, and Zheng (2020) examined 325 cities in the PRC from 1 January to 2 May 2020 to investigate the effect of COVID-19 lockdowns on air quality improvement. Using the human mobility-based difference-in-differences method, the paper estimated that concentration levels of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, and CO dropped by 13.1%, 15.3%, 4%, 3.3%, and 3.3%, respectively, in cities implementing a lockdown. In the context of Viet Nam, Dang and Trinh (2021) employed the Regression Discontinuity Design (RDD) model to estimate the lockdown impacts on air quality in Viet Nam and found a 24%–32% reduction of ambient NO<sub>2</sub> exposure two weeks after the COVID-19 lockdown. Brodeur, Cook, and Wright (2021) found the same evidence of air quality improvement with a reduction in PM<sub>2.5</sub> emissions due to the “safer-at-home” policies in the United States. Nevertheless, Chang, Meyerhoefer, and Yang (2021) also found that air pollution increased by 3%–7% in the concentration level of CO, O<sub>3</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> in the two largest cities in Taipei, China. This study examined the impact of COVID-19 lockdowns on air quality in a full period, which was over two years rather than a year or less.

Despite the growing body of literature investigating the positive impacts of lockdowns on air quality in various countries, there are few studies focusing on low- or low-middle-income countries. Within the realm of emerging markets, Viet Nam stands out as a unique and intriguing case study. As a country with severe air pollution, Viet Nam faces an estimated annual economic contraction of 5% of total GDP due to air pollution. This makes it worthwhile to investigate potential measures to minimize air pollution in Viet Nam. Furthermore, the country implemented early lockdowns on both national and local scales to combat multiple waves of the pandemic, emerging as a global success story with zero deaths recorded. For instance, the Vietnamese government enforced a nationwide lockdown lasting 15 days from 1 April to 15 April 2020. This lockdown entailed restrictions on mobility and the cessation of nonessential economic activities, allowing only for essential goods and services such as food and medical necessities. While these measures understandably imposed social constraints and triggered economic downturns from advanced to emerging economies, the lockdown exhibited a significant impact on air quality. Dang and Trinh (2021) discovered that the global concentration of PM<sub>2.5</sub> decreased by 4% after the lockdown (Dang and Trinh 2021). In Viet Nam specifically, the average PM<sub>2.5</sub> concentration annually decreased from 28 µg/m<sup>3</sup> in 2020 to 24.7 µg/m<sup>3</sup> in 2021 (IQAir 2022).

In this paper, we analyze the impacts of the lockdowns during the COVID-19 pandemic on air quality in Viet Nam. Our study contributes to the growing body of literature examining the impact of lockdown measures on air quality in developing economies. The purpose of this study is twofold. First, it is crucial to gain a thorough knowledge of how lockdown measures impacted air quality. A better understanding of various aspects of the economic, environmental, and health impacts of the COVID-19 pandemic is crucial for accelerating recovery and extracting valuable lessons applicable to future pandemics. Second, global mortality rates are closely linked to air pollution (Bruneekreer and Holgate 2002; Li et al. 2019). Given that the restriction of human activities and mobility during the pandemic can be viewed as a natural experiment, our study facilitates the exploration of the causal relationship between human activities and environmental changes, particularly in the context of air pollution. This experimental approach provides scientific evidence supporting the effectiveness of lockdown policies in reducing air pollution, offering policymakers valuable insights for making informed decisions in future situations that they may need to give consideration to restricting business or transportation activities.

Similarly to the study conducted by Dang and Trinh (2021), our empirical analysis involves variations in both the measurement of air quality and lockdown durations for the years 2020 and 2021. To gather data on air quality, we utilized real-time readings from 11 cities and provinces in Viet Nam affected by lockdown measures. The data span three-years from 1 January 2020 to 31 December 2022, diverging from Dang and Trinh's (2021) study, which focused on the period from 1 January 2022 to 10 January 2023 (Dang and Trinh 2021).

Our primary empirical approach investigates the impact of lockdowns on air quality across diverse cities and provinces, considering variations in both time and space. One of the challenges in our identification strategy arises from potential heterogeneous effects based on the locations, attributed to differing socioeconomic statuses and levels of exposure to air pollution. Recent findings by Briole, Colette, and Lavaine (2023) emphasize a significant spatial heterogeneity in lockdown effects (Briole, Colette, and Lavaine 2023). This heterogeneity implies that the effects of lockdown on air quality may either be diminished or intensified depending on the specific characteristics of each location.

To address this spatial heterogeneity concern, we conducted a subsample analysis by locations: northern and southern, with or without airports, and high-GDP versus low-GDP regions. Employing a linear model with temporal and spatial fixed effects, our analysis revealed that implementing an extra day of lockdown (with or without the required social distancing) resulted in a decrease of 1.018 ppm in the CO level, while a stricter full lockdown (with the required social distancing) for an additional day led to a drop of 1.369 ppm.

We have organized the remainder of the paper as follows: Section 2 discusses the background; Section 3 describes the related data sets; Section 4 introduces the empirical strategy; Section 5 discusses the estimation results and policy implications; and Section 5 concludes the paper.

## 2. BACKGROUND

### 2.1 Air Quality in Viet Nam

Over the past few decades, Viet Nam has experienced rapid economic growth. According to data from the World Bank and OECD national accounts, the country's GDP per capita soared from \$235 in 1985 to over \$4,000 in 2022. However, within this progress, Viet Nam is facing escalating air pollution, particularly in major cities like Ha Noi and Hai Phong.

**Figure 1: Long-term Air Pollution (Dang and Trinh 2021)**

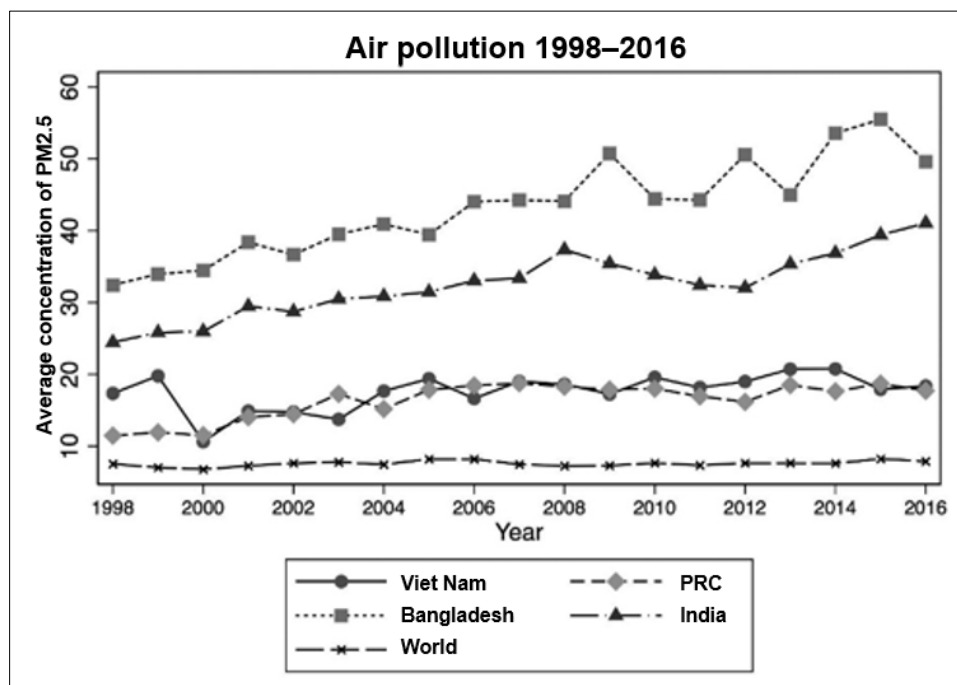


Figure 1 illustrates the annual PM2.5 concentrations in Viet Nam from 1998 to 2016. The data reveal that Viet Nam's average PM2.5 levels are comparable to the PRC's annual levels, but still significantly lower—approximately five to six times—than the more polluted air in Bangladesh and India. Nevertheless, they are approximately twice as high as the global standard average level. According to the historical data from 2018



to 2022 on the world's most polluted countries and regions, Viet Nam ranked 30th with an annual average PM<sub>2.5</sub> concentration of 27.2 ( $\mu\text{g}/\text{m}^3$ ), while the WHO standard level was 0–5 ( $\mu\text{g}/\text{m}^3$ ). The capital city, Ha Noi, ranked as the second most polluted city in Southeast Asia, after Pasarkemis in Indonesia (VnExpress 2023).

Many recent studies have shown evidence of the negative impacts of air pollution on mortality rates and human health (Andersen et al. 2021; Hanigan et al. 2021; Bourbeau et al. 2022; Nguyen et al. 2022). Several studies have also identified possible diseases due to exposure to air pollution, including lung cancer, obstructive pulmonary disease (COPD), stroke, cardiovascular disease, and diabetes (Li et al. 2019; Bourbeau et al. 2022). Vu et al. (2020) examined the association between poor air quality and mortality in Ho Chi Minh City, Viet Nam and found that the possible impacts of air pollution on human health included ischemic heart disease (IHD), cardiopulmonary disease, and lung cancer, which resulted from air pollutants including PM<sub>2.5</sub>, NO<sub>2</sub>, and SO<sub>2</sub>.

Human activities, particularly those associated with power plants, vehicles, and industrial processes, are recognized as the primary contributors to outdoor air pollution. In a study by Kopplitz et al. (2017), an investigation into coal emissions from coal-fired power plants in Southeast Asia in 2011 revealed a significant impact on ambient PM<sub>2.5</sub> and ozone. Indonesia and Viet Nam, in particular, faced a significant mortality rate attributable to coal emissions, with 7,480 excess deaths per year in Indonesia and 4,250 in Viet Nam.

Transportation is another substantial source of air pollution, emanating from motorized vehicles. According to the World Bank's 2014 data, transportation contributed 22% to CO<sub>2</sub> emissions in Viet Nam, while in the PRC it accounted for 8.6% of air pollution, and in the US it contributed 33.4%. Vu et al. (2020) conducted a comprehensive analysis of 24 districts in Ho Chi Minh City, Viet Nam, determining that transportation was the foremost contributor to PM<sub>2.5</sub>, responsible for 44.5% of total emissions. Industrial activities followed with 33.6%, and other sources contributed 22.6%.

Similarly, a study by Cohen et al. (2010) focused on Ha Noi city from 2001 to 2008, highlighting the contributions of traffic, industrial activities, and other sources to air pollution. The findings indicated that traffic accounted for 40%, industrial activities for 36%, and other sources for 24% of the overall air pollution in the city during the specified period.

## **2.2 COVID-19 Lockdown Policies in Viet Nam**

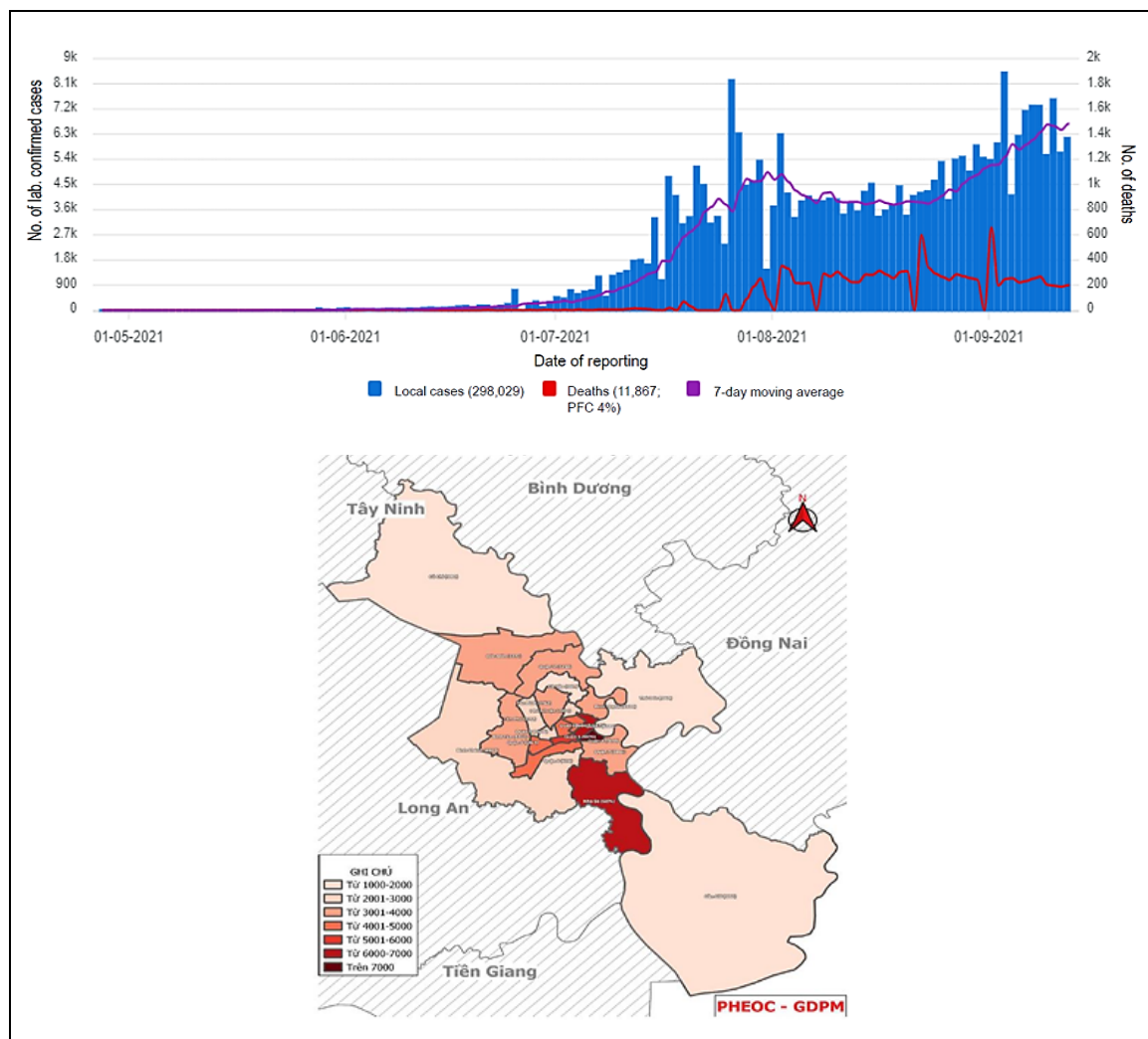
Throughout the COVID-19 pandemic, Viet Nam encountered four waves starting from early January 2020, as depicted in Figure 2. There were fewer than 1,000 documented cases in the first three waves, with either no deaths or a very low number of fatalities. However, the impact of the fourth wave was substantially greater than the previous waves, primarily due to the emergence of the Delta variant of the coronavirus.

With reference to the Viet Nam Coronavirus Disease 2019 Situation Report provided by the Representative Office for Viet Nam of the WHO, Figure 3 highlights the five most affected cities with the highest number of cases: Ho Chi Minh, Binh Duong, Dong Nai, Long An, and Tien Giang. In particular, the situation took an alarming turn, and the fourth wave presented unprecedented challenges. By 10 October 2021, the infection cases were reported to be contained across the nation, encompassing 62 cities and provinces, according to a report from the Ministry of Health in Viet Nam. This marked a crucial development in the ongoing efforts to manage and mitigate the impact of the pandemic.

**Figure 2: Four Waves of the COVID-19 Pandemic in Viet Nam**

Wave 1 23 Jan–16 Apr 2020 (85 days)	Wave 2 25 Jul–1 Dec 2020 (129 days)	Wave 3 28 Jul–25 Mar 2021 (57 days)	Wave 4 27 Apr 2021–24 Jan 2022 (286 days)
<ul style="list-style-type: none"> <li>• Original virus strain from Wuhan</li> <li>• 100 community cases</li> <li>• No deaths</li> </ul>	<ul style="list-style-type: none"> <li>• D614G variant</li> <li>• 554 community cases</li> <li>• 35 deaths</li> </ul>	<ul style="list-style-type: none"> <li>• Alpha variant</li> <li>• 910 community cases</li> <li>• No deaths</li> </ul>	<ul style="list-style-type: none"> <li>• Delta variant</li> <li>• 601,349 community cases</li> <li>• 15,018 deaths</li> </ul>

Source: Ministry of Health (MOH), Viet Nam.

**Figure 3: Epidemiological Curve of New Cases and Deaths by Date of Reporting and Geographical Distribution of COVID-19 Cases per 100,000 Population by District, Ho Chi Minh City, 29 April–12 September 2021**Source: [https://www.who.int/docs/default-source/wpro---documents/countries/viet-nam/covid-19/viet-nam-moh-who-covid-19-sitrep\\_12sep2021.pdf?sfvrsn=9972a12c\\_5](https://www.who.int/docs/default-source/wpro---documents/countries/viet-nam/covid-19/viet-nam-moh-who-covid-19-sitrep_12sep2021.pdf?sfvrsn=9972a12c_5).

The Vietnamese government implemented multiple measures in order to prevent the outbreak of the COVID-19 pandemic from the beginning of January 2020. One of the key measures was a series of lockdown policies. The government imposed the first commune lockdown in Ho Chi Minh City on 22 January 2020 when the first two cases were tested positive. However, due to the rapidly increasing number of COVID-19 cases, the government implemented a stricter lockdown policy following Directive No. 16, which lasted for 15 days from 1 April to 15 April 2020. This was also the first nationwide lockdown in Viet Nam. Besides providing treatment for infected patients, the lockdown measures included travel restrictions, quarantine, isolation, and social distancing, thereby preventing people from going outside, except for buying necessity goods. Later, the lockdown policy was extended to 21 days or more in 12 provinces exposed to higher risk. Similar lockdowns continued to happen in targeted cities, provinces, and districts in Viet Nam after the first wave occurred.

Prime Minister's Directives No. 15, No. 16, and 16 plus, including a stay-at-home order, were implemented. Directive No. 15 imposed restrictions on public gatherings, meetings, and events with more than 20 attendees. Groups of people could not exceed ten outside of workplaces, schools, and hospitals. In public areas, there had to be a minimum of 2 meters between people. Any religious ceremonies and activities involving 20 individuals or more had to be suspended in places of worship. All community establishments that provided services had to temporarily halt operations, except for those that provided necessities like food and shelter. Directive No. 15 did not require social distancing.

Under a new, stricter Directive No. 16, troops were once more stationed in Ho Chi Minh City on 23 August 2021 to intensify the lockdown. Every citizen was required to stay at home and only leave for emergencies, such as buying food and medicine, or to work at factories, production facilities, or important product and service suppliers (uninterruptible places). Everyone had to take seriously implementing a 2-meter minimum communication distance. Additionally, it prohibited groups of more than two people from congregating in areas such as public spaces, schools, hospitals, and workplaces. In this paper, Directive 16 is considered a full lockdown while Directive 15 is considered a partial lockdown.

According to the General Statistics Office, Vietnamese economic growth was harmed by the COVID-19 pandemic. The fourth wave had a significant impact on growth results. Comparing the third quarter of 2021 to the same period in the previous year, the GDP fell by 6.17%, the steepest decrease since Viet Nam's quarterly GDP was estimated and released.

### **3. DATA AND VARIABLES**

#### **3.1 Data**

The main variables of our analysis are constructed based on two main panel data sets. The first data set was collected from the World Air Quality Index (WAQI) project team's website, which provides historical air quality data to relevant institutions and organizations working in environmental awareness and air quality monitoring. The AQI is based on the six atmospheric pollutants, namely fine particulates (PM<sub>2.5</sub>), suspended particulates (PM<sub>10</sub>), ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and carbon monoxide (CO), which were obtained from the air quality monitoring stations in three centrally run cities and eight provinces in Viet Nam from 1 January

2020 to 31 December 2021. Table 1 presents a description of the pollutants that are the main outcome variables in this study.

**Table 1: Description of Dependent Variables**

Dependent Variables	Types of Variables	Description
<i>PM2.5</i>	Continuous	Atmospheric particulate matters that have a diameter of less than 2.5 micrometers ( $\mu\text{g}/\text{m}^3$ )
<i>PM10</i>	Continuous	Atmospheric particulate matters that have a diameter of less than 10 micrometers ( $\mu\text{g}/\text{m}^3$ )
<i>O<sub>3</sub></i>	Continuous	Ozone (ppm)
<i>NO<sub>2</sub></i>	Continuous	Nitrogen Dioxide (ppb)
<i>SO<sub>2</sub></i>	Continuous	Sulfur Dioxide (ppb)
<i>CO</i>	Continuous	Carbon Monoxide (ppm)

Notes:  $\mu\text{g}/\text{m}^3$ : micrograms (one millionth of a gram) per cubic meter of air; ppm: parts per million; ppb: parts per billion.

The second data set recorded the lockdown periods at two levels in 11 cities and provinces in Viet Nam, namely Ha Noi, Bac Ninh, Cao Bang, Lao Cai, Quang Ninh, Thai Nguyen, and Phu Tho in the north; Da Nang, Gia Lai, and Thua Thien Hue in the center; and Ho Chi Minh in the south. There was no comprehensive record of all lockdown periods in Viet Nam, so the data set was collected based on the news about the starting and ending times of lockdown periods in each region, following Directives 15 and 16 on COVID-19 prevention and control.

The two datasets were then combined into one panel at the area-day level from 1 January 2020 to 31 December 2021. All areas with lockdown data were matched with the location where air quality variables were collected. The data set records the dates and locations, and *PM2.5*, *PM10*, *O<sub>3</sub>*, *NO<sub>2</sub>*, *SO<sub>2</sub>*, and *CO* concentrations with 12,432 observations, representing 11 cities and provinces in Viet Nam where air quality data were obtained.

In addition, data containing other indicators were collected to facilitate robustness checks. These indicators include: (i) seasonal effects (further details can be found in Appendix 1 on Viet Nam's climatic features) and (ii) airport presence or absence. According to Riley et al. (2021), commercial airport activity can have a negative impact on the quality of the air in the vicinity of airports, and hence millions of people living close to major airports in the United States. These investigations repeatedly demonstrated that there was an increase in ultrafine particle (UFP) matter in and around airports. Several studies also revealed higher concentrations of black carbon, criterion pollutants, polycyclic aromatic hydrocarbons, and particulate matter with a diameter of 2.5 microns (*PM2.5*). To further investigate the heterogeneity of impacts, information on the contribution of each province to Viet Nam's GDP in 2021 was gathered.

### 3.2 COVID-19 Lockdown

The key explanatory variable in our main empirical specification is *lockdown*. It is anticipated that an increase in lockdown times in one location will be associated with better local air quality. Our analysis also contains time variables: *year*, *month*, and *weekend*; and other variables: *season*, *airport*, and *GDP contribution* as control variables. Table 2 describes the main independent variables of our analysis.

**Table 2: Description of Independent Variables**

Independent Variables	Types of Variables	Description
<i>lockdown</i>	Binary	= 1 for any type of lockdown
<i>partial_lockdown</i>	Binary	= 1 if lockdown was implemented under Directive 15 (the less strict measures) * Detail can be found in Section 2.2
<i>full_lockdown</i>	Binary	= 1 if lockdown was implemented under Directive 16 (the stricter measures) * Detail can be found in Section 2.2
<i>2021</i>	Binary	= 1 if survey year is 2021 and = 0 if survey year is 2020
<i>month</i>	Binary	dummies for months 2 through 12
<i>weekend</i>	Binary	= 1 if it is Saturday or Sunday
<i>winter_north</i>	Binary	= 1 for winter (in northern areas)
<i>spring_north</i>	Binary	= 1 for spring (in northern areas)
<i>summer_north</i>	Binary	= 1 for summer (in northern areas)
<i>fall_north</i>	Binary	= 1 for fall (in northern areas)
<i>dry_south</i>	Binary	= 1 for dry season (in southern areas)
<i>rainy_south</i>	Binary	= 1 for rainy season (in southern areas)
<i>south</i>	Binary	= 1 for southern areas
<i>airport</i>	Binary	= 1 if there is any airport
<i>gdpcontribution</i>	Binary	= 1 for high GDP contribution proportion to the country GDP, and 0 for low GDP contribution proportion

Table 3 presents the descriptive statistics of the variables used to estimate the outcome of air quality.

**Table 3: Descriptive Statistics**

Variable	Obs	Mean	Std. Dev.	Min	Max
<i>PM2.5</i>	10,013	58.083	44.379	1	313
<i>PM10</i>	8,817	36.651	30.548	1	313
<i>O<sub>3</sub></i>	6,823	17.509	17.352	1	500
<i>NO<sub>2</sub></i>	9,106	8.959	6.597	1	107
<i>SO<sub>2</sub></i>	8,589	14.946	36.7	1	500
<i>CO</i>	8,791	6.408	9.859	1	96
<i>lockdown</i>	12,432	.08	.272	0	1
<i>full_lockdown</i>	12,432	.058	.234	0	1
<i>partial_lockdown</i>	12,432	.022	.147	0	1
<i>weekend</i>	12,432	.717	.45	0	1

The sample data set consists of observations of daily average air quality data in 11 cities and provinces in Viet Nam with the indicators PM2.5, PM10, O<sub>3</sub>, NO<sub>2</sub>, SO<sub>2</sub>, and CO concentrations with 12,432 observations of lockdowns at two levels (full lockdown and partial lockdown) in the two-year period between 2020 and 2021.

## 4. EMPIRICAL APPROACH

Donggyu Sul (2019) suggests that with a sufficiently large number of observations in panel data, it is feasible to identify and estimate fixed effects. This approach was employed by Li et al. (2019) in their analysis of air quality and subway coverage data in Beijing from 2008 to 2016. Their aim was to investigate whether subway expansion had a positive impact on air quality. Following their methodology, this study examined the impact of lockdown on air quality outcomes using a regression model on panel data with a fixed effect on location. The concentrations of *PM2.5*, *PM10*, *O<sub>3</sub>*, *NO<sub>2</sub>*, *SO<sub>2</sub>*, and *CO* are the outcome variables in our analysis. The regression model estimated in this study is as follows:

$$y_{it} = \alpha + \mathbf{LD}_{it}\boldsymbol{\beta} + \mathbf{s}_t\boldsymbol{\tau} + a_i + u_{it}, \quad (1)$$

where  $y_i$  denotes the outcome variables, including *PM2.5*, *PM10*, *O<sub>3</sub>*, *NO<sub>2</sub>*, *SO<sub>2</sub>*, and *CO* concentrations. The variables of interest are **LD**, which are different measures of the lockdown policy including *lockdown*, *partial\_lockdown*, and *full\_lockdown*. The vector of variables,  $\mathbf{s}$ , is the time-related fixed effects, including year, month, weekdays, and seasons. Finally,  $a_i$  is the location fixed effects that capture the unobservable, location-related factors that have an impact on air quality.

## 5. FINDINGS

### 5.1 Main Results

Table 4 shows the estimation results of the effect of lockdown on *PM2.5*. The main parameter of interest, denoted by *lockdown*, shows a negative and significant impact on *PM2.5* concentration in the simple model. With one more day in lockdown, the *PM2.5* concentration decreased by 18.859  $\mu\text{g}/\text{m}^3$ . It can be easily seen that *partial\_lockdown* had a bigger impact than *full\_lockdown*. Specifically, *partial\_lockdown* reduced *PM2.5* by 21.091  $\mu\text{g}/\text{m}^3$  while *full\_lockdown* lowered it by 17.961  $\mu\text{g}/\text{m}^3$ . In the full model with all control variables, all the lockdown variables have negative impacts on *PM2.5* concentration. The marginal effect of *partial\_lockdown* is statistically significant after we include the linear time trend in the model. The estimation results are presented in Table 4.

Table 5 shows the estimation results of the effect of lockdown on *PM10*. During an additional day of lockdown, the *PM10* concentration fell by 11.107  $\mu\text{g}/\text{m}^3$ . The effects of both partial and full lockdown on *PM10* concentration were comparable (11.030  $\mu\text{g}/\text{m}^3$  and 11.144  $\mu\text{g}/\text{m}^3$ , respectively). Like *PM10*, *PM2.5* concentrations were impacted negatively but insignificantly by lockdown in the full model with all control variables. With one more day in lockdown, *PM10* concentration decreased by 4.545  $\mu\text{g}/\text{m}^3$ . Table 5 displays the estimation results.

**Table 4: Estimation Results of the Effect of Lockdown on PM2.5**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	-18.859*** (4.002)		-3.785 (3.859)		-6.634 (4.030)	
<i>partial_lockdown</i>		-21.091*** (6.362)		-7.77 (5.916)		-10.850* (6.018)
<i>full_lockdown</i>		-17.961*** (3.718)		-2.306 (3.621)		-4.956 (3.700)
<i>Y2021</i>	4.952 (3.075)	4.971 (3.059)	0.566 (2.942)	0.613 (2.923)	8.968 (9.103)	8.893 (9.108)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	10,013	10,013	10,013	10,013	10,013	10,013
R-sq	0.022	0.022	0.263	0.263	0.279	0.278

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 5: Estimation Results of the Effect of Lockdown on PM10**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	-11.107*** (3.292)		-3.924 (2.969)		-4.545 (3.048)	
<i>partial_lockdown</i>		-11.030** (4.910)		-5.115 (4.804)		-5.681 (4.772)
<i>full_lockdown</i>		-11.144*** (2.935)		-3.396 (2.476)		-4.01 (2.482)
<i>Y2021</i>	2.76 (2.286)	2.76 (2.279)	0.28 (2.237)	0.296 (2.225)	7.811 (5.889)	7.793 (5.895)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	8,817	8,817	8,817	8,817	8,817	8,817
R-sq	0.015	0.015	0.191	0.191	0.205	0.205

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

The estimation results of the effect of lockdown on O<sub>3</sub> are presented in Table 6. According to the results, lockdown did not impose a negative effect on O<sub>3</sub> concentration in all models.

**Table 6: Estimation Results of the Effect of Lockdown on O<sub>3</sub>**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	3.067 (2.414)		2.455 (2.109)		3.552* (1.881)	
<i>partial_lockdown</i>		3.026 (3.997)		0.44 (4.675)		3.004 (3.587)
<i>full_lockdown</i>		3.084 (2.253)		3.321** (1.554)		3.820* (2.065)
<i>Y2021</i>	-3.305 (2.382)	-3.305 (2.392)	-3.509 (2.667)	-3.49 (2.675)	5.617 (5.416)	5.595 (5.360)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	6,823	6,823	6,823	6,823	6,823	6,823
R-sq	0.012	0.012	0.042	0.042	0.067	0.067

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

Table 7 presents the estimation results of the effect of lockdown on NO<sub>2</sub>. Lockdown has a negative and significant impact on NO<sub>2</sub> concentration in the simple model. Specifically, NO<sub>2</sub> levels fell by 2.712 ppb after an additional day of lockdown. Full lockdown had a greater and more significant effect on NO<sub>2</sub> levels than partial lockdown with control variables (excluding the linear time trend). Under the influence of all control factors, one extra day of lockdown reduced NO<sub>2</sub> by 0.986 to 0.658 ppb.

**Table 7: Estimation Results of the Effect of Lockdown on NO<sub>2</sub>**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	-2.712*** (0.766)		-0.986* (0.534)		-0.658 (0.491)	
<i>partial_lockdown</i>		-2.231*** (0.678)		-0.318 (0.638)		-0.057 (0.644)
<i>full_lockdown</i>		-2.917*** (0.890)		-1.259** (0.585)		-0.926 (0.574)
<i>Y2021</i>	1.415 (0.891)	1.408 (0.887)	1.155 (1.031)	1.145 (1.029)	1.586 (2.850)	1.6 (2.855)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	9,106	9,106	9,106	9,106	9,106	9,106
R-sq	0.027	0.027	0.193	0.193	0.204	0.204

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

Table 8 reports the regression results of the effect of lockdown on SO<sub>2</sub>. There was no significant effect of lockdown on SO<sub>2</sub> concentration in any of the models.



**Table 8: Estimation Results of the Effect of Lockdown on SO<sub>2</sub>**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	0.312 (2.076)		2.033 (1.293)		3.919 (2.987)	
<i>partial_lockdown</i>		-0.47 (2.249)		1.975 (1.606)		4.587 (3.393)
<i>full_lockdown</i>		0.707 (2.025)		2.06 (1.446)		3.574 (2.812)
<i>Y2021</i>	8.929* (4.514)	8.943* (4.518)	11.678* (6.436)	11.679* (6.446)	23.601 (14.795)	23.628 (14.808)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	8,589	8,589	8,589	8,589	8,589	8,589
R-sq	0.019	0.019	0.065	0.065	0.103	0.103

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

Table 9 shows the effect of lockdown on CO. The results from our model specifications suggest that CO concentration was found to be negatively and significantly impacted by the lockdown in all models. An additional day of lockdown caused the CO level to drop by 1.527 ppm under the influence of all control factors. The impact of full lockdown was greater with a decline of 1.515 ppm for an extra day in full lockdown.

**Table 9: Estimation Results of the Effect of Lockdown on CO**

	(1)	(2)	(3)	(4)	(5)	(6)
<i>lockdown</i>	-1.527*** (0.506)		-1.126** (0.399)		-1.262*** (0.374)	
<i>partial_lockdown</i>		-0.796 (0.459)		-0.387 (0.530)		-0.708 (0.693)
<i>full_lockdown</i>		-1.861*** (0.557)		-1.448*** (0.439)		-1.515*** (0.385)
<i>Y2021</i>	0.687 (0.463)	0.679 (0.465)	0.667 (0.551)	0.656 (0.554)	0.029 (0.684)	0.033 (0.683)
Location FE	Y	Y	Y	Y	Y	Y
Month FE	N	N	Y	Y	N	N
Season FE	N	N	Y	Y	Y	Y
Weekend FE	N	N	Y	Y	Y	Y
Linear time trend	N	N	N	N	Y	Y
N	8,791	8,791	8,791	8,791	8,791	8,791
R-sq	0.015	0.016	0.045	0.046	0.056	0.057

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

## 5.2 Heterogeneous Effects of Lockdowns

In general, lockdown imposed negative effects on four air pollutants, namely PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, and CO, while having no significant effects on O<sub>3</sub> and SO<sub>2</sub>. However, due to the significant regional differences in the economy and environment, which may increase or decrease the effects of lockdown, these effects could be heterogeneous. A subsample analysis was carried out to examine the heterogeneous effects of lockdown on northern and southern regions, and areas with and without airports.

Tables 10–15 present the results from the heterogeneous effects of lockdown on six atmospheric pollutants in the north and south.

**Table 10: Effects of Lockdown on PM<sub>2.5</sub> in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-1.183 (4.303)		-5.158 (4.682)		-12.067** (3.634)		-10.492* (3.650)	
<i>partial_lockdown</i>		-7.998 (7.707)		-12.459 (7.774)		-7.72 (3.297)		-6.188* (2.235)
<i>full_lockdown</i>		1.426 (3.552)		-2.292 (3.762)		-13.661** (3.995)		-13.000* (4.745)
<i>Y2021</i>	-0.399 (3.503)	-0.342 (3.469)	6.539 (10.750)	6.31 (10.771)	3.357 (2.497)	3.231 (2.506)	8.013 (11.944)	8.034 (11.943)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

**Table 11: Effects of Lockdown on PM<sub>10</sub> in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-3.164 (3.344)		-4.6 (3.406)		-8.072*** (0.355)		-2.393 (2.507)	
<i>partial_lockdown</i>		-4.825 (5.462)		-6.454 (5.477)		-5.387 (2.516)		-0.829 (2.406)
<i>full_lockdown</i>		-2.415 (2.772)		-3.765 (2.767)		-8.894*** (0.819)		-3.097 (3.238)
<i>Y2021</i>	-0.733 (2.389)	-0.713 (2.374)	1.826 (5.510)	1.783 (5.524)	4.755 (3.794)	4.702 (3.755)	11.467 (8.804)	11.47 (8.810)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

**Table 12: Effects of Lockdown on O<sub>3</sub> in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	4.385 (2.540)		5.254** (2.316)		-3.043 (1.409)		0.82 (0.545)	
<i>partial_lockdown</i>		2.466 (5.810)		5.265 (4.104)		-6.790* (2.196)		-2.264 (0.846)
<i>full_lockdown</i>		5.318*** (1.697)		5.248* (2.736)		-2.172 (1.483)		1.637** (0.231)
<i>Y2021</i>	-5.185 (2.931)	-5.177 (2.926)	1.915 (4.141)	1.916 (4.076)	3.145 (3.879)	3.274 (3.942)	19.756* (6.324)	19.737* (6.367)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 13: Effects of Lockdown on NO<sub>2</sub> in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-0.936 (0.635)		-0.634 (0.586)		-0.457 (1.029)		0.405 (0.496)	
<i>partial_lockdown</i>		-0.149 (0.708)		0.159 (0.746)		-0.766 (1.675)		-0.326 (0.905)
<i>full_lockdown</i>		-1.278* (0.693)		-0.991 (0.676)		-0.384 (0.914)		0.604 (0.294)
<i>Y2021</i>	0.886 (1.140)	0.876 (1.140)	3.384 (2.754)	3.405 (2.761)	2.795 (2.607)	2.806 (2.581)	-1.696 (3.579)	-1.7 (3.587)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 14: Effects of Lockdown on SO<sub>2</sub> in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	1.423 (1.459)		4.14 (3.686)		5.311 (1.861)		4.259*** (0.074)	
<i>partial_lockdown</i>		1.012 (1.639)		4.963 (4.121)		7.764 (3.497)		5.040* (1.361)
<i>full_lockdown</i>		1.624 (1.783)		3.712 (3.500)		4.64 (1.716)		4.002*** (0.375)
<i>Y2021</i>	11.845 (7.868)	11.854 (7.880)	26.769 (18.006)	26.813 (18.022)	11.881 (4.984)	11.799 (4.907)	8.270*** (0.276)	8.278*** (0.277)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 15: Effects of Lockdown on CO in the North and South**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-1.238** (0.496)		-1.599*** (0.510)		-1.18 (0.586)		-0.673 (0.478)	
<i>partial_lockdown</i>		-0.394 (0.707)		-1.03 (1.079)		-0.629 (0.599)		-0.228 (0.470)
<i>full_lockdown</i>		-1.639*** (0.536)		-1.858*** (0.433)		-1.305 (0.595)		-0.796 (0.508)
<i>Y2021</i>	1.102 (0.728)	1.095 (0.729)	1.118 (0.954)	1.129 (0.947)	-0.468 (0.295)	-0.482 (0.292)	-1.128 (0.994)	-1.126 (0.993)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

PM<sub>2.5</sub> and PM<sub>10</sub> concentration in the southern regions was negatively and significantly affected by the lockdown while there were no significant changes in the northern regions. An additional day of lockdown in the south reduced PM<sub>2.5</sub> by 10.492  $\mu\text{g}/\text{m}^3$  and PM<sub>10</sub> by 2.393  $\mu\text{g}/\text{m}^3$ . On the other hand, lockdowns did not exhibit a negative impact on O<sub>3</sub> concentration in the northern regions, while they significantly and negatively impacted this in the southern regions. The effects of lockdowns on NO<sub>2</sub> are negative in general, although most of the estimates are statistically insignificant. Though there are no negative lockdown effects on NO<sub>2</sub>, it is observed that a full lockdown had a negative and significant impact on the CO content in the northern regions. NO<sub>2</sub> levels were reduced by 1.347 ppb and CO levels by 1.599 ppm with one extra day of full lockdown in the northern regions.

The next analysis concerns the heterogeneous effects of the lockdowns depending on the existence of an airport in the local area, since airports are one of the main sources of air pollution. Tables 16 to 21 present the results obtained from the subsample analysis based on the presence of an airport.

**Table 16: Effect of Lockdown on PM<sub>2.5</sub> in Areas With and Without an Airport**

	North				South			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-2.352 (7.662)		-9.12 (7.692)		-8.571** (3.178)		-9.539*** (2.667)	
<i>partial_lockdown</i>		-9.54 (8.333)		-17.176* (8.428)		-5.000** (2.222)		-3.778 (2.448)
<i>full_lockdown</i>		5.574 (7.376)		-0.586 (7.521)		-9.064** (3.571)		-10.809*** (3.219)
<i>Y2021</i>	0.974 (6.073)	1.291 (6.102)	10.327 (15.328)	10.277 (15.317)	0.565 (3.126)	0.533 (3.135)	10.796 (9.336)	10.825 (9.324)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 17: Effect of Lockdown on PM10 in Areas With and Without an Airport**

	Area Without Airport		Area With Airport	
	(1)	(2)	(3)	(4)
	PM10	PM10	PM10	PM10
<i>partial_lockdown</i>	0.459 (5.738)		-6.412*** (0.864)	
<i>full_lockdown</i>	5.515 (5.348)		-10.378*** (1.433)	
<i>Y2021</i>	0.44 (3.437)	0.412 (3.434)	1.805 (2.110)	1.809 (2.105)
<i>lockdown</i>		2.827 (5.464)		-10.081*** (1.331)
<i>Constant</i>	56.566*** (3.593)	56.574*** (3.590)	32.628*** (1.130)	32.620*** (1.141)
Season FE	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes
N	4,897	4,897	3,920	3,920
R-sq	0.154	0.153	0.178	0.178

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 18: Effect of Lockdown on O<sub>3</sub> in Areas With and Without an Airport**

	Without Airport				With Airport			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	0.331 (5.466)		3.175 (2.660)		1.78 (2.459)		4.309* (1.959)	
<i>partial_lockdown</i>		-0.334 (6.825)		2.907 (2.880)		-7.188*** (1.597)		-4.444* (1.922)
<i>full_lockdown</i>		1.333 (4.560)		3.62 (5.103)		2.619 (2.289)		5.286** (1.894)
<i>Y2021</i>	-10.685*** (2.853)	-10.662*** (2.851)	-9.088*** (1.642)	-9.090*** (1.645)	1.262 (2.103)	1.346 (2.128)	14.598** (5.055)	14.542** (5.069)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 19: Effect of Lockdown on NO<sub>2</sub> in Areas With and Without an Airport**

	Without Airport				With Airport			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	0.346 (0.505)		-0.369 (0.686)		-2.051** (0.847)		-0.707 (0.735)	
<i>partial_lockdown</i>		0.784 (0.644)		-0.122 (0.718)		-1.476 (1.933)		-0.451 (1.712)
<i>full_lockdown</i>		-0.122 (0.518)		-0.623 (0.740)		-2.093** (0.820)		-0.73 (0.741)
<i>Y2021</i>	-0.958 (1.286)	-0.976 (1.279)	-3.357* (1.660)	-3.356* (1.661)	3.001** (0.927)	2.997** (0.922)	4.665 (3.656)	4.666 (3.655)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 20: Effect of Lockdown on SO<sub>2</sub> in Areas With and Without an Airport**

	Without Airport				With Airport			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-0.914 (1.687)		5.013 (6.120)		3.046* (1.571)		3.739 (2.372)	
<i>partial_lockdown</i>		-1.641 (2.418)		5.91 (6.629)		11.544** (4.108)		10.990** (4.006)
<i>full_lockdown</i>		-0.053 (1.730)		4.064 (5.595)		2.271 (1.245)		2.89 (2.259)
<i>Y2021</i>	22.644 (14.882)	22.676 (14.924)	8.079 (6.754)	8.077 (6.756)	4.442 (2.671)	4.369 (2.616)	7.853*** (1.330)	7.879*** (1.329)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

**Table 21: Effect of Lockdown on CO in Areas With and Without an Airport**

	Without Airport				With Airport			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
<i>lockdown</i>	-0.263 (0.668)		-0.348 (0.593)		-1.874** (0.699)		-1.473 (1.158)	
<i>partial_lockdown</i>		0.01 (0.550)		0.009 (0.562)		-1.207* (0.620)		-0.801 (1.016)
<i>full_lockdown</i>		-0.585 (0.892)		-0.752 (0.794)		-1.929** (0.722)		-1.541 (1.180)
<i>Y2021</i>	1.265 (0.800)	1.252 (0.796)	2.928** (1.123)	2.929** (1.123)	0.373 (0.732)	0.369 (0.734)	-0.933 (0.519)	-0.932 (0.519)
Location FE	Y	Y	Y	Y	Y	Y	Y	Y
Month FE	Y	Y	N	N	Y	Y	N	N
Season FE	Y	Y	Y	Y	Y	Y	Y	Y
Weekend FE	Y	Y	Y	Y	Y	Y	Y	Y
Linear time trend	N	N	Y	Y	N	N	Y	Y

Robust standard errors clustered by location are in parentheses. \* p < 0.10, \*\* p < 0.05, \*\*\* p < 0.01.

Our empirical analysis finds that lockdown had negative and significant effects on PM<sub>2.5</sub> and PM<sub>10</sub> in areas with airports but had no significant negative impact on the three remaining air pollutants. One extra day of lockdown lowered the concentration of PM<sub>2.5</sub> and PM<sub>10</sub> by 9.539  $\mu\text{g}/\text{m}^3$  and 6.9  $\mu\text{g}/\text{m}^3$ , respectively. Both partial and full lockdown significantly reduced PM<sub>2.5</sub>, PM<sub>10</sub>, and CO levels in places with airports.

## 6. DISCUSSION AND CONCLUSIONS

To prevent the spread of COVID-19 across the country, Viet Nam implemented containment measures with various restriction policies. Although lockdown caused an economic contraction, it unexpectedly improved the environment, especially air pollution. This research examined how the COVID-19 lockdown affected Viet Nam's air quality in the years 2020 and 2021. The panel data sets of air quality before and after the COVID-19 lockdown as well as the data set of lockdown times at two levels in 11 cities and provinces were combined for this study. Overall, the investigation offered solid proof of the COVID-19 lockdown's beneficial effects on air quality.

Our findings revealed a negative relationship between lockdown and three air pollutants, namely PM<sub>2.5</sub>, PM<sub>10</sub>, and CO. Since vehicular emissions are the main source of fine particulate matter and the concentration is primarily localized near major roadways, they also showed that the concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> decreased to a greater extent, which is consistent with Chauhan and Singh's (2020) findings in major cities throughout the world. However, lockdown policies in Viet Nam inhibited both industrial production and people mobility, which led to a more significant decrease in fine particulate matter.

These results are consistent in the analysis for heterogeneous effects. In southern regions, there is a negative correlation between COVID-19 lockdown and air pollution levels for PM<sub>2.5</sub> and PM<sub>10</sub> (decreased by 10.492  $\mu\text{g}/\text{m}^3$  and 2.393  $\mu\text{g}/\text{m}^3$ , respectively). Furthermore, areas with an airport nearby experienced a decline in PM<sub>2.5</sub> and PM<sub>10</sub> by 9.539  $\mu\text{g}/\text{m}^3$  and 6.9  $\mu\text{g}/\text{m}^3$ , respectively, during lockdown periods.

During the COVID-19 pandemic, diminished traffic and industrial operations led to a decline in emissions, presenting a distinctive opportunity to evaluate the health advantages associated with improved air quality. Our findings carry significant implications for the formulation of future air pollution reduction policies, providing policymakers with valuable insights for informed decision-making. Additionally, the pandemic afforded an exceptional opportunity to conduct natural experiments, enhancing our comprehension of how the Vietnamese economy reacts to alterations in pollution emissions. Such insights can prove invaluable for guiding future endeavors in industrial restructuring.

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## APPENDIX

### A1. Viet Nam's Climatic Features

According to the Viet Nam assessment report on climate change (2009), Viet Nam has the monsoon tropical climate of a peninsula in the southeast of the European-Asian continent, which spans across 15 latitudes. The territory of Viet Nam consists of the mainland with a size of 332,000 square kilometers, and the waters surrounding it, which are several times bigger, along with thousands of islands of different sizes in the East Sea. The population of Viet Nam was predicted to be 96.4 million in 2019, with around a third of those people residing in the urban areas of its two megacities, Ha Noi and Ho Chi Minh City (Climate Risk Country Profile: Viet Nam 2021).

Four seasons were classified in the northern parts of Viet Nam in the Viet Nam assessment report on climate change (2009): winter (November through March), summer (May through September), spring (April), and fall (October). The Climate Risk Country Profile: Viet Nam (2021) stated that in the south, only two seasons were present: a dry and a rainy season. The rainy season extends from May to October while the dry season lasts from November to April. Average temperatures in the northern parts range from 22°C to 27.5°C in the summer and from 15°C to 20°C in the winter. On the other hand, the southern regions have a higher range of 26°C to 29°C throughout the whole year.

### A2. Data Sources of Lockdown Periods

The following are the websites for collecting the data about the starting and ending times of lockdown periods in each region:

No.	Name	Link
1	00.-Bao-cau-phan-tich-KT-2021- _14-01-2022_-ok	<a href="https://www.gso.gov.vn/wp-content/uploads/2022/01/00.-Bao-cau-phan-tich-KT-2021-_14-01-2022_-ok.pdf">https://www.gso.gov.vn/wp-content/uploads/2022/01/00.-Bao-cau-phan-tich-KT-2021-_14-01-2022_-ok.pdf</a>
2	Nien-giam-Tom-Tat-2020Ban- quyen	<a href="https://www.gso.gov.vn/wp-content/uploads/2021/07/Nien-giam-Tom-Tat-2020Ban-quyen.pdf">https://www.gso.gov.vn/wp-content/uploads/2021/07/Nien-giam-Tom-Tat-2020Ban-quyen.pdf</a>
3	ijerph-18-00559	<a href="https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7828055/pdf/ijerph-18-00559.pdf">https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7828055/pdf/ijerph-18-00559.pdf</a>
4	Info chi thi 15 16 chinh phu	<a href="https://hcdc.vn/hoidap/index/chitiet/c885f7ce005a3a83daf6c7281501c8c7">https://hcdc.vn/hoidap/index/chitiet/c885f7ce005a3a83daf6c7281501c8c7</a>
5	Bac Ninh CT 16-18/5/2021	<a href="https://bacninh.gov.vn/news/-/details/20182/thanh-pho-bac-ninh-gian-cach-xa-hoi-theo-chi-thi-16-cua-chinh-phu-tu-06h00-ngay-18-5#:~:text=(BNP)%20%2D%20Th%E1%BB%B1c%20hi%E1%BB%87n%20ch%E1%BB%89,khi%20c%C3%B3%20th%C3%B4ng%20b%C3%A1o%20m%E1%BB%9Bi">https://bacninh.gov.vn/news/-/details/20182/thanh-pho-bac-ninh-gian-cach-xa-hoi-theo-chi-thi-16-cua-chinh-phu-tu-06h00-ngay-18-5#:~:text=(BNP)%20%2D%20Th%E1%BB%B1c%20hi%E1%BB%87n%20ch%E1%BB%89,khi%20c%C3%B3%20th%C3%B4ng%20b%C3%A1o%20m%E1%BB%9Bi</a>
6	4. BC kết quả 02 năm triển khai công tác phòng, chống dịch COVID-19	<a href="https://moh.gov.vn/documents/174521/1197117/4.+BC+k%E1%BA%BFt+qu%E1%BA%A3+02+n%C4%83m+tri%E1%BB%83n+khai+c%C3%B4ng+t%C3%A1c+ph%C3%B2ng%2C+ch%E1%BB%91ng+d%E1%BB%8Bch+COVID-19.pdf/e3254b2a-c902-4696-b0c7-cc4427b8f992">https://moh.gov.vn/documents/174521/1197117/4.+BC+k%E1%BA%BFt+qu%E1%BA%A3+02+n%C4%83m+tri%E1%BB%83n+khai+c%C3%B4ng+t%C3%A1c+ph%C3%B2ng%2C+ch%E1%BB%91ng+d%E1%BB%8Bch+COVID-19.pdf/e3254b2a-c902-4696-b0c7-cc4427b8f992</a>
7	28 tỉnh, thành phố tiếp tục thực hiện Chỉ thị 16/CT-TTg	<a href="https://moh.gov.vn/hoat-dong-cua-lanh-dao-bo/-/asset_publisher/TW6LTp1ZtwaN/content/28-tinh-thanh-pho-tiep-tuc-thuc-hien-chi-thi-16-ct-ttg">https://moh.gov.vn/hoat-dong-cua-lanh-dao-bo/-/asset_publisher/TW6LTp1ZtwaN/content/28-tinh-thanh-pho-tiep-tuc-thuc-hien-chi-thi-16-ct-ttg</a>
8	từ 1/4/2020 cả nước đã thực hiện giãn cách xã hội theo Chỉ thị 16 CT-TTg của Thủ tướng Chính phủ	<a href="https://ncov.vnnet.vn/tin-tuc/trong-ca-ba-giai-doan-viet-nam-deu-kiem-soat-tot-dich-benh-covid-19/549a11b0-43c4-4b17-931a-bc52a4ab9a8c">https://ncov.vnnet.vn/tin-tuc/trong-ca-ba-giai-doan-viet-nam-deu-kiem-soat-tot-dich-benh-covid-19/549a11b0-43c4-4b17-931a-bc52a4ab9a8c</a>
9	Điều này đồng nghĩa với việc từ hôm nay (23.4) không còn tỉnh, TP trực thuộc T.Ư' nào phải thực hiện cách ly xã hội.	<a href="https://thanhnien.vn/dung-cach-ly-xa-hoi-song-chung-voi-dich-post949191.html">https://thanhnien.vn/dung-cach-ly-xa-hoi-song-chung-voi-dich-post949191.html</a>

*continued on next page*

**Appendix table continued**

No.	Name	Link
10	Từ 0 giờ ngày 28-7-2020: Thực hiện cách ly xã hội theo Chỉ thị số 16/CT-TTg tại 6 quận trong vòng 15 ngày	<a href="https://www.danang.gov.vn/chi-tiet?id=40207&amp;_c=100000150,3,9">https://www.danang.gov.vn/chi-tiet?id=40207&amp;_c=100000150,3,9</a>
11	Tiếp tục thực hiện cách ly toàn xã hội theo Chỉ thị số 16/CT-TTg từ 0 giờ ngày 12-8/2020	<a href="https://www.danang.gov.vn/chinh-quyen/chi-tiet?id=40505&amp;_c=9">https://www.danang.gov.vn/chinh-quyen/chi-tiet?id=40505&amp;_c=9</a>
12	Bắt đầu từ 18 giờ 00 phút ngày 31/7/2021, Đà Nẵng thực hiện giãn cách xã hội toàn TP	<a href="https://dangcongsan.vn/y-te/da-nang-tu-18-gio-00-phut-ngay-31-7-thuc-hien-gian-cach-xa-hoi-toan-thanh-pho-586880.html">https://dangcongsan.vn/y-te/da-nang-tu-18-gio-00-phut-ngay-31-7-thuc-hien-gian-cach-xa-hoi-toan-thanh-pho-586880.html</a>
13	ai ở đâu thì ở đó" từ 8 giờ ngày 16/8/2021 đến 8 giờ ngày 5/9/2021	<a href="https://ncov.vnnet.vn/tin-tuc/nhin-lai-cuoc-chien-chong-dich-covid-19-tai-da-nang-neu-cao-vai-tro-cua-nguoi-dan/a62430ef-cb6a-4ef6-8b24-45c90b8ae1e5">https://ncov.vnnet.vn/tin-tuc/nhin-lai-cuoc-chien-chong-dich-covid-19-tai-da-nang-neu-cao-vai-tro-cua-nguoi-dan/a62430ef-cb6a-4ef6-8b24-45c90b8ae1e5</a>
14	Đà Nẵng: Sẽ ban hành Chỉ thị nói lỏng giãn cách, thực hiện từ 0 giờ ngày 30-9	<a href="https://nld.com.vn/thoi-su/da-nang-se-ban-hanh-chi-thi-noi-long-gian-cach-thuc-hien-tu-0-gio-ngay-30-9-20210928190503996.htm">https://nld.com.vn/thoi-su/da-nang-se-ban-hanh-chi-thi-noi-long-gian-cach-thuc-hien-tu-0-gio-ngay-30-9-20210928190503996.htm</a>
15	Đà Nẵng dự kiến nói lỏng giãn cách từ ngày 1/10	<a href="https://vnexpress.net/da-nang-du-kien-noi-long-gian-cach-tu-ngay-1-10-4361375.html">https://vnexpress.net/da-nang-du-kien-noi-long-gian-cach-tu-ngay-1-10-4361375.html</a>
16	Đà Nẵng: Nói lỏng nhiều hoạt động từ ngày 16/9	<a href="https://moit.gov.vn/tin-tuc/dia-phuong/da-nang-noi-long-nhieu-hoat-dong-tu-ngay-16-9.html#:~:text=T%E1%BB%91%2014%2F9%2C%20Ch%E1%BB%A7%20t%E1%BB%8Bch,t%E1%BB%AB%208h%20ng%C3%A0y%2016%2F9">https://moit.gov.vn/tin-tuc/dia-phuong/da-nang-noi-long-nhieu-hoat-dong-tu-ngay-16-9.html#:~:text=T%E1%BB%91%2014%2F9%2C%20Ch%E1%BB%A7%20t%E1%BB%8Bch,t%E1%BB%AB%208h%20ng%C3%A0y%2016%2F9</a>
17	từ 6h sáng nay (18/5), áp dụng biện pháp giãn cách xã hội theo Chỉ thị 16/CT-TTg	<a href="https://covid19.gov.vn/hoa-toc-tp-bac-ninh-gian-cach-xa-hoi-tu-6-gio-sang-nay-tam-dinh-chi-cac-co-so-san-xuat-kinh-doanh-dich-vu-1717326837.htm">https://covid19.gov.vn/hoa-toc-tp-bac-ninh-gian-cach-xa-hoi-tu-6-gio-sang-nay-tam-dinh-chi-cac-co-so-san-xuat-kinh-doanh-dich-vu-1717326837.htm</a>
18	CT 15 and 16	<a href="https://baodanang.vn/english/infographics/202009/differences-between-national-governments-directives-no-15-16-and-19-on-covid-19-prevention-and-control-3703977/">https://baodanang.vn/english/infographics/202009/differences-between-national-governments-directives-no-15-16-and-19-on-covid-19-prevention-and-control-3703977/</a>
19	Bắc Ninh và Bắc Giang dự kiến quay lại trạng thái "bình thường mới" từ 10/7	<a href="https://covid19.gov.vn/bac-ninh-va-bac-giang-du-kien-quay-lai-trang-thai-binh-thuong-moi-tu-10-7-1717387631.htm">https://covid19.gov.vn/bac-ninh-va-bac-giang-du-kien-quay-lai-trang-thai-binh-thuong-moi-tu-10-7-1717387631.htm</a>
20	Từ 00h00, ngày 11/6/2021, Bắc Ninh điều chỉnh áp dụng biện pháp cách ly xã hội huyện Yên Phong từ Chỉ thị 16 sang Chỉ thị 15	<a href="https://moh.gov.vn/hoat-dong-cua-lanh-dao-bo/-/asset_publisher/TW6LTp1ZtwaN/content/bac-ninh-co-ban-a-khong-che-uoc-dich-benh-giam-gian-cach-xa-hoi-tai-3-huyen?inheritRedirect=false">https://moh.gov.vn/hoat-dong-cua-lanh-dao-bo/-/asset_publisher/TW6LTp1ZtwaN/content/bac-ninh-co-ban-a-khong-che-uoc-dich-benh-giam-gian-cach-xa-hoi-tai-3-huyen?inheritRedirect=false</a>
21	2021_10_14_9_10_5_t10-14-PL_vung theo mau.pdf	<a href="http://kiemsoatbenhtatphutho.gov.vn/portals/0/AttachFiles/2021/10/14/2021_10_14_9_10_5_t10-14-PL%20vung%20theo%20mau.pdf">http://kiemsoatbenhtatphutho.gov.vn/portals/0/AttachFiles/2021/10/14/2021_10_14_9_10_5_t10-14-PL%20vung%20theo%20mau.pdf</a>
22	Pleiku từ 00h ngày 28/8 theo Chỉ thị số 16/CT-TTg ngày 31/3/2020 của Thủ tướng Chính phủ	<a href="https://baochinhphu.vn/gian-cach-xa-hoi-theo-chi-thi-16-toan-tp-pleiku-102299332.htm">https://baochinhphu.vn/gian-cach-xa-hoi-theo-chi-thi-16-toan-tp-pleiku-102299332.htm</a>
23	TP Pleiku dừng thực hiện giãn cách theo Chỉ thị 16 từ ngày 09/9	<a href="https://baotainguyenmoitruong.vn/tp-pleiku-dung-thuc-hien-gian-cach-theo-chi-thi-16-tu-ngay-09-9-330431.html">https://baotainguyenmoitruong.vn/tp-pleiku-dung-thuc-hien-gian-cach-theo-chi-thi-16-tu-ngay-09-9-330431.html</a>
24	ngày 26-7, thành phố Pleiku (tỉnh Gia Lai) bắt đầu thực hiện giãn cách xã hội theo Chỉ thị số 15/CT-TTg	<a href="https://www.qdnd.vn/xa-hoi/tin-tuc/thanh-pho-pleiku-thuc-hien-gian-cach-xa-hoi-theo-chi-thi-15-cua-thu-tuong-chinh-phu-666508">https://www.qdnd.vn/xa-hoi/tin-tuc/thanh-pho-pleiku-thuc-hien-gian-cach-xa-hoi-theo-chi-thi-15-cua-thu-tuong-chinh-phu-666508</a>
25	Từ 13 giờ ngày 4-8, cho phép TP. Pleiku ngừng triển khai các quy định chung theo Chỉ thị 15	<a href="https://baogialai.com.vn/channel/8301/202108/gia-lai-tu-13-gio-ngay-4-8-cho-phep-tp-pleiku-ngung-trien-khai-cac-quy-dinh-chung-theo-chi-thi-15-5746623/">https://baogialai.com.vn/channel/8301/202108/gia-lai-tu-13-gio-ngay-4-8-cho-phep-tp-pleiku-ngung-trien-khai-cac-quy-dinh-chung-theo-chi-thi-15-5746623/</a>
26	Differences between Directives 15, 16, and 19 on COVID-19 prevention and control	<a href="https://en.vietnamplus.vn/differences-between-directives-15-16-19-on-covid19-prevention-control/209386.vnp">https://en.vietnamplus.vn/differences-between-directives-15-16-19-on-covid19-prevention-control/209386.vnp</a>