Nitrogen Dioxide (NO$_2$) Level Changes during the Control of COVID-19 Pandemic in Thailand

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ABSTRACT

The first case of COVID-19 infection was confirmed in Thailand on January 13, 2020; since then, work from home and lockdown measures have slowed the spread of COVID-19. A more stringent, curfew regulation was imposed on April 3, 2020. Under these measures, the activities of businesses, transportation, and industrial sectors were reduced or temporally closed. Therefore, this study aims to investigate the changes in the nitrogen dioxide (NO$_2$) level in the whole of Thailand and specifically in the Bangkok metropolitan area. The concentrations of tropospheric NO$_2$ were extracted from the Sentinel-5P satellite data. The Google Earth Engine JavaScript API was used to retrieve and calculate the NO$_2$ data. Python was also used to extract NO$_2$ values from the output raster data. The results showed that the level of NO$_2$ increased by 47.4% during the COVID-19 pandemic in the whole of Thailand; NO$_2$ declined by 4.8% in the Bangkok metropolitan area, but there was no significant difference compared to before the COVID-19 pandemic. NO$_2$ level during curfew regulation declined by 9.5% in the whole of Thailand and decreased by 20.1% in the Bangkok metropolitan area. After comparing the same time duration in 2019 and 2020 on a monthly basis, the results revealed that NO$_2$ level in 2020 declined by 9.1% and 9.8% for the whole of Thailand and Bangkok metropolitan area, respectively. Our findings support that these measures can temporarily reduce NO$_2$ levels. Once all sectors resume as normal, we concern that the NO$_2$ emissions will rebound. Hence, the challenge after the COVID-19 pandemic is how to improve and protect our environment while restoring the economy, which is a crucial issue that policymakers should fully address.

Keywords: COVID-19 pandemic, Nitrogen dioxide, Sentinel-5p, Lockdown, Work from home, Curfew

1 INTRODUCTION

Since the COVID-19-a coronavirus outbreak occurred in Wuhan, China as an infectious disease, presumably spilling over from an animal reservoir and transmitted by respiratory droplets (Whitworth, 2020; Wu et al., 2020a; Zhou et al., 2020), the pandemic disease rapidly distributed into 210 countries and killed over 100,000 people around the world in less than half a year (Worldometer, 2020). The common symptom of COVID-19 infection is atypical pneumonia with fever, dry cough, and tiredness; it is more often severe in the elderly and people with underlying diseases (Guan et al., 2020; WHO, 2020a). With approximately a 14-day incubation period, 2019-nCoV has a high potential for wide distribution via nosocomial outbreaks, social contact, aerosol contamination, and surface stability (Perlman, 2020; van Doremalen et al., 2020). From recent reports, over two million people have tested positive for COVID-19 with a mortality rate of 3.4%
(WHO, 2020b). Currently, the specific vaccine and therapy are still lacking for COVID-19 (Wu et al., 2020b). As such, this outbreak may affect human activity and also shape ecosystem dynamics as well as the environment in the long term.

To slow down the COVID-19 outbreak, travel restrictions were primarily employed in China to mitigate the epidemic spatially (Kraemer et al., 2020). Isolation, quarantine, social distancing, and community restraint were recommended to limit human-to-human transmission in many countries, such as China, the United States, and Italy. Several other countries instituted limits on public gathering when the numbers of cases and deaths were increasing (Fauci et al., 2020; Haffajee and Mello, 2020). In Thailand, the first cases of COVID-19 infection occurred in Bangkok and then spread to approximately 1,000 people in 50 provinces over a 25-day period. The significant increase of COVID-19 cases since March 15, 2020 pressed the government to impose public health control measures, including screening flights returning from heavily affected countries, providing 14 days of self-quarantine for the at-risk group, recommending people work from home, and minimizing mass congregation. On April 3, 2020, under 2005 (B.E. 2548) Emergency Decree on Public Administration in Emergency Situation of Thailand, civilians were prohibited to use public places and transportation from 22.00 hr to 4.00 hr and temporarily banned domestic flights for a month. Most restaurants, stores, and entertainment venues were forced to close by the state of emergency except for essential services (Office of the Prime Minister Thailand, 2020).

By these, most economic activities declined in traffic that may have temporarily reduced the levels of urban air pollution observed from satellite data in China (Dutheil et al., 2020; NASA, 2020), Spain (Tobías et al., 2020), and Italy (Patel, 2020).

In urban areas, the non-CO2 air pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), methane (CH4), sulfur dioxide (SO2), and volatile organic compounds (VOCs), typically arise due to exposure from the transportation sector (Karner et al., 2010; Pongpiachan and Iijima, 2016; Pongpiachan et al., 2017; ChooChuay et al., 2020a, b, c). Transportation-related air emissions play a major role for heat-trapping in atmospheric layers (UN, 1992; IPCC, 2014; Yue and Gao, 2018), while agricultural waste burning is another important source of air pollution (Oppenheimer et al., 2004; Cheng et al., 2009; Castellanos et al., 2014; Pongpiachan, 2016), leading to human health impact (Chiusolo et al., 2011; Zhang et al., 2012; Hoek et al., 2013; Crouse et al., 2015; Pongpiachan and Paowa, 2015; Pongpiachan et al., 2018; He et al., 2020a). Nitrogen dioxide (NO2) has been considered worldwide as an important indicator of environmental pollution and is listed as one of six typical air pollutants by The World Health Organization (WHO) (Brunekreef and Holgate, 2002). It is also considered highly lethal to human health, which can cause respiratory diseases, asthma, cellular inflammation (He et al., 2020a), cardiovascular disorders, blood pressure, and lung cancer (Le Tertre et al., 2002; Koken et al., 2003). In addition, NO2 causes the formation of nitric acid (HNO3) and acid rain, which is concerned harmful to the total environment (Zhang et al., 2020). The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have tracked and reported the concentration of NO2 in the atmosphere to monitor air quality (NASA Earth Observatory, 2016).

Since the beginning of the COVID-19 pandemic, the NASA and ESA has released reports about NO2 reduction in Asian and European countries due to COVID-19 lockdowns. The ESA collects air quality data by using TROPOMI instruments using Sentinel – 5P satellite. ESA (2020) reported that there were 70% and 20–30% NO2 reduction in India and China, respectively, during the lockdowns. According to ESA (2020), the NO2 reduced 20–30% in European countries (i.e., Spain, Italy, and France) due to lockdown applied by respective governments. The Ozone Monitoring Instrument (OMI) on NASA’s Aura satellite measures the concentrations of atmospheric NO2. NASA satellite measurements have revealed significant reductions in air pollution over the major metropolitan areas of the Northeast United States (NASA, 2020) due to the lockdowns and shelter-in-place orders as a result of the spread of COVID-19. Hichem et al. (2020) carried out the measurements of NO2 collected over mainland France from May 2018 to June 2019 using Sentinel-5P satellite data. Moreover, the work done by Tobias et al. (2020) related to changes in air quality during the COVID-19 lockdown in Barcelona, Spain; they measured particulate matter, NO2, SO2, and ozone (O3) levels using Sentinel-5P satellite data with the integration of ground measurement data from air quality monitoring stations.

Comparing with chemiluminescence method, Phosri et al. (2019) studied the short-term effects of O3, NO2, SO2, PM10, and CO on the risk of daily hospital admissions for cardiovascular
and respiratory diseases in Bangkok. They used daily air pollution data, including O₃, NO₂, SO₂, PM₁₀, and CO, were extracted from the database of the Pollution Control Department (PCD) of Thailand. The chemiluminescence method is applied by PCD for measuring O₃ and NO₂; UV-fluorescence for SO₂; Tapered Element Oscillation Microbalance for PM₁₀; and Non-Dispersive Infrared Detection for CO. Using PCD data is more favourable to go into details about pollution problems in a certain area if the study area size is small (provincial or district scale). However, it would be a big task to compile PCD data which cover the whole country when conducting a national-scale research. Sentinel-5P data allow the researchers to study air pollution research at any scale, local or national or regional or global scale and to investigate temporal and spatial variations of key atmospheric constituents, including O₃, NO₂, SO₂, CO, CH₄, formaldehyde as well as cloud and aerosol properties. To date, there are a very small number of studies in which TROPOMI NO₂ retrievals are validated against ground-based observations. Ialongo et al. (2020) made a comparison between satellite-based Sentinel-5P’s TROPOMI NO₂ products and ground-based observations in Helsinki (Finland). They compared TROPOMI NO₂ total (summed) columns with the measurements performed by the Pandora spectrometer between April and September 2018. The mean relative and absolute bias between the TROPOMI and Pandora NO₂ total columns is about 10% and 0.12 × 10¹⁵ molec. cm⁻², respectively. The dispersion of these differences (estimated as their standard deviation) is 2.2 × 10¹⁵ molec. cm⁻². They also found that there is high correlation (r = 0.68) between satellite- and ground-based data and TROPOMI slightly overestimates (within the retrieval uncertainties) relatively small NO₂ total columns. These reports and the recently published papers which use satellite-derived air quality data inspired us to conduct this research.

To find out how the COVID-19 outbreak affects the environment, we focused on the concentrations of tropospheric NO₂ in this study due to the changes in NO₂ concentration as a link to transportation emissions and an indicator of local air pollution exposure on a wide scale (Levy et al., 2014). To the best of our knowledge, this is the first study in Thailand. We aimed to investigate the changes in spatial NO₂ concentration during work from home, lockdown and curfew measures in Thailand due to the controlling transmission of COVID-19 pandemic.

1.1 COVID-19 in Thailand

The COVID-19 case detected in Wuhan, China was first reported to the WHO Country Office in China on December 31, 2019. After that, Thailand’s Department of Disease Control activated the Emergency Operation Center on January 4, 2020. The first confirmed case of COVID-19 infection was announced by Thai authorities on January 13, 2020. Since then, traveling to at-risk countries was recommended to be postponed, and people who entered Thailand needed to be screened under the disease screening protocol. The first death caused by COVID-19 in Thailand was reported on March 1, 2020. Then, all local and international schools and universities were closed. The Governor of the Bangkok Metropolitan Administration and provincial governors in surrounding zones ordered temporary closures for places at risk. This caused the people to move from Bangkok into provincial areas on March 22, 2020. Moreover, a second wave of people who had been working in the Bangkok metropolitan region returned to their hometowns on March 29, 2020. The migration caused the government to impose more restriction measures that all returnees must be quarantined at specific places for 14 days to control the disease, regardless of symptom presentation. To combat COVID-19, a curfew regulation was imposed on April 3, 2020, and all passenger flights were banned. During the pandemic, Songkran’s holiday (April 11–15, 2020) was officially postponed to stop the traveling of people. At the same time, under these lockdown and curfew regulations, work from home and social distancing have been strictly implemented. The proactive search is also performed by focusing on two main groups: at-risk people who work with a large number of people and/or who work in public places with the opportunity to meet more patients, such as health personnel, public vehicle drivers, and so on.

Based on the report by the Thai government’s Centre for COVID-19 Situation Administration (CCSA) on May 11, 2020, there were 3,015 total cumulative cases, 2,796 have recovered, 163 are still receiving care, and 56 have died. Bangkok had confirmed the highest number of 1,530 cases, followed by Phuket (224 cases), Nonthaburi (156 cases), Yala (125 cases), Samut Prakan (115 cases), Chonburi (87 cases), Pattani (79 cases), Songkhla (44 cases), Chiang Mai (40 cases), and Pathum Thani (39 cases) (Department of Disease Control, 2020). As the time of writing this,
the number of cases are continuously updated. However, the information on May 11, 2020 were reported here because it is the end of the study and consistent with the last day for collecting the data from Sentinel-5P satellite.

2 DATA AND METHODS

The Sentinel-5P satellite was successfully launched on October 13, 2017, by the ESA; it monitors the density of several atmospheric gases, aerosols, and cloud distributions affecting air quality and climate. The satellite carries a single instrument called TROPOspheric Monitoring Instrument (TROPOMI), which provides accurate and timely observations of key atmospheric species.

The TROPOMI is a multispectral imaging spectrometer that detects solar radiation reflected or scattered back to space from Earth’s atmosphere and surface. The spectral fingerprint of each target atmospheric trace gas is known, so each concentration can be calculated through the identification of the unique fingerprints of these constituents in different parts of the electromagnetic spectrum. TROPOMI has a full global coverage each day, but with a much-improved resolution compared to its predecessors. TROPOMI has also more spectral bands than its predecessors: ultraviolet and visible (270–500 nm), near-infrared (675–777 nm), and shortwave infrared (2305–2385 nm). This allows TROPOMI to measure a wider range of trace atmospheric gases such as NO2, O3, SO2, CH5, and CO. TROPOMI has high spatial resolution (3.5 $\times$ 7 km2 for all trace gases, except for CH5 and CH4, which are 7 $\times$ 7 km2), so its observations are expected to be important for estimating pollutant concentrations and emissions at the scale of smaller towns, individual power plants, wildfires, and major infrastructure. Operational data products, including NO2, became available in July 2018 (Veefkind et al., 2012; Theys et al., 2019). Griffin et al. (2019) validated TROPOMI NO2 product against aircraft and ground-based data over the Athabasca Oil Sands Region (AOSR) in northeastern Alberta, Canada. Their research proved that there is a good correlation ($R^2 \approx 0.68$) between TROPOMI NO2 data and the ground-based in situ and airborne measurements. They also found a low bias of $-15\%$ to $-30\%$ of the TROPOMI tropospheric NO2 columns over the AOSR that was consistent for all of the comparisons carried out in their study. The accuracy and precision requirements for the TROPOMI L2 (Level-2) products have been formulated by the L2 Quality Working Group and agreed on with the Sentinel-5P Mission Advisory Group. The accuracy of the tropospheric NO2 VCD (Vertical Column Density) product is expected around 25–50%, with a precision of 0.7 $\times$ 1015 molec. cm–2 (Fehr, 2016). Tack et al. (2021) used NO2 Slant Column Density detection limits of 5.6 $\times$ 1014 molec. cm–2 in their study. In their work, a threshold is used to identify whether or not a NO2 signal within a TROPOMI pixel is still detectable, and is defined as the sum of the urban background VCD of 3 $\times$ 1015 molec. cm–2 and a NO2 VCD detection limit of 2.1 $\times$ 1015 molec. cm–2, defined as three times the TROPOMI theoretical precision requirement.

The overview of land use in Thailand comprises 31.89% of forest, 46.53% of agricultural areas, and 21.57% of other areas (Information Technology and Communication center, Department of Agricultural Extension, 2016). Bangkok is the capital of Thailand and one of the biggest cities in the world. The economic activities focus on businesses, transportation, and industrial sectors, which are the main sources of NO2 levels in metropolitan Bangkok together with surrounding areas where are mainly agriculture areas (e.g., paddy fields, vegetables, and orchard). During the COVID-19 pandemic, Bangkok had the highest number of cumulative confirmed cases (1,530 cases, May 11, 2020) compared with other provinces in Thailand. For this reason, this study aimed to detect changes in NO2 level for the whole of Thailand and more detailed changes in the Bangkok metropolitan area. In this study, we made three types of comparisons for changes of NO2 level. The first comparison focused on changes of NO2 level before and during the COVID-19 pandemic. The arrival date of the 2020 coronavirus pandemic to Thailand was January 13, 2020, as such the interval “During Pandemic” was defined as January 13 to May 11, 2020 (the end of the study). To properly compare NO2 level changes before and during the pandemic, the intervals of “Before Pandemic” and “During Pandemic” had the same lengths; therefore, “Before Pandemic” was defined as the period between September 15, 2019 and January 13, 2020. The second comparison investigated the change of NO2 level after the curfew regulation (April 3, 2020). The third comparison contrasted NO2 levels “During Pandemic” period of 2020 with the same period in 2019 on a monthly basis.
Google Earth Engine JavaScript API was used for downloading Sentinel-5P data, exporting NO2 raster data, organizing and visualizing maps, and analyzing changes over different periods (Gorelick et al., 2017). Python was also used for the extraction of NO2 values from the output raster data. A change detection task was carried out in ArcGIS 10.2 software (ESRI, Redlands, USA) to detect changes of NO2 level between two different intervals. The t-test was conducted to identify the significant differences of NO2 level between before and during the pandemic, and before and after curfew regulation during pandemic. A paired t-test was used to compare NO2 levels during COVID-19 pandemic period of 2020 with the same period in 2019 (without COVID-19 pandemic). All the statistical analysis were done by using SPSS Version 20.0 (Chicago, IL, USA).

Simple linear regression analysis was carried out to investigate the correlation between NO2 levels and meteorological factors. In Bangkok area, the correlation between daily NO2 levels and weather variables (temperature and precipitation) was studied for “During Pandemic” period of 2020 with the same period in 2019 on a monthly basis. Daily weather data comes from Climate Forecast System (CFS) Reanalysis dataset developed by National Centers for Environmental Prediction (NCEP) of the United States and the data extraction was done on Climate Engine Application. Moreover, the correlation between 5-month mean NO2 values and weather variables was also performed in each province of Thailand for 2019–2020 comparison. Using the ERA5 Monthly aggregates, the latest climate reanalysis data produced by ECMWF [European Centre for Medium-Range Weather Forecasts]/Copernicus Climate Change Service, 5-month mean values of temperature and precipitation was calculated on Google Earth Engine Platform. Then, the zonal statistics of climate data for each province was calculated using geopandas, pandas, rasterio, rasterstats and matplotlib python modules.

To simply compare the congruence of NO2 level from Sentinel-5P satellite with those reported by PCD in Thailand, we gathered the NO2 concentration data from Thailand’s air quality and situation reports (http://air4thai.pcd.go.th/webV2/download.php), which obtained data from twelve ground stations of PCD in the Bangkok metropolitan area, covering Wang Thonglang, Phaya Thai, Din Dang, Thon Buri, Pathum Wan, Yannawa, Bang Kapi, Bang Na, and Bangkhuntien areas. The data in 2020 (during COVID-19 pandemic) were taken and averaged to present the trend and compare with the data from Sentinel-5P satellite, while the past 3 years data (2017, 2018 and 2019) were also analyzed and compared as without COVID-19 pandemic situation.

3 RESULTS

3.1 Correlation between NO2 Levels and Weather Variables

According to the regression analysis for each province of Thailand, there is a positive linear relationship between NO2 level and temperature, resulting R2 values 0.2679 for January–May, 2019 period and 0.2963 for January–May, 2020 (During Pandemic) period, respectively. Similarly, NO2 level is really affected by precipitation. The regression analysis proved that NO2 level is negatively correlated to precipitation, in contrast to temperature-NO2 relationship. The two variables have a stronger relationship in January–May, 2019 period. However, as all of R2 values are well below 0.5, we can conclude that the correlations between NO2 level and each climate variable is not strong in each province of Thailand (Figs. 1(a) and 1(b)).

In the Bangkok metropolitan area, the regression model yielded higher determination coefficient (R2) of 0.4127 in January-May, 2020 (During Pandemic) period compared to January–May, 2019 period (R2 = 0.3781). It means that there is a positive linear relationship between NO2 level and temperature in both periods and stronger relationship in “During Pandemic” period. However, as R2 values are 0.00004 and 0.046 respectively for “During Pandemic” and January–May, 2019 periods and relatively closed to zero in the regression analysis for NO2-precipitation comparison, they are said to have little or no correlation. Overall, it can be said that there is poor relationship between NO2 level and temperature and no correlation between NO2 level and precipitation in Bangkok Metropolis (Figs. 1(c) and 1(d)).

3.2 NO2 Level Changes in the Whole of Thailand

NO2 levels differs from a national perspective before and during the pandemic (Fig. 2). We found a significant difference of the average NO2 VCD values between the two periods of before
and during the pandemic, with values of 16.55 µmol m⁻² and 24.4 µmol m⁻² ($p = 0.000; p < 0.01$), respectively, which increased 47.4% compared to before pandemic. The NO₂ VCD values for before and after curfew regulation periods were significantly different, with the average values of 25.2 µmol m⁻² and 22.8 µmol m⁻² for before and after curfew regulation periods ($p = 0.091; p < 0.1$), respectively, which decreased by 9.5%.

In October, November, and December of 2019, the NO₂ VCD values ranged between 5 µmol m⁻² and 30 µmol m⁻². In January and February of 2020, a gentle rise in NO₂ level was notable; the NO₂ VCD values ranging from 10 to 30 µmol m⁻² in most days of these two months. A more remarkable

![Fig. 1.](image-url)

**Fig. 1.** The correlation between daily NO₂ levels and weather variables in the whole Thailand and Bangkok metropolitan area. (a) correlation between NO₂ levels and precipitation in the whole Thailand, and (b) correlation between NO₂ levels and temperature in the whole Thailand.
increase in NO\textsubscript{2} level can be found in March of 2020, with NO\textsubscript{2} VCD values ranging from 8 µmol m\textsuperscript{-2} to 80 µmol m\textsuperscript{-2}. After that, a slight decrease in NO\textsubscript{2} level can be seen in April and the first week of May, with NO\textsubscript{2} VCD values below 30 µmol m\textsuperscript{-2} in most days of this period (Fig. 2).

Concerning each region of Thailand, we found the increasing of NO\textsubscript{2} level during the COVID-19 pandemic (January 13 to May 11, 2020) in every regions, which increased by +101.1%, +51.8%, +30.5%, +24.7%, +23.1%, and +1.5% in the northern, northeastern, eastern, western, and central regions, respectively (Table S1). The highest reduction of NO\textsubscript{2} level during the COVID-19 pandemic was detected in Samut Sakhon (−56.4%), where the heavy traffic and various factories are located, followed by Samut Songkhram (−33.1%), Samut Prakan (−32.1%), Bangkok metropolitan

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Fig. 1. (continued). (c) correlation between NO\textsubscript{2} levels and precipitation in the Bangkok metropolitan area, and (d) correlation between NO\textsubscript{2} levels and temperature in the Bangkok metropolitan area.
The highest increase of NO$_2$ level during the COVID-19 pandemic was found in the northern region of Thailand due to biomass burning and forest fires, mainly in Mae Hong Son (+133.6%), Nan (+130.9%), Phayao (+125.5%), Chiang Rai (+110.7%), Phrae (+97.4%), and Chiang Mai (+89.4%) (Table S1; Figs. 3 and 4).

According to the results derived from Sentinel-5P satellite data (Fig. 5), there was no significant change in NO$_2$ level between January of 2019 and the same month of 2020, with NO$_2$ VCD values ranging from 10 to 30 µmol m$^{-2}$. The NO$_2$ level in February of 2019 and 2020 also had no significant change. In March, a steady increase of NO$_2$ level was observed in both 2019 and 2020. However, a gentle decrease occurs in March of 2020 but not 2019. The NO$_2$ VCD values in March of 2019 ranged between 20 µmol m$^{-2}$ and 60 µmol m$^{-2}$ in most days, whereas the NO$_2$ level of March of 2020 were between 10 µmol m$^{-2}$ and 40 µmol m$^{-2}$ in most days. After this rise in March, a gentle decrease was observed in April, which has NO$_2$ VCD values in the range of 10–30 µmol m$^{-2}$ in both 2019 and 2020. Comparing the same period (January 13–May 11) of 2019 and 2020, both years have the same trend of NO$_2$ level change and the slight decrease in March. Comparing the same months between the years, the NO$_2$ VCD values were significantly different ($p = 0.001, p < 0.01$), with the average values of 28.2 µmol m$^{-2}$ and 24.0 µmol m$^{-2}$ for 2019 and 2020, respectively. It can be seen that the reduction of NO$_2$ levels in the whole of Thailand occurred in the year of the COVID-19 pandemic.

The comparison of monthly mean NO$_2$ VCD values should deserve special interest to see the overall change between 2019 and 2020. In January 2020, the decline can be seen in minimum, maximum and average NO$_2$ VCD with 13.5%, 17.2% and 5.9% respectively compared to last January. The 15.7%, 4.8% and 6.4% decreases can be seen in minimum, maximum and average NO$_2$ VCDs of February 2020. A significant decline was observed in March 2020, 20.9% at minimum, 25.5% at maximum and 19.9% at average. The next two months, April and May of 2020, also show gentle decrease compared to last year, having around 5% decrease for both months. Overall, 11.8%, 17.2% and 9.1% declines in minimum, maximum and average NO$_2$ VCDs is found during 5-month pandemic period, and the significant difference was also detected ($p = 0.001, p < 0.01$) (Figs. 6 and 7).
Fig. 3. The spatial distribution of NO$_2$ level “Before and During COVID-19 Pandemic” in the whole of Thailand.

Fig. 4. The spatial distribution of NO$_2$ level changes “Before and During COVID-19 Pandemic” in the whole of Thailand.
3.3 NO₂ Level Changes in the Bangkok Metropolitan Area

Although the significant change of the average NO₂ VCD values were not detected between the two periods of before (79.8 µmol m⁻²) and during the pandemic (76.0 µmol m⁻²) in the Bangkok metropolitan area ($p = 0.468$), the NO₂ level decreased 4.8% during the pandemic. The NO₂ VCD values between the periods of before and after curfew regulation during the pandemic were significantly change ($p = 0.014; p < 0.05$), with average values of 81.2 µmol m⁻² and 64.9 µmol m⁻² for before and after curfew regulation, respectively, resulting in a 20.1% decrease in NO₂ level.

Tropospheric NO₂ VCD in the last two weeks of September 2019 was below 75 µmol m⁻². In October 2019, the highest tropospheric NO₂ VCD was 137 µmol m⁻² and the lowest was 28 µmol m⁻², whereas the peak vertical column density in November 2019, was 160 µmol m⁻² and the lowest was 35 µmol m⁻². Between December 9 and 13, 2019, a high VCD was observed in the Bangkok metropolitan area; the maximum value reached 222 µmol m⁻² in December 11, 2019. In January of 2020, the NO₂ level was high for most days of the month. The significant NO₂ VCD values in January were 320 µmol m⁻² on January 10 and 272 µmol m⁻² on January 28. This high NO₂ VCD in

Fig. 5. Comparison of NO₂ levels in the same period (January 13–May 11) of 2019 and 2020 in the whole of Thailand.
Fig. 6. The spatial distribution of NO$_2$ level changes at the same time duration on the monthly basis of the years of 2019 (January 2019–May 2019) and 2020 (January 2020–May 2020) in the whole of Thailand.
Fig. 6. (continued).
Fig. 6. (continued).

Fig. 7. The level of NO2 changes at the same time duration on the monthly basis of the years of 2019 (January 2019–May 2019) and 2020 (January 2020–May 2020) in the whole of Thailand.
January means that the COVID-19 pandemic did not affect the NO$_2$ level at the beginning of its arrival to Thailand. Starting from the beginning of February, we can see a significant decrease in the NO$_2$ level in the Bangkok metropolitan area. In February, the NO$_2$ VCD value was below 100 $\mu$mol m$^{-2}$ for the whole month, apart from a few days. A more remarkable decline can be seen in March; the NO$_2$ VCD value was below 75 $\mu$mol m$^{-2}$ for most days. In April, the NO$_2$ VCD value was around 50 $\mu$mol m$^{-2}$ in the first, second, and third weeks, and a slight rise was observed in the last week. In the period between May 1 and 11, the range of NO$_2$ VCD value was 43–120 $\mu$mol m$^{-2}$ (Fig. 8).

As shown in Table S2, Figs. 9 and 10, the highest reduction of NO$_2$ level during COVID-19 pandemic was in Bangkhuntien (–61.2%), followed by Bang Bon (–61.1%), Nongkheam (–57.5%), Thungkru (–55.9%), while the highest increases of NO$_2$ level occurred in Khlong Sam Wa (+26.4%), followed by Bang Khen (+24.4%), Nong Chok (+22.5%), and Khan Na Yao (+21.4%).

While it is interesting that the NO$_2$ level was lower “during pandemic” compared to “before pandemic,” it deserves to be investigated with the same period of without COVID-19 pandemic. A significant difference was detected between 2019 and 2020, with average NO$_2$ VCD values of 84.3 $\mu$mol m$^{-2}$ and 76.0 $\mu$mol m$^{-2}$, respectively ($p = 0.049$, $p < 0.05$). This indicates that the NO$_2$ level in the Bangkok metropolitan area was reduced in the year of the COVID-19 pandemic. Comparing January of 2019 and 2020, we observed almost the same trend of NO$_2$ level, ranging from 30 to 68 $\mu$mol m$^{-2}$ at the lowest and 250 to 270 $\mu$mol m$^{-2}$ at the highest. In the comparison of 2019 and 2020, there were no significant differences in NO$_2$ levels in February, with NO$_2$ VCD values between 55 and 135 $\mu$mol m$^{-2}$. A significant difference in NO$_2$ level was found when comparing March, 2019 to March 2020. The NO$_2$ VCD value was above 75 $\mu$mol m$^{-2}$ in the nearly whole month of March, 2019, whereas the NO$_2$ VCD value was below 75 $\mu$mol m$^{-2}$ in most days of March, 2020. The same trend can also be seen when comparing April, 2019 to April 2020. In the period between May 1 and 11, the range of NO$_2$ level was 60–120 $\mu$mol m$^{-2}$. These results suggest that the COVID-19 pandemic affected the NO$_2$ level significantly in March and April 2020, in the Bangkok metropolitan area (Fig. 11).

As the comparison of the daily NO$_2$ VCD values is too much detailed to interpret overall change between 2019 and 2020, we also perform change detection analysis on monthly mean and

![NO$_2$ emission in Bangkok Metropolis area “Before and During COVID-19 Pandemic”](image)

**Fig. 8.** NO$_2$ level changes “Before and During COVID-19 Pandemic” in the Bangkok metropolitan area (red line is the trend line).
overall NO₂ VCD change. Comparing monthly mean NO₂ VCD of January of 2019 and 2020, the minimum value increases by 18.8%, the maximum decreases by 1.9%, and the average increases by 5.8%. In February 2020, the minimum and maximum monthly mean NO₂ VCD go down by 8.4% and 17.5 respectively and the average rises by 0.1% compared to last February. A remarkable decline can be seen in March 2020, 27.1% at minimum, 26.0% at maximum and 25.0% at average. The declining trend continues till May, with the average decline 22.0% and 13.0% in April and May. The overall NO₂ VCD change during 5-month period during pandemic is that the minimum, maximum and average values drop 9.4%, 1.9% and 9.8% respectively, with significant difference ($p = 0.001, p < 0.01$) (Figs. 12 and 13).

Moreover, the NO₂ concentration data from the ground station of PCD in the Bangkok metropolitan area show the declining trend during COVID-19 pandemic (2020) and lower level compared to the past 3-years (without COVID-19 pandemic), which is consistent with the trends of Sentinel-5P's satellite-derived NO₂ measurements (Fig. 14(a)). Our comparison also found a highly significant correlation between the data from ground-based NO₂ concentration and tropospheric NO₂ VCD (Fig. 14(b)), indicating that the tropospheric NO₂ column data from the Sentinel-5P's TROPOMI are reliable as the ground-based data.

4 DISCUSSION

The results of this study showed that the NO₂ level increased over the COVID-19 pandemic period from a national perspective (country scale) in Thailand (Figs. 2, 3 and 4). However, a decrease in NO₂ level was observed in the Bangkok metropolitan area (Figs. 8, 9 and 10). This means that the COVID-19 pandemic reduced some economic and human activities, resulting in the decrease of NO₂ levels. However, essential businesses such as food shops, medicine stores,
and gasoline stations, as well as travel to areas within the provinces and inter-provincial travel (if needed) are allowed under lockdown measures in Thailand. Curfew regulations are another measure to end the COVID-19 situation in Thailand. Under the curfew, people were prohibited from staying outside their premises, from 22.00 hr to 04.00 hr, except in case of necessities. Work from home measures aimed to prevent and reduce the spread of COVID-19 by restricting people to stay at home and work. By implementing these measures, traffic pollution in the Bangkok metropolitan area is reduced as the main source of NO₂ emissions, which caused improvement of air quality. However, the overall NO₂ level in the whole of Thailand increased during the COVID-19 pandemic due to the exodus of Thai and foreign workers from Bangkok to their hometowns by personal vehicle, and they still use the vehicle as a normal day at their hometowns. The reason for the return to the hometown is that their workplaces were temporarily closed, resulting in their incomes being insufficient for living in Bangkok. Macromill South East Asia (Thailand) (2020) reported that northeastern Thailand was the biggest destination for traveling back to hometown (28.1%), followed by the northern area (21.3%), and the southern area (18.4%). As could be expected, a personal vehicle was the most popular mode of transport used to return to their hometowns (54.7%) because the personal vehicles maintain appropriate social distancing protocols more effectively than public transportation.

The National Aeronautics and Space Administration (NASA) reported that the reduction of NO₂ emission was first apparent near Wuhan, China, and spread worldwide (NASA, 2020). Our findings in Thailand are consistent with other countries. Paital et al. (2020) concluded that lockdown measures to prevent the spread COVID-19 has helped the environment for self-regeneration such as improving air quality and water pollution in many polluted cities. Tropospheric NO₂ is an important indicator of air pollution (Biswas et al., 2019). During the lockdown, the measure...
caused a significant decreases of NO₂ level by 40–50% in Mumbai, Pune, and Ahmedabad in India (Wright, 2020), 52.68% in Delhi, India (Mahato et al., 2020), 18% in over 22 cities in different regions of India (Sharma et al., 2020), 24.1–32.9% in Rio de Janeiro, Brazil (Dantas et al., 2020), 54.3% in the state of São Paulo, Brazil (Nakada and Urban, 2020), 30% in China (He et al., 2020b; Liu et al., 2020), 24.67% in North China (Bao and Zhang, 2020), 45–51% in Barcelona, Spain (Tobias et al., 2020), 35% in Almaty, Kazakhstan (Kerimray et al., 2020), and 96% in Salé City, Morocco (Otmami et al., 2020). Even though COVID-19 brings the crisis to humans, our environment is given a short period break. In Bangkok, people have experienced cleaner air and blue sky due to the reduction of vehicles on the road. Wild animals and sea animals in Thailand are showing up again due to fewer disturbances from tourists.

Moreover, after comparisons of NO₂ levels in the same period (January 13–May 11) of 2019 and 2020 in the whole of Thailand (Fig. 5) and the Bangkok metropolitan area (Fig. 11) indicates that the decrease of NO₂ levels in 2020 (during COVID-19 pandemic) was due to the reduction of human activities. This is because we found the same trend of NO₂ values between 2019 (without

Fig. 11. Comparison of NO₂ level in the same period (January 13–May 11) of 2019 and 2020 in the Bangkok metropolitan area.
Fig. 12. The spatial distribution of NO\textsubscript{2} level changes at the same time duration on a monthly basis in 2019 (January 2019–May 2019) and 2020 (January 2020–May 2020) in the Bangkok metropolitan area.
Fig. 12. (continued).
Fig. 12. (continued).

Fig. 13. The level of NO$_2$ changes at the same time duration on the monthly basis of the years of 2019 (January 2019–May 2019) and 2020 (January 2020–May 2020) in the Bangkok metropolitan area.
Fig. 14. Comparison of the NO\textsubscript{2} concentration on the monthly basis between the data from ground based NO\textsubscript{2} concentration and tropospheric NO\textsubscript{2} VCD in the Bangkok metropolitan area. (a) Comparison of the NO\textsubscript{2} concentration on the monthly basis between in the year during COVID-19 pandemic (2020) and in the past 3 years (without COVID-19 pandemic), and (b) Linear regression analysis between the data from ground-based NO\textsubscript{2} concentration in 2020 and tropospheric NO\textsubscript{2} VCD in 2020. Remark for Fig. 14(b): (1) This graph is presented the data from January to October 2020 due to the ground-based NO\textsubscript{2} concentrations data were not available on November and December 2020; (2) Meanwhile, the average NO\textsubscript{2} VCD values from Sentinel-5P satellite were 130.4 µmol m\textsuperscript{-2} and 210.9 µmol m\textsuperscript{-2} on November and December 2020, respectively.

COVID-19 pandemic) and 2020 (Figs. 5 and 11), which may not due to the seasonal cycles of NO\textsubscript{2}. Based on the study by Lalitaporn (2017), who used tropospheric NO\textsubscript{2} columns retrieved from the Ozone Monitoring Instrument (OMI) satellite during 2008-2015 over six regions of Thailand; the
central region had the highest level of NO$_2$ followed by the eastern, northern, northeastern, and southern regions. In the northern and northeastern regions, the maximum levels of NO$_2$ were detected during January–April; this coincides with the burning period for agricultural residues (e.g., rice, maize, and sugarcane), which peaks in March; there are also forest fires in some areas during this time (Lalitaporn; 2017; Arunrat et al., 2018, 2020; Sereenonchai et al., 2020; Arunrat et al., 2021). This is similar with the result in Figs. 6 and 7 of this study. For the central and eastern regions, the highest values of NO$_2$ VCDs were observed during the winter (November–February), which is the dry period. In the southern region, the highest levels were during November–April on the west coast and May–October on the east coast (Lalitaporn, 2017). Furthermore, a study by Ghude et al. (2009) indicated that high levels of NO$_2$ VCDs were detected in the central region of Thailand during 2003–2006, and around the Map Ta Phut Industrial Estate in the eastern region, where the petrochemical and related industries are located. As compared with these studies, we assured that NO$_2$ levels were dropped due to the changes of human activities under lockdown, work from home, and curfew measures during COVID-19 pandemic. This is because the same pattern change of NO$_2$ levels of each month of each region on this study (Figs. 6, 7, 12, and 13) are consistent with the previous studies. Our results are also consistent with Kanniah et al. (2020), who used aerosol optical depth (AOD) observations from Himawari-8 satellite and tropospheric NO$_2$ column density from Aura-OMI to analyze the changes of air pollution over Malaysia and Southeast Asian countries. They found a reduction of NO$_2$ levels during the COVID-19 lockdown in Bangkok (−22%), Jakarta (−34%), and Phnom Penh (−6%), compared to the same time during the baseline (2015–2019).

In this study, we did not try to judge whether lockdown, work from home, and curfew measures are perfect or poor implementations because it is still the controversial issues in various aspects. Although lower NO$_2$ levels during the COVID-19 pandemic is a short-term change, all sectors should learn the pros and cons of these measures in order to long-term planning. Hence, the challenge after the COVID-19 pandemic is how to improve and protect our environment while restoring the economy, which is a crucial issue that policymakers should fully address.

5 RECOMMENDATIONS

Although we have some evidences about the decline of NO$_2$ level during COVID-19 pandemic, there are still some limitations and shortcomings in this paper. We use Sentinel-5P NRTI NO$_2$ dataset in this research. Since this dataset is only available on Google Earth Engine platform starting from July 2018, the longer time-scale fluctuation studies cannot be implemented to prove if the NO$_2$ decline during pandemic is seasonal or not. Only comparison of monthly mean NO$_2$ emission of 2019 and 2020 can be made in this study. The dataset of tropospheric NO$_2$ columns from the Ozone Monitoring Instrument (OMI) aboard the NASA Aura spacecraft, which has been in service since 2004 should be used combining with tropospheric NO$_2$ column data from the Sentinel-5P’s TROPOMI to do the longer time-series analysis in further studies. Moreover, we recommend investigating the correlation of NO$_2$ level fluctuation with other contributing factors for further studies, such as other meteorological factors, and regional transport of pollutants. Besides, as Bangkok metropolitan area is a hotspot area where approximately 50% of COVID-19 cases are observed, more detailed studies should be done by integrating available satellite data and ground measurement data in sub-district scale.

6 CONCLUSION

In the whole of Thailand, the average NO$_2$ VCD values increased by 47.4% during the COVID-19 pandemic, but it was decreased by 4.8% in the Bangkok metropolitan area; however, there was not a significant difference compared to before the COVID-19 pandemic. These results indicate that human activities, especially the combustion of fossil fuels were not reduced in the whole of Thailand, whereas the reduction NO$_2$ level in the Bangkok metropolitan area was due to people leaving Bangkok to return their hometown during the COVID-19 pandemic. The NO$_2$ level decreased by 9.5% in the whole of Thailand after the curfew regulation was imposed, while it helpfully decreased by 20.1% in the Bangkok metropolitan area. After comparing the same time
duration in 2019 and 2020 on a monthly basis, the results revealed that NO2 level in 2020 declined by 9.1% and 9.8% for the whole of Thailand and Bangkok metropolitan area, respectively. Our findings support that these measures can temporarily reduce NO2 levels. Once all sectors resume as normal, we concern that the amount of NO2 emissions will rebound.

ADDITIONAL INFORMATION

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://doi.org/10.4209/aaqr.200440

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