



# Impact of Covid-19 partial lockdown on PM<sub>2.5</sub>, SO<sub>2</sub>, NO<sub>2</sub>, O<sub>3</sub>, and trace elements in PM<sub>2.5</sub> in Hanoi, Vietnam

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## Abstract

Covid-19 lockdowns have improved the ambient air quality across the world via reduced air pollutant levels. This article aims to investigate the effect of the partial lockdown on the main ambient air pollutants and their elemental concentrations bound to PM<sub>2.5</sub> in Hanoi. In addition to the PM<sub>2.5</sub> samples collected at three urban sites in Hanoi, the daily PM<sub>2.5</sub>, NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub> levels were collected from the automatic ambient air quality monitoring station at Nguyen Van Cu street to analyze the pollution level before (March 10th–March 31st) and during the partial lockdown (April 1st–April 22nd) with “current” data obtained in 2020 and “historical” data obtained in 2014, 2016, and 2017. The results showed that NO<sub>2</sub>, PM<sub>2.5</sub>, O<sub>3</sub>, and SO<sub>2</sub> concentrations obtained from the automatic ambient air quality monitoring station were reduced by 75.8, 55.9, 21.4, and 60.7%, respectively, compared with historical data. Besides, the concentration of PM<sub>2.5</sub> at sampling sites declined by 41.8% during the partial lockdown. Furthermore, there was a drastic negative relationship between the boundary layer height (BLH) and the daily mean PM<sub>2.5</sub> in Hanoi. The concentrations of Cd, Se, As, Sr, Ba, Cu, Mn, Pb, K, Zn, Ca, Al, and Mg during the partial lockdown were lower than those before the partial lockdown. The results of enrichment factor (EF) values and principal component analysis (PCA) concluded that trace elements in PM<sub>2.5</sub> before the partial lockdown were more affected by industrial activities than those during the partial lockdown.

**Keywords** Air pollution · Partial quarantine · Metals · SARS-CoV-2 · Hanoi

## Introduction

Coronavirus was first reported in the city of Wuhan, China, in December 2019 (Huang et al. 2020; Huijun et al. 2020) and was declared a pandemic by March 11, 2020 (WHO 2020). In Vietnam, the first two coronavirus cases were confirmed on January 23, 2020. Since then, the Vietnamese government has

taken a series of measures to prevent coronavirus outbreaks such as closing schools and universities, travel restrictions, quarantining residential areas, and restrictions on public gatherings. By December 12, 2020, there have been 1385 confirmed cases and 35 deaths in Vietnam (Ministry of Health of Vietnam 2020).

On April 1, 2020, a partial national lockdown was ordered by the Vietnamese government (Vietnam 2020), closing

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shopping malls, restaurants, fitness centers, kindergartens, elementary, middle, high schools, and universities. Travel restrictions were also implemented, and public transportation was stopped. Supermarkets and drugstores started working with a safety distance of 2 m during communication.

Recent studies have reported air quality improvements related to partial/full lockdowns and the consequent decrease of anthropogenic sources, including road traffic and industrial activities in Asia (Kerimray et al. 2020), China (Li et al. 2020; Wang et al. 2020a), and several European (Chauhan and Singh 2020) and American countries (Berman and Ebisu 2020; Nakada and Urban 2020). For example, Chauhan and Singh (2020) revealed a decline in PM<sub>2.5</sub> concentration due to lockdown in major cities (New York, Los Angeles, Zaragoza, Rome, Dubai, Delhi, Mumbai, Beijing, and Shanghai) around the world. Kanniah et al. (2020) used the Himawari-8 satellite to quantify the changes in aerosol and air pollutants in southern Asian countries and observed 27–30% reduction of NO<sub>2</sub> during the lockdown compared with the same period in 2018 and 2019. The authors also showed 26–31%, 23–32%, 63–64%, 9–20%, and 25–31% reduction of PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub>, SO<sub>2</sub>, and CO, respectively, during the lockdown in an urban area in Malaysia compared with the same period in 2018 and 2019. Otmani et al. (2020) also analyzed the data in Salé city (North-Western Morocco) using field measurement (PM<sub>10</sub>) and in situ measurements (SO<sub>2</sub> and NO<sub>2</sub>) to assess the impact of Covid-19 lockdowns on air quality. The authors observed 75, 49, and 96% reduction of PM<sub>10</sub>, SO<sub>2</sub>, and NO<sub>2</sub>, respectively, during the lockdown compared with the day before the lockdown. Nakada and Urban (2020) analyzed data from air quality stations to assess air quality during the partial lockdown in São Paulo, Brazil. The authors observed approximately 77, 54, and 65% reduction of NO, NO<sub>2</sub>, and CO, respectively, during the partial lockdown compared with the 5-year monthly mean. However, these studies which have focused on assessing common ambient pollutants (PM<sub>10</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, and NO<sub>2</sub>) in the environment metals associated with PM<sub>2.5</sub> have not been reported. It is well known that toxic heavy metals bound to PM<sub>2.5</sub> cause harm to human bodies via inhalation, ingestion, and dermal contact. These metals originate from anthropogenic sources, including road traffic and industrial activities (Bi et al. 2020; Ledoux et al. 2017). Thus, this study aims to assess the variation of PM<sub>2.5</sub>, SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>2.5</sub>-bound elements in Hanoi city before and during the partial lockdown implemented due to the Covid-19 pandemic.

## Materials and methods

### Study area and sampling sites

Hanoi is a populous city with a total population of 7.4 million people (General Statistic Office of Vietnam 2019), about 623,668 automobiles and 6,013,582 motorbikes (TDSI

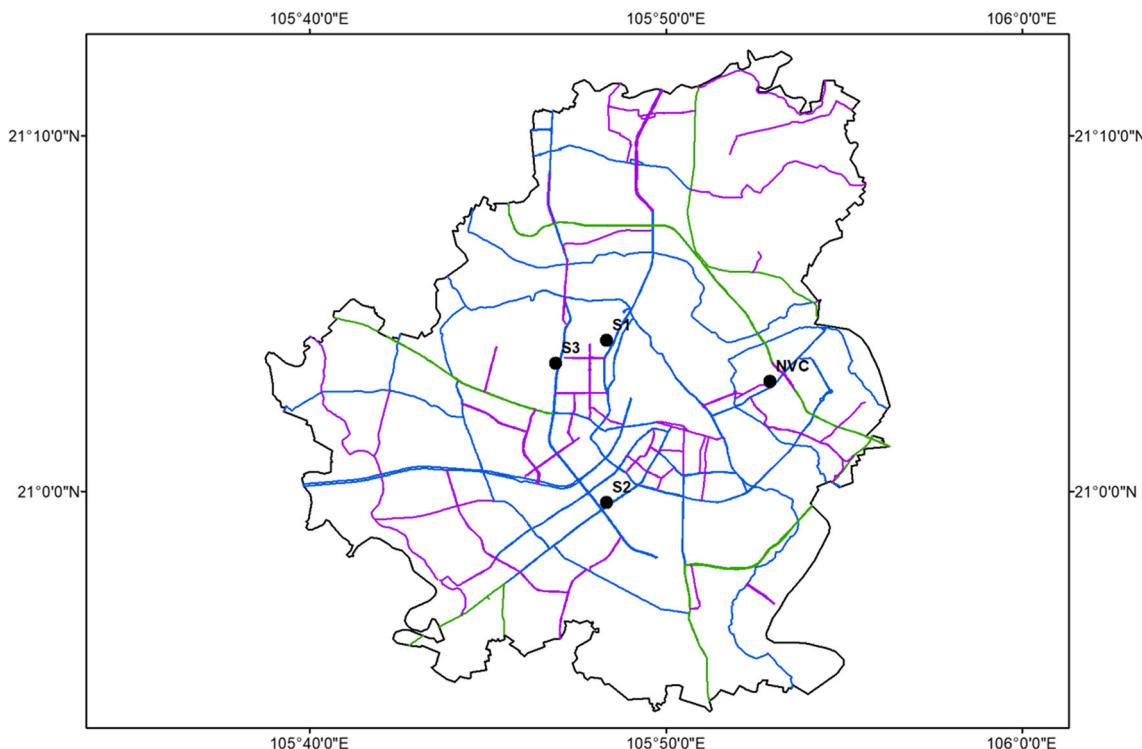
2017). It is the second largest city in Vietnam and covers an area of about 3328 km<sup>2</sup>. However, the city has faced serious air pollution (Cohen et al. 2013; Ly et al. 2018). The PM<sub>2.5</sub> sampling was conducted in inner urban Hanoi city at three sites, namely S1, S2, and S3 (Fig. 1). The coordinates of the S1, S2, and S3 sampling sites were 21°04'14.7" N, 105°48'189" E; 20°59'50" N, 105°49'22" E; and 21°04'14.7" N, 105°48'189" E, respectively. All the sampling sites were situated on the rooftop of houses. The height above the ground of sampling points was in the range of 16–20 m. Furthermore, the S1 and S2 sites were within close range of 2nd ring roads, namely, Vo Chi Cong and Truong Chinh, respectively, while the S3 site was 100 m away from the 3rd ring road named Pham Van Dong. Also, the distance from the North Thang Long industrial park to both the S1 and S3 sites was approximately 6 km, whereas the S2 site was about 8 km far away from the Sai Dong industrial park. The North Thang Long industrial park is located at the North of the S3 site and the Northwest of the S1 site. The Sai Dong industrial park is located at the Northeast of the S2 site.

### PM<sub>2.5</sub> sampling

The PM<sub>2.5</sub> sampling was conducted consecutively at three sites from February 17, 2020, to March 23, 2020 (5 weeks before the partial lockdown), and from April 1, 2020, to April 22, 2020 (3 weeks during the partial lockdown). PM<sub>2.5</sub> was collected using a high-volume air sampler (Shibata HV 500R, Japan) for 36 h at an average flow rate of 15 m<sup>3</sup>/h on quartz fiber filters (Advance, QR-100, size 110mm, Japan), which was baked at 550 °C for 6 h before use. A total of 17 PM<sub>2.5</sub> samples (8 before the partial lockdown and 9 during the partial lockdown) were collected at three sampling sites. The collected PM<sub>2.5</sub> samples were wrapped in aluminum foil, transported to the laboratory, and stored in a desiccator with silica gel particles until analysis. To determine PM<sub>2.5</sub> mass concentration, the filters were preconditioned before and after sampling (48 h in desiccators with a temperature of 25 ± 2 °C and relative humidity 50 ± 5%) and weighed using a microbalance (Adam AEA-160DG, sensitivity ± 0.01 mg). After weighing, the filter samples were stored under refrigeration at -30°C until chemical analysis.

### Air pollution and meteorological data

Besides the PM<sub>2.5</sub> mass concentrations obtained from field-work at three sampling sites in Hanoi, this study utilized further air pollution data including PM<sub>2.5</sub>, sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), and ozone (O<sub>3</sub>) concentrations. Daily pollutant concentrations from March to April 2020 at Nguyen Van Cu monitoring point were downloaded from the Northern Center for Environmental Monitoring (NCEM) (<http://cem.gov.vn/>) (Fig. 1). The mean concentration of PM<sub>2.5</sub>, NO<sub>2</sub>,



**Fig. 1** Location of sampling sites (S1, S2, S3) and the automatic ambient air monitoring station (NVC)

$O_3$ , and  $SO_2$  from the automatic ambient air quality monitoring station before the partial lockdown (March 10–March 31) and during the partial lockdown (April 1–April 22) was calculated to analyze the variation of pollutant concentrations.

Besides, we utilized the hourly meteorological data including precipitation, temperature, boundary layer height, dew point temperature, and surface solar radiation. These are fifth-generation atmospheric reanalysis products of the European Centre for Medium-Range Weather Forecasts (ECMWF). The relative humidity was computed using the dew-point temperature and temperature data based on the method described in (Alduchov and Eskridge 1996). The mean precipitation, temperature, and relative humidity before and during partial lockdown were computed from the corresponding hourly data to analyze the impact of meteorology on the pollution level.

The variations in the contributions of stationary and mobile sources were analyzed using mass concentration ratios of  $[NO_2]/[SO_2]$  (Lian et al. 2020).  $[NO_2]/[SO_2]$  from the stationary and mobile sources had the range from 0.2 to 0.8 and from 24 to 119, respectively (Fiedler et al. 2009). Therefore, we computed mass concentration ratios of  $[NO_2]/[SO_2]$  during and before the partial lockdown in 2020 and in past years to investigate the contribution of mobile sources and stationary sources.

To estimate the possible emission sources of elements in  $PM_{2.5}$ , the enrichment factor (EF) analysis and principal

component analysis (PCA) were conducted. The enrichment factor (EF) analysis was used to determine the natural or anthropogenic sources of elements in  $PM_{2.5}$  (Kim et al. 2019; Zhang et al. 2018). The EF of each element was calculated according to the equation below:

$$EF_x = \left(\frac{X}{R}\right)_{PM_{2.5}} / \left(\frac{X}{R}\right)_{crust}$$

where  $(X/R) PM_{2.5}$  and  $(X/R) crust$  are the concentration of the X element and reference element R in  $PM_{2.5}$  and crust, respectively. The concentration of elements in crust refers to their concentrations in Earth's Crust proposed by Taylor (Taylor 1964). Ti, Si, Al, and Fe were generally used as reference elements of crustal materials (Cesari et al. 2012; Kim et al. 2002; Song et al. 2016). In this study, the element Ti was selected as the crustal reference element. If  $EF_x$  value is close to 1, the element is mainly originated from natural sources. If  $EF_x$  value is larger than 10, the element is mainly derived from anthropogenic sources. The value of  $EF_x$  between 1 and 10 is indicated the elements emitted from both the natural and anthropogenic sources; however, the influences of anthropogenic sources on the element are small.

## Analytical methods

The quarter filter of the sample filter was treated for analysis of heavy metals by the digestion method according to EPA method IO-3.1(U.S.EPA 1999). The sample filter was first to cut into pieces, then digested in 10 ml of mixed acid solution

( $\text{HNO}_3$ :  $\text{HCl}$  in a ratio of 1:3), and kept on a hot plate at a high temperature until the transparent solution was boiled. After complete digestion, the digested sample was heated at a low temperature until nearly dry to remove excess acid. Then, the solution was diluted to a 25-ml volumetric flask with distilled water. Samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS, ELAN 9000, Perkin Elmer) for Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Ti, Zn, and V. In the analysis, a blank sample, a duplicated sample, and a spiked sample were measured for the quality control. The relative standard deviation of each element is within 10%, and the analytical errors were < 10%. The detection limit of all the trace elements was 0.01 ng/m<sup>3</sup> except for Cd (0.002 ng/m<sup>3</sup>).

## Statistical analysis

In this study, principal component analysis (PCA) was performed to determine potential sources of elements in PM<sub>2.5</sub> using SPSS 22.0 software (IBM, USA). The concentration of elements in PM<sub>2.5</sub> was normalized by dividing them by the total concentration of each sample. The rotation method was varimax, and eigenvalues higher than one were used for the principal components (PCs) extraction criterion.

## Results and discussion

### The concentration of PM<sub>2.5</sub>, SO<sub>2</sub>, O<sub>3</sub>, and NO<sub>2</sub> obtained from the automatic ambient air quality monitoring station

In this study, we considered ambient air quality data during the partial lockdown (April 1st–April 22nd) and prior to the

partial lockdown period (March 10th–March 31st). Air quality data in 2020 represented “current” data. Due to a lack of monitoring data in 2015, 2018, and 2019, air quality measurements in 2017, 2016, and 2014 were considered as the “historical” data. Table 1 presented the concentration of PM<sub>2.5</sub>, NO<sub>2</sub>, O<sub>3</sub>, and SO<sub>2</sub> and meteorological data in Hanoi before and during the partial lockdown. As reported in Table 1, most of the meteorological parameters before and during the partial lockdown witnessed small variations. The change of mean temperature, precipitation, and relative humidity from before the partial lockdown in the current year and past years (shown in parentheses) were -3.7% (-11.8%), 8.7% (-4.2%), and 1.2% (-0.1%), respectively. Therefore, the impact of temperature, precipitation, and relative humidity on the changes of pollution level during the partial lockdown would be minor.

The decrease of air pollutants mainly resulting from the closing of non-essential public places, small industry, and reduced traffic during the Covid-19 lockdown period was also reported in previous studies (Berman and Ebisu 2020; Chauhan and Singh 2020; Nakada and Urban 2020; Otmani et al. 2020). The NO<sub>2</sub> concentration dropped from 21.6 µg/m<sup>3</sup> to 5.2 µg/m<sup>3</sup>, showing a significant reduction (-75.8%) during the current partial lockdown period compared with historical data. There was also a significant NO<sub>2</sub> decline (-55.1%) with an absolute reduction of -6.4 µg/m<sup>3</sup> before and during the partial lockdown in 2020. A decrease of NO<sub>2</sub> concentrations was consistent with the value of -52.7% in Delhi, India (Mahato et al. 2020), and higher than the value of -46.6% in São Paulo, Brazil (Nakada and Urban 2020). The sharp variation of NO<sub>2</sub> concentration is possibly associated with the abrupt decrease in vehicular traffic during the partial lockdown resulting from “work-from-home” and international and national travel limitations. Hien et al. (2014)

**Table 1** Mean concentration of PM<sub>2.5</sub>, SO<sub>2</sub>, NO<sub>2</sub>, O<sub>3</sub>, and average meteorological parameters recorded in Hanoi before the partial lockdown (March 10–31) and during the partial lockdown (April 1–22)

	Historical mean during the partial lockdown	Prior to the partial lockdown	During the partial lockdown	Difference [variation in %]	
				A	B
PM <sub>2.5</sub> (µg/m <sup>3</sup> )	98.4	52.9	43.4	-55.0 [-55.9]	-9.5 [-18.0]
NO <sub>2</sub>	21.6	11.6	5.2	-16.3 [-75.8]	-6.4 [-55.1]
SO <sub>2</sub>	13.0	4.5	5.1	-7.9 [-60.7]	0.6 [13.5]
O <sub>3</sub>	21.8	12.2	17.1	-4.7 [-21.4]	4.9 [40.7]
Temperature (°C)	25.4	23.3	22.4	-3 [-11.8]	-0.8 [-3.7]
Precipitation (mm/day)	2.4	2.1	2.3	-0.1 [-4.2]	0.2 [8.7]
Relative humidity (%)	83.9	84.8	83.8	-0.1 [-0.1]	-1 [1.2]
Surface solar radiation (MJ/m <sup>2</sup> )	0.5	0.3	0.4	-0.1 [-20]	0.1 [20]
BLH	476.9	414.0	418.0	-58.9 [-12.4]	4.0 [0.2]

A: Differences of mean concentration during the partial lockdown period in 2020 vs in historical years

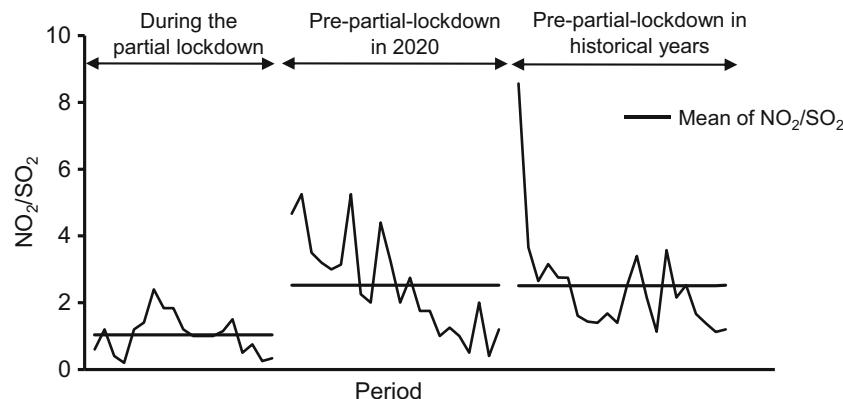
B: Differences of mean concentration during the partial lockdown vs before the partial lockdown in 2020

demonstrated that exhaust emissions of motorbikes are a major source of  $\text{NO}_2$  in Hanoi. Additionally,  $\text{SO}_2$  declined 60.7% during the partial lockdown compared with the same dates in historical years. The  $\text{SO}_2$  reduction in this study is higher than other researchers found in the Yangtze River Delta Region (15–26%) (Li et al. 2020) and Malaysia (9–20%) (Kanniah et al. 2020). However, a slight increase of  $\text{SO}_2$  (13.5%) was observed during the partial lockdown compared with the pre-partial-lockdown period in 2020. The small increase of  $\text{SO}_2$  concentration during the lockdown in Almaty, Kazakhstan, was reported by Kerimray et al. (2020), which could be statistically insignificant. The reduction of vehicular traffic and the closure of non-essential shops and businesses during the partial lockdown could cause a decrease of  $[\text{NO}_2]/[\text{SO}_2]$ . Both mobile sources (motorcycles (with two-stroke petrol engines), diesel trucks, buses, cars, and boats) and stationary sources (industry, power generation, and burning of biomass) are responsible for air pollution in big cities in Vietnam. Biomass burning sources include cooking and heating activities in homes and the street, burning of rubbish, and burning of rice straw and fresh vegetation in surrounding rural areas. Additionally, construction activities are both mobile and stationary sources that have made significant contributions to air pollution in Hanoi. Figure 2 illustrates a significant decrease of  $[\text{NO}_2]/[\text{SO}_2]$  during the partial lockdown period compared with that of historical years and before the lockdown period in 2020. The mean values of  $[\text{NO}_2]/[\text{SO}_2]$  before the partial lockdown were two times higher than that of the partial lockdown period. There was a significant drop in traffic during the partial lockdown, which caused the reduction of mobile emission sources. Although the industrial sector was affected by the Covid-19 pandemic, the industry factories and power plants in Vietnam still operate during the partial lockdown, which may lead to an insignificant change in the contribution of stationary sources. Thus, a drastic reduction of  $[\text{NO}_2]/[\text{SO}_2]$  during the partial lockdown was observed in Hanoi due to a significant reduction of mobile sources (vehicular traffic). Lian et al. (2020) also reported a significant reduction of  $[\text{NO}_2]/[\text{SO}_2]$  during the Covid-19 lockdown period in

Wuhan, China. The partial lockdown in Hanoi experienced a reduction of –55.9% in  $\text{PM}_{2.5}$  concentration with the absolute decline of  $-55.0 \mu\text{g}/\text{m}^3$  compared with the same period in the past years. The reduced concentration of  $\text{PM}_{2.5}$  during the quarantine compared with historical years was higher than findings of other recent publications.  $\text{PM}_{2.5}$  reduction rate during the partial lockdown compared with historical years was 27.12% in megacity Delhi, India (Mahato et al. 2020), 39.0% in Gujarat state of India (Selvam et al. 2020), 29.8% in São Paulo state (Nakada and Urban 2020), and 32% in New York, USA (Chauhan and Singh 2020). A lower reduction of  $\text{PM}_{2.5}$  (–18.0%) during the partial lockdown compared with the pre-partial-lockdown in 2020 was recorded, which was less than a reduction of 23–32% in  $\text{PM}_{2.5}$  concentration in Malaysia (Kanniah et al. 2020). The decline of  $\text{PM}_{2.5}$  was less than the reduction of  $\text{NO}_2$ , which may be because  $\text{PM}_{2.5}$  was emitted from multiple non-transportation sources such as industrial factories and biomass burning (Berman and Ebisu 2020).

The average concentration of  $\text{O}_3$  decreased by –21.4% from  $21.6 \mu\text{g}/\text{m}^3$  (average of historical years) to  $17.1 \mu\text{g}/\text{m}^3$  (2020). However, an increase of 40.7% in  $\text{O}_3$  from  $12.2 \mu\text{g}/\text{m}^3$  (before the partial lockdown) to  $17.1 \mu\text{g}/\text{m}^3$  (during the partial lockdown) occurred in 2020. This result could be attributed to a high association between solar activity levels and the concentration of  $\text{O}_3$  (Nakada and Urban 2020). An increase of 20% in surface solar radiation during the partial lockdown period compared with the same days in historical years would lead to an increase in  $\text{O}_3$  concentration. On the other hand, a decline of  $\text{O}_3$  concentration in 2020 compared with historical data could be explained that surface solar radiation during the partial quarantine was 20% higher than the value measured before the partial lockdown period in 2020. The amplified  $\text{O}_3$  pollution was observed in cities worldwide. Sicard et al. (2020) reported the daily  $\text{O}_3$  mean concentrations increased at urban stations by 24% in Nice, 14% in Rome, 27% in Turin, 2.4% in Valencia, and 36% in Wuhan during the lockdown in 2020. Besides the high solar radiation activities, the increase of  $\text{O}_3$  can be attributed to the effect of chemical reactions

**Fig. 2** Mass concentration ratio of  $[\text{NO}_2]/[\text{SO}_2]$  before and during the partial lockdown in 2020 and in historical years



caused by the strong decrease of nitrogen oxide emissions and PM<sub>2.5</sub> (Chen et al. 2020; Menut et al. 2020; Sicard et al. 2020).

### PM<sub>2.5</sub> concentrations obtained from fieldwork

The PM<sub>2.5</sub> concentration and average elemental concentration in PM<sub>2.5</sub> at three sites in Hanoi prior to and during the partial lockdown period were shown in Table 2. The average PM<sub>2.5</sub> concentration ranged from 73.65 to 90.67 µg/m<sup>3</sup> before the partial lockdown period, which was higher than the ambient air quality standard in Vietnam for 24-h (50 µg/m<sup>3</sup>) and the annual standard (25 µg/m<sup>3</sup>) (QCVN 05:2013/BNMNT). Besides, the mean PM<sub>2.5</sub> mass observed in this study was about 1.9 to 3.6 times higher than the guideline value suggested by WHO 24-h (25 µg/m<sup>3</sup>). Our study showed that the average PM<sub>2.5</sub> concentration during the partial lockdown (47.85 µg/m<sup>3</sup>) was lower than the ambient air quality standards in Vietnam for 24-h, a decreased of –41.8 % compared with that before the partial lockdown. The average PM<sub>2.5</sub> during the partial lockdown in this study was much higher than that in New York, USA (9.48 µg/m<sup>3</sup>), in Zaragoza, Spain (29.38 µg/m<sup>3</sup>) (Chauhan and Singh 2020), and in São Paulo, Brazil (12.4–12.5 µg/m<sup>3</sup>) (Nakada and Urban 2020).

However, this study reported lower daily mean PM<sub>2.5</sub> than in Megacity Delhi, India (60 µg/m<sup>3</sup>) (Mahato et al. 2020). A reduction of –41.8 % in PM<sub>2.5</sub> in our study was much higher than that in Delhi, India (– 53.11%) (Mahato et al. 2020), in São Paulo state, Brazil (– 29.8%) (Nakada and Urban 2020), in Malaysia (23–32%) (Kanniah et al. 2020) and was similar to findings reported by Zoran et al. (2020).

### Relationship between PM<sub>2.5</sub> pollution and the boundary layer height (BLH)

Several studies have shown that the high boundary layer height (BLH) being associated with the low pollution level of particulate matter and vice versa (Chen and Xie 2014; Chu et al. 2019). Therefore, this study investigated the relationship between the BLH and PM<sub>2.5</sub> concentrations obtained from both fieldwork and the automatic ambient air quality monitoring station in Hanoi. The hourly BLH data was first obtained from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis. After that, it was aggregated to the daily mean values and the mean values according to the sampling time to analyze its correlation with PM<sub>2.5</sub> data from the automatic

**Table 2** Average concentrations (average ± standard deviation) of metals in PM<sub>2.5</sub> before the partial lockdown and during the partial lockdown in Hanoi (unit: ng/m<sup>3</sup>; except for the units of PM<sub>2.5</sub> with \* µg/m<sup>3</sup>)

	Before the partial lockdown			During the partial lockdown	Difference [variation in %]
	XL (n = 4)	HVT (n = 4)	Average		
PM <sub>2.5</sub> *	90.7 ± 33.2	73.6 ± 19.7	82.17 ± 26.45	47.9 ± 8.0	– 34.3 [41.7]
Cd	0.79 ± 0.37	0.86 ± 0.41	0.83 ± 0.37	0.48 ± 0.28	– 0.35 [42.5]
As	2.13 ± 0.65	2.44 ± 0.95	2.29 ± 0.77	1.67 ± 0.91	– 0.62 [27.2]
Cr	3.16 ± 1.12	2.96 ± 0.96	3.07 ± 0.97	4.23 ± 6.34	+ 1.16 [37.9]
Ca	930.49 ± 239.23	1237.05 ± 136.67	1083.77 ± 243.69	757.94 ± 216.64	– 325.83 [30.1]
Mn	11.66 ± 63.73	17.26 ± 9.97	14.46 ± 7.58	11.08 ± 5.31	– 3.38 [23.4]
Al	91.26 ± 19.08	169.11 ± 22.35	130.19 ± 45.84	95.67 ± 29.97	– 34.52 [26.5]
Fe	467.79 ± 75.16	1835.90 ± 1235.18	1151.85 ± 1091.36	1011.72 ± 1260.26	– 140.13 [12.2]
Mg	91.45 ± 23.55	144.38 ± 26.82	117.92 ± 36.69	94.65 ± 24.52	– 23.27 [19.7]
Ba	5.26 ± 1.98	6.01 ± 1.85	5.64 ± 1.82	3.8 ± 1.21	– 1.81 [32.1]
Co	0.16 ± 0.04	0.23 ± 0.09	0.19 ± 0.07	0.35 ± 0.55	+ 0.16 [82.6]
Cu	6.05 ± 1.75	5.68 ± 1.81	5.87 ± 1.66	3.21 ± 1.05	– 2.66 [45.3]
Pb	19.72 ± 9.72	36.30 ± 16.49	28.01 ± 15.35	13.29 ± 5.21	– 14.73 [52.6]
Ti	6.56 ± 2.44	5.98 ± 1.28	6.27 ± 1.83	4.75 ± 0.86	– 1.52 [24.2]
V	0.58 ± 0.08	0.64 ± 0.09	0.61 ± 0.09	0.66 ± 0.34	+ 0.05 [7.9]
Zn	121.44 ± 60.03	472.24 ± 227.26	296.84 ± 242.57	143.25 ± 115.43	– 153.59 [51.7]
Ni	1.13 ± 0.44	1.64 ± 0.67	1.38 ± 0.59	2.26 ± 0.91	+ 1.24 [89.7]
Sr	3.15 ± 0.61	4.54 ± 1.09	3.85 ± 1.10	2.82 ± 0.75	– 1.03 [26.8]
K	361.42 ± 134.62	287.50 ± 79.71	324.46 ± 109.78	179.37 ± 35.22	– 145.09 [44.7]
Na	78.31 ± 38.39	62.43 ± 18.80	70.37 ± 29.24	80.76 ± 51.91	+10.39 [14.8]
Mo	0.31 ± 0.11	0.28 ± 0.05	0.30 ± 0.08	0.44 ± 0.53	+ 0.14 [48.7]

ambient air quality monitoring station and sampling sites, respectively. As shown in Fig. 3, the significantly negative correlation between the BLH and the  $\text{PM}_{2.5}$  obtained from the automatic air monitoring station ( $R = -0.37$ ) and the  $\text{PM}_{2.5}$  obtained from fieldwork ( $R = -0.47$ ) indicated that the shallow BLH would exacerbate the  $\text{PM}_{2.5}$  pollution. The significant negative correlation between the BLH and the daily  $\text{PM}_{2.5}$  concentration was also reported in Miao et al. (2017) with the range of R-value from  $-0.32$  to  $-0.37$ . The negative correlation between the BLH and the  $\text{PM}_{2.5}$  concentrations could be explained by the fact that the vertical volume for dispersion and dilution of pollutants was regulated by the BLH, which modulates the  $\text{PM}_{2.5}$  concentration (Miao et al. 2019). In addition, the reduction of the  $\text{PM}_{2.5}$  pollution level would lead to an increase in the BLH due to the increment of surface solar radiation (Wang et al. 2020b). Therefore, to some extent, the increment of the BLH and surface solar radiation as shown in Table 1 would be partially attributed to the reduction of  $\text{PM}_{2.5}$  in Hanoi.

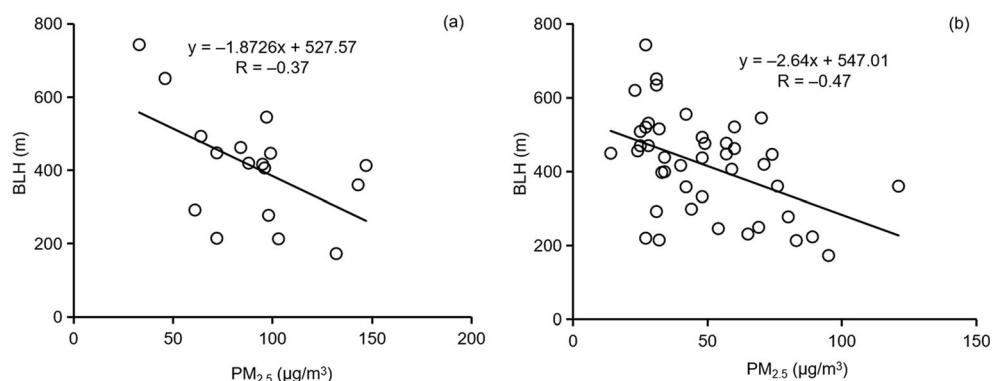
### Concentration of elements bound to $\text{PM}_{2.5}$

Twenty elements in  $\text{PM}_{2.5}$  (Al, Na, Mg, V, K, Ba, Mn, Co, Ca, Fe, Cr, Cu, Ni, Mo, As, Pb, Zn, Cd, Ti, and Sr) were measured in this study. As shown in Table 2, the concentration of the most abundant elements (Fe, Al, Ca, K, Na, Mg, and Zn) was significantly higher than those of others at all sites before and during the partial lockdown. These elements were representative of crustal elements. The concentrations of Cd, As, Ba, Cu, Mn, Pb, K, Zn, Ca, Al, Mg, and Sr before the partial lockdown were higher than those during the partial lockdown, while the concentrations of V prior to and during the partial lockdown were similar. Our results showed that concentrations of Cd, Cu, Pb, Zn, and K were substantially decreased by 42.5, 45.2, 52.6, 51.7, and 44.7%, respectively, during the partial lockdown. Cu, Pb, Zn, are Fe are emitted from non-exhaust traffic sources such as tire and brake wear (Alves et al. 2018). Moreover, Jeong et al. (2019) showed that non-exhaust emissions contained a high contribution of trace elements (74% of

Ba, 56% of Cu, and 42% of Fe). Denier van der Gon et al. (2007) showed that brake wear emissions accounted for up to 75% of Cu emissions into the air. Therefore, the decreases in the concentration of these metals could be the result of restriction on the traffic activities during the partial lockdown.

Lower reduction of trace metals concentration (Se (33.4%), As (27.2%), Sr (26.8%), Ba (32.1%), Ti (24.2%), Mn (23.4%), Mg (19.7%), Al (26.5%), Fe (12.2%), and Ca (30.1%)) were observed during the partial lockdown compared with before the partial lockdown. Al, K, Fe, Mn, Ni, and Cr were emitted from re-suspension of road dust (Chang et al. 2009; Lee and Hieu 2011; Lim et al. 2010; Manoli et al. 2002). Emission of Ni, Cd, Mn, As, Pb, Zn, and Cu could be emitted from metallurgical industry, boiler factories, thermal power plants, and coal combustion into the atmosphere (Chang et al. 2009; Cheng et al. 2017; Manoli et al. 2002; Tian et al. 2012). In addition, combustion of oil/ petrochemical plants (As, Cd, Cu, Cr, Zn, V, Ni, ) (Dai et al. 2015; Nielsen et al. 2013; Pacyna and Pacyna 2001; Querol et al. 2007), non-ferrous metal production (As, Cd, Cr, Cu, In, Mn, Zn) (Pacyna and Pacyna 2001), and gasoline combustion (Pb, Sr, Cu, Mn) (Pacyna and Pacyna 2001; Sanderson et al. 2014) also contributed to industrial emissions of trace metals. It is therefore assumed that reduction of anthropogenic emissions (industrial emissions, construction operations, mainly traffic) contributed to the reduction of metal concentrations. Li et al. (2020) and Kanniah et al. (2020) indicated that the reduction of air pollution was mainly related to the restriction on traffic and industrial activities. However, an increase in concentrations of Co (82.6%), Mo (47.8%), Ni (89.7%), and Cr (37.9%) found during the partial lockdown compared with the prior to the partial lockdown could be attributed to the activities of factories in an industrial park being close to CN site under the impact of atmospheric condition. Furthermore, Wang et al. (2020a) indicated that the restriction on anthropogenic activities would not help avoid severe air pollution due to the impact of weather conditions. Thus, the increments of these metal concentrations during the partial lockdown need further investigation.

**Fig. 3** Scatter plot between BLH and  $\text{PM}_{2.5}$  level in Hanoi (a)  $\text{PM}_{2.5}$  from field work and (b)  $\text{PM}_{2.5}$  from the automatic air quality monitoring station



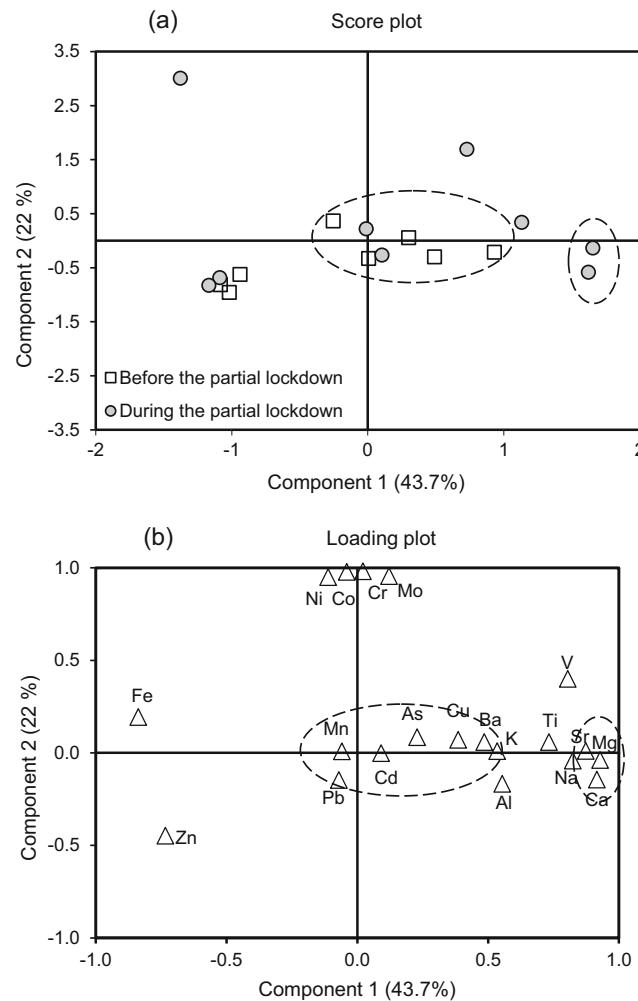
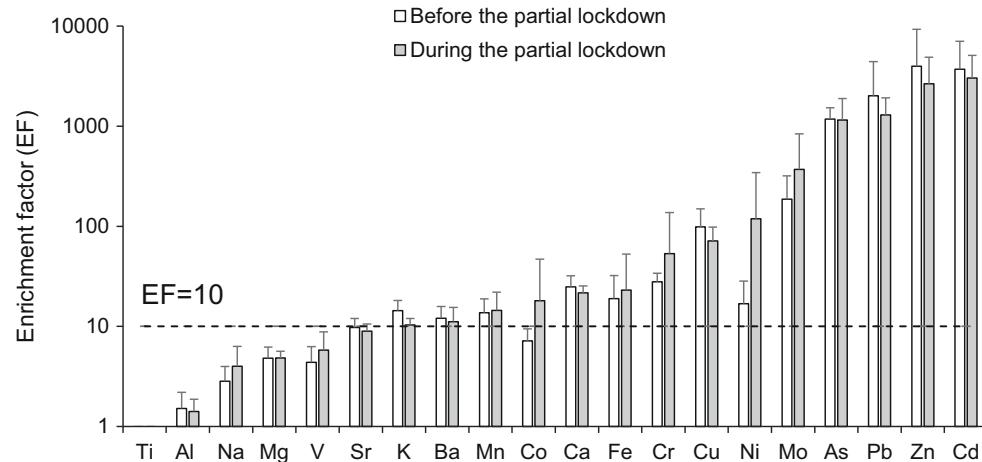
## Identification of elemental emission sources

Except for Co, a low EF (EF < 10) was observed for crustal metal (Ti, Al, Na, Mg, V, K, and Sr) during the partial lock and before the partial lockdown (Fig. 4). Conversely, high EF values (EF > 10) of Ca, Fe, Cr, Cu, Ni, Mo, As, Pb, Cd, and Se were observed both during the partial lock and before the partial lockdown (Fig. 4), which suggested that these elements originated from human activities. In particular, the EFs of As, Pb, Zn, and Cd were higher than 1000, which implied that the influence of the anthropogenic sources on these elements was dominant. The EFs for Ba and Mn were around 10 during the partial lockdown and a little bit higher than 10 before the partial lockdown, which indicated that their emissions were affected by both natural and anthropogenic sources.

The results of the PCA (i.e., the loading plots of the 20 metals and the score plots of the individual periods) were presented in Fig. 5. Two PCs having eigenvalues greater than one were extracted; in general, they account for 65.7% of the total data variance (first PC: 43.7% and second PC: 22.0%). The score and loading plots were used to estimate relations between the periods and trace elements.

In general, the samples during the partial lockdown and before the partial lockdown were not strongly separated from each other in the score plot (Fig. 5a). However, some of the samples before the partial lockdown on the horizontal line of the score plot was separated from the samples during the partial lockdown on the right side and left side of the score plot. The separation of these three groups (group 1, group 2, and group 3) can be explained by the loading plot (Fig. 5). Group 1 (Zn) was located at a lower side of the loading plot, group 2 (Na, Sr, Mg, and Ca) were located at the right side of the loading plot, and group 3 (Mn, Pb, Cd, As, Cu, Ba, and K) were located at the horizontal line of the loading plot. This spatial distribution of these elements in the loading plot can be correlated with the distribution of the sample prior to and during the partial lockdown in the score plot.

**Fig. 4** Element concentrations in PM<sub>2.5</sub> before and during the partial lockdown in Hanoi



**Fig. 5** Results of PCA represented by the score and loading plots of samples before the partial lockdown (open squares) and during the partial lockdown (close circles). Open triangle represented trace elements in PM<sub>2.5</sub> samples

Some of the samples during the partial lockdown in the score plot, which were determined by Zn and group 3 (Na, Sr, Mg, and Ca), were at the left side and right side of the

loading plot, respectively. Some researchers reported that the high loadings of Mg and Ca were the typical elements of the crustal source (soil) (Gu et al. 2014; Kim et al. 2019; Morawska and Zhang 2002). Machado et al. (2008) and Zhai et al. (2014) found that Zn is mainly associated with non-exhaust traffic sources such as the brake and tire wear and other transport processes. This result implied that these metals during the partial lockdown originated from crustal sources/natural sources and were matched with their low EF values (Fig. 4) and non-exhaust traffic sources.

In addition, most of the samples (five out of eight samples) before the partial lockdown in the score plot can be explained by the distribution of elements in the loading plot, characterized by Mn, Pb, Cd, As, Cu, Ba, and K. These elements were representative of elements produced by industrial processes (Kim et al. 2019; Querol et al. 2007; Soleimani et al. 2018). Additionally, Cu and Ba were emitted from non-exhaust traffic sources such as brake wear (Jeong et al. 2019; Pant and Harrison 2013). Besides, other samples before the partial lockdown on the left side of the score plots were determined by the distribution of Zn in the loading plot. Hence, this result suggested that these elements before the partial lockdown were emitted from industrial activities and non-exhaust traffic, which was consistent with their high EF values (Fig. 4). This finding indicated that samples before the partial lockdown were more affected by industrial activities than those during the partial lockdown.

## Conclusions

This study investigated the impact of the partial lockdown caused by Covid-19 on main air pollutants and the elements bound to PM<sub>2.5</sub> in Hanoi. During the partial lockdown, NO<sub>2</sub>, PM<sub>2.5</sub>, O<sub>3</sub>, and SO<sub>2</sub> decreased by 75.8, 55.9, 21.4, and 60.7%, respectively, compared with historical data. In addition, PM<sub>2.5</sub> at sampling sites was reduced by -41.8%, which was consistent with the ground-based measurements. A noticeable increase of O<sub>3</sub> (40.7%) concentration compared with the period before partial quarantine could be attributed to both high solar activities and the effect of chemical reactions caused by the strong decrease of NO<sub>2</sub> emission and PM<sub>2.5</sub>. A slight increase in SO<sub>2</sub> level (+ 13.5%) compared to pre-partial lockdown is possibly statistically insignificant. In addition, a significant negative correlation between the BLH and PM<sub>2.5</sub> concentration was observed in Hanoi. However, the trivial variations of mean temperature, precipitation, and relative humidity prior to and during partial lockdown indicate a minor impact on the changes of pollutants level. Lower concentrations of Cd, As, Ba, Cu, Mn, Pb, K, Zn, Ca, Al, and Mg were observed during the partial lockdown. The values of EFx and results obtained from PCA indicated that Zn, Na, Sr, Mg, and Ca during the partial lockdown originated from crustal sources/nature

sources and non-exhaust traffic sources, while Mn, Pb, Cd, As, Cu, Ba, and K before the partial lockdown period were emitted from industrial sources and non-exhaust traffic sources. This study demonstrated that decreases of air pollutants and elements bound to PM<sub>2.5</sub> in this study area would mainly be attributed to a significant decrease in emissions from vehicle exhaust and the close of the small industry during the Covid-19 lockdown period.

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**Authors' contributions** TPMN and THB designed and wrote the manuscript draft, read, corrected, and approved the final manuscript. KMN contributed to the interpretation of the results. THN provided facilities, technical and evaluated the results and discussion of these results. VTV and HLP contributed to the analysis of the samples. All authors read and approved the final manuscript.

**Data availability** All data generated or analyzed during this study are included in this published article.

## Declarations

**Ethics approval and consent to participate** Not applicable

**Consent for publication** Not applicable

**Competing interest** No potential conflict of interest was reported by the authors. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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