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

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Air pollution impacts from COVID-19 pandemic control strategies in Malaysia

Murnira Othmana,*, Mohd Talib Latifb

a Institute for Environment and Development (LESTARI), Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia
b Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia

Abstract

Mitigation measures and control strategies relating to novel coronavirus disease 2019 (COVID-19) have been widely applied in many countries in order to reduce the transmission of this pandemic disease. A Movement Control Order (MCO) was implemented in Malaysia starting from the March 18, 2020 as a pandemic control strategy which restricted all movement and daily outdoor activities. To investigate the impact of MCO, air pollutants: particulate matter with an aerodynamic diameter less than 10 μm (PM10), particulate matter with an aerodynamic diameter less than 2.5 μm (PM2.5), sulphur dioxide (SO2), nitrogen dioxide (NO2), ozone (O3) and carbon monoxide (CO) in nine major cities in Malaysia were measured before and during the implementation of the MCO. The non-carcinogenic health risk assessments of the air pollutants are also determined using the United States Environmental Protection Agency (USEPA) Health Risk Assessment method. Overall, NO2 recorded an average percentage reduction of 40% with the highest reduction observed at Kota Kinabalu (62%). The largest reductions of PM10, PM2.5, SO2, O3 and CO were recorded at Kota Kinabalu (17%), Kuantan (9.5%), Alor Star (38%), Kota Bharu (15%), and Ipoh (27%) respectively. All cities had hazard quotient (HQ) values of <1 suggesting no non-carcinogenic health effects. The highest HQ was observed for PM2.5 during the MCO period (4.53E-02) in Kuala Lumpur. An average hazard index (HI) value of 1.44E-01 (before the MCO) and 1.40E-01 (during the MCO) showed higher human health risks before the MCO than during the MCO. This study gives confidence to regulatory bodies that the reduction of human activities significantly reduces air pollution and increases human health and so good air pollution control strategies can provide crucial impacts, especially in reducing air pollution and improving human health.

© 2021 Elsevier Ltd. All rights reserved.

1. Introduction

Anthropogenic air pollutants are of concern to human health, especially in urban areas where economic activities and rapid industrialization are associated with poor air pollution. Studies on air pollution and human health have been performed in order to explore links between air pollution and human health in terms of toxicity effects (Hanedar et al., 2013), DNA damage (Kalemba-Drozdz, 2015), reduced lung function (Panis et al., 2017), preterm delivery for pregnant women (Sun et al., 2019), mutagenic effects (Feretti et al., 2019), mortality and morbidity (Gallouros et al., 2020; Sarnat et al., 2008) and cardiopulmonary disease (Wang et al., 2018). There are also links between elevated risk of hospital admissions and severe air pollution episodes which indicates the crucial relationship between air pollution and human health. Significant health affects due to the respiratory disease Coronavirus SARS-CoV-2 (COVID-19) have impacted almost all countries in the world; this epidemic is characterized as a pandemic due to its impact worldwide. COVID-19 was first identified in December 2019 near Wuhan, China. Up to the April 20, 2020, there was a total of 2,314,621 cases of COVID-19 in the world and the risk assessment was characterized as very high (WHO, 2020). The initial cause of this pandemic is Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) which affects the lower respiratory tract and acts in a similar way to pneumonia (Sohrabi et al., 2020). The symptoms of COVID-19 are fever, cough and dyspnoea (Ogen, 2020). COVID-19 was suggested to be spread by direct contact due to touching an infected person or a surface that an infected person has touched and droplets that contain the virus can remain stable for few days (Morawska and Cao, 2020). Due to the highly contagious nature of this virus, strict epidemic and pandemic control strategies have been implemented in China and other infected countries.
In Malaysia, COVID-19 control strategies were implemented and named a movement control order (MCO) starting from the March 18, 2020 with phases 1, 2 and 3 (Nadzir et al., 2020). The MCO in Malaysia prohibits any government and private operations except for several important sectors. No educational activities by universities and schools are allowed, with day care and shopping complexes also being closed. Mass gathering are also prohibited and tourism and recreational activities are restricted. The MCO aims to reduce the transmission of COVID-19 nationally. A study on COVID-19 control measures in China found that the implementation of control measures successfully reduced the eventual epidemic size, suggesting strict monitoring and early detection of COVID-19 cases should remain in place until the end of April 2020 (Yang et al., 2020). Moreover, the scenario of the lockdown event in China was studied to investigate the influence of emissions reduction due to reduced anthropogenic activities. A decrease in PM2.5 was observed between 5.35 and 30.79 μg m⁻³ (Wang et al., 2020).

Previous studies (as shown in Table S1) critically investigated lockdown effects toward concentrations of air pollutants (Abdullah et al., 2020; Nakada and Urban, 2020; Tanzer-Gruener et al., 2020; Tobias et al., 2020; Venter et al., 2021; Yuan et al., 2021); air pollution relationship with COVID-19 cases (Accarino et al., 2021; Tello-Leal and Macías-Hernández, 2020); meteorology and air pollutants changes (Hossain et al., 2021; Sulaymon et al., 2021); traffic and mobility changes (Aoi et al., 2020); and the application of statistical and modelling (Bao and Zhang, 2020; He et al., 2020; Liu et al., 2020b) while this study focuses mainly on air pollutants effects in cities with the analysis related to population exposure to non-carcinogenic risks. The COVID-19 pandemic affected human activities, primarily when the MCO was implemented to reduce the chain of infection among the population in Malaysia. Thus, the aim of this study is to investigate the potential changes in concentrations of air pollutants caused by MCO in nine major cities in Malaysia, which had different types of economic activities and number of populations. Differences in air pollutant concentrations before and during the MCO period were evaluated in order to understand the impact of changes in emission on air pollution and human health, in particular on inhalation of non-carcinogenic pollutants for the city population. As the research related to the impact of reduced outdoor activities and COVID-19 pandemic mitigation measures in major cities in Malaysia have not been studied to present, therefore, this study may provide some background reference to the concentration of air pollution for the impact of “stay at home” strategy. In order to achieve this, the result of this study will provide insight into the implementation of policies aimed at reducing air pollution in a sector such as transportation, especially in the city.

2. Materials and method

2.1. Study area

In this study, nine major cities in Malaysia covering different regions, the North, Central, South, East Coast and West Malaysia, were chosen. The cities were Kuala Lumpur (Central); Seremban and Johor Bahru (South); Kuantan and Kota Bharu (East Coast); Kuching and Kota Kinabalu (East Malaysia); and Ipoh and Alor Star (North). Kuala Lumpur is the capital city of Malaysia known to have experienced rapid development, especially industrial activities such as manufacturing, factories, processing, shipping and tourism. The locations of the selected cities in this study are shown in Fig. S1.

2.2. Data collection

The MCO in Malaysia started on the March 18, 2020 where almost all economic and daily activities were restricted in order to reduce the transmission of the COVID-19 disease. The concentrations of the air pollutants, PM10, PM2.5, SO2, NO2, O3 and CO before the MCO (January 1 to March 17, 2020) were compiled and compared with the concentrations during the MCO period (March 18 until April 21, 2020).

The hourly air pollution dataset recorded at the Continuous Air Quality Monitoring Station (CAQMS) was obtained from the Malaysian Department of Environment (DOE). The instrument used for the measurements of PM10 and PM2.5 was a Thermo Scientific Model TEOM 1450-Df while for SO2, NO2, CO and O3 the instruments were Thermo Scientific Models 431, 421, 48i and 49i respectively. Each instrument was calibrated monthly to ensure the accuracy and precision. The concentration of each pollutant was determined at 10 min intervals and then calculated for 1 h averages.

The numbers of COVID-19 cases for each state in Malaysia are published daily by the Malaysian Ministry of Health (http://covid-19.moh.gov.my/) and were mapped using ArcGIS Version 10.5 (ESRI Inc, United States).

2.3. Air mass trajectories

Air mass trajectories for 5 days backward analysis for Kuala Lumpur were simulated for before MCO and during MCO using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPIT) developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL). The longitude and latitude of the modelled backward trajectories was 3.1390 N, 101.6869 E with input meteorological data from Global Data Assimilation System (GDAS) 1.0 × 1.0 resolution global data.

2.4. Statistical analysis

A descriptive analysis was performed to explore the city-specific characteristics of air pollutants. Statistical analyses (t-test and one-way ANOVA) were used to investigate the relationship of air pollutant concentrations between cities and the effects of the MCO on air pollutants. SPSS V. 21 and Openair packages R software (Carslaw, 2015) were used for the statistical analyses in this study.

2.5. Health risk assessment

In this study, health risk assessments were performed for the non-carcinogenic risk to exposure by inhalation of ambient PM10, PM2.5, SO2, NO2, O3 and CO based on the USEPA Risk Assessment Guidance for Superfund (USEPA, 2009). The exposure concentration (EC) was calculated as in Eq. (1):

\[
EC = \frac{CA \times ET \times EF \times ED}{AT}
\]

where CA is the pollutant concentration (μg m⁻³ or ppb), ET is exposure time (24 h), EF is the exposure frequency (30 days), ED is the exposure duration (1 year) and AT is the averaging time (ED × 365 days year⁻¹ × 24 h day⁻¹). The hazard quotients (HQ) for non-carcinogenic risk were calculated by dividing the EC with the reference exposure level (REL) which is a toxic threshold dose (Matroane and Diah, 2003). In this study, the Standard 2020 for air pollutants implemented under the Malaysia Ambient Air Quality...
Standard was used, where REL values are 100 \mu g m^{-3} for PM_{10}, 35 \mu g m^{-3} for PM_{2.5}, 80 \mu g m^{-3} for SO_{2}, 70 \mu g m^{-3} for NO_{2}, 100 \mu g m^{-3} for O_{3} and 10 \mu g m^{-3} for CO. HQ values of <1 suggest no significant risk of non-carcinogenic effects from air pollutants (Othman et al., 2020). Notation of all abbreviations is listed in Table S2.

3. Results and discussion

3.1. COVID-19 cases in Malaysia

As of April 20, 2020, a total of 5,425 cases of COVID-19 were reported in Malaysia and the fractions by states are shown in Fig. S2. The highest number of cases was recorded in Selangor state with 1,352 cases, of which 1,008 were in Kuala Lumpur. These numbers reflect the high population of these areas. During the study period (February 18 to April 20, 2020) there were 89 deaths in Malaysia reported due to COVID-19. The COVID-19 pandemic had significantly impacted almost all countries in the world.

The results show that the highest numbers of cases were recorded in the high-population city of Kuala Lumpur. The numbers of COVID-19 cases are suggested to increase in the weeks ahead. The relationship of COVID-19 cases and meteorological factors was studied by Liu et al. (2020) where the results indicated that COVID-19 transmission may be favoured by low temperatures, mild diurnal temperature ranges and low humidity, while a study by Ma et al. (2020) found significant positive relationship between daily temperature and the daily mortality from COVID-19 and a negative relationship between COVID-19 mortality and relative humidity. Moreover, as exposure to high air pollution concentration can cause several health problems, such as cardiovascular disease, heart problem and respiratory diseases, especially in city areas, it is one of the possible causes of infection with COVID-19 disease. As reported by Conticini et al. (2020) and Ogen (2020) exposure to atmospheric pollution can cause cilia, and the upper airways defence may be weakened, which explains the higher prevalence and lethality of COVID-19. Zhu et al. (2020) who studied the association between air pollution and COVID-19 cases, had found that there is a statistically significant relationship between air pollution and COVID-19 infection, suggesting that further laboratory analysis is crucial to the investigation of the air pollution-related mechanism and the COVID-19 pandemic.

3.2. Characteristics of air pollutants before and during MCO

Fig. 1a to Fig. 1f illustrate the daily 24 h average concentrations of six criteria air pollutants in Kuala Lumpur, Alor Star, Ipoh, Seremban, Johor Bahru, Kuantan, Kota Bharu, Kuching and Kota Kinabalu. The measurements were divided into two periods, before the MCO (January 1, 2020 to March 17, 2020) and during the MCO (March 18 to April 21, 2020). A descriptive summary of each pollutant is given in Table S3. The calculated average daily, weekday and monthly concentrations are illustrated in Fig. 2 to Fig. 4.

3.2.1. PM_{10} and PM_{2.5}

PM_{10} and PM_{2.5} had similar trends with no clear decreasing concentrations after the MCO was implemented in all cities (Fig. 1a and b). Moreover, peaks in concentrations were observed in Alor Star, Ipoh and Kota Kinabalu in the early part of the MCO while Kota Bharu had the highest peak during the MCO on April 7, 2020. A similar trend of PM_{10} and PM_{2.5} concentrations were determined for Kuala Lumpur and Seremban city. The highest mean of PM_{10} was recorded at Kota Bharu with a mean concentration of 26.7 \mu g m^{-3} (range 4.98–74.6 \mu g m^{-3}) before the MCO and a mean concentration of 25.0 \mu g m^{-2} (range 3.95–203 \mu g m^{-3}) during the MCO. For PM_{2.5}, the highest mean was recorded at Kuala Lumpur for both before and during MCO period with a mean concentration of 18.6 \mu g m^{-3} and range of 0.26–133 \mu g m^{-3} for before the MCO period and a mean concentration of 19.3 \mu g m^{-3} and range of 0.24–172 \mu g m^{-3} during the MCO (Table S3). A reduction in PM_{10} concentrations during the MCO was recorded at all cities except Alor Star (which showed an increase of 11.2%) while for PM_{2.5} a reduction in concentrations was recorded for Kuantan (9.5% reduction), Kuching (4.6% reduction) and Kota Kinabalu (3.4% reduction). Statistical analysis (t-test) showed that there were significant differences (r < 0.05) in PM_{10} and PM_{2.5} concentrations before and during the MCO period at all cities. We also examined the impact of MCO on the level of air quality using the difference in differences (DiD) model. For this analysis, 2019 data was used as a control group, while MCO was used as a treatment group. The result is shown in Table S4. Negative values of DiD suggested that there were reduction of air pollutant concentration after MCO was implemented. Cities such as Kota Kinabalu, Kuantan and Kuching recorded negative DiD values for PM_{10} while only Kuching had a negative DiD value for PM_{2.5} that suggested a decrease in concentration during MCO.

PM_{10} and PM_{2.5} concentrations were found to have peak concentrations at midnight in Alor Star, Ipoh, Kota Bharu and Kota Kinabalu while for Kota Bharu, a steady increase in concentrations was observed in the early morning followed by decreases until around 18:00 (Fig. 2a and b). Two clear peaks between 12:00 and 18:00 were observed for Kota Kinabalu before the MCO period with maximum values of 60 \mu g m^{-3} (PM_{10}) and 40 \mu g m^{-3} (PM_{2.5}). When comparing PM_{10} and PM_{2.5} concentrations between months, a clear reduction was observed only for Alor Star, Ipoh, Johor Bahru and Kota Kinabalu in April 2020 which is in the MCO period. PM_{10} and PM_{2.5} concentrations were also analysed for their variations during days in the week where, during the MCO, higher concentrations were observed on Wednesday in Alor Star and on Saturdays for Kota Bharu for both PM_{10} and PM_{2.5}. Higher PM_{10} concentrations for all days were observed before the MCO compared to during the MCO in Kuantan, Kuching, Kota Kinabalu and Johor Bahru, while for PM_{2.5}, higher concentrations were observed during the MCO compared to before the MCO for Alor Star and Kota Bharu for all days of the week.

Slightly higher PM_{2.5} concentrations during the MCO compared to before the MCO suggested contributions from regional sources, e.g. transport of air masses and the resuspension of dust. Five day trajectories of air masses arriving in Kuala Lumpur during the MCO showed the contribution of two wind directions, one from the South China Sea and one from Northern Peninsular Malaysia while before the MCO period, air masses were from the South China Sea (Fig. S3). From these trajectories, it can be seen that regional sources can be factors in air pollutant variation, especially for fine particulates. Moreover, during the MCO, lorries used for the transportation of food and crucial supplies were not prohibited and thus the concentrations of both PM_{10} and PM_{2.5} may have originated from these transportation activities and the resuspension of dust for Kuala Lumpur city. Amato et al. (2009) reported that dust resuspension, particularly road dust, plays a significant role in PM concentrations for urban areas. On the contrary, a reduction in PM_{2.5} concentrations was suggested by Bao and Zhang (2020), He et al. (2020), Liu et al. (2020a), Sulaymon et al. (2021) and Wang et al. (2020) during the COVID-19 outbreak where lockdown had been implemented in China. Reductions in PM_{10} and PM_{2.5} were reported to be 31% and 43% during the lockdown period in India which suggested the effects of lockdown and restricted human activities were substantial (Sharma et al., 2020) while reductions of up to 58% in PM_{2.5} concentrations in Malaysia were thought to be linked to the restrictions of activities in Malaysia such as mass
gatherings and the closure of government and private agencies (Abdullah et al., 2020). Higher drop of PM$_{10}$ and PM$_{2.5}$ concentration during the pollution control measures for APEC Meeting in Beijing, China was recorded by Li et al. (2017) compared to this study where the control measures had provided short-term enhancement in air quality. PM$_{10}$ and PM$_{2.5}$ can significantly reduce with continually upgrading the quality of gasoline with additional systematic design of series of policies to mitigate PM pollution (Yang et al., 2020a).

3.2.2. SO$_2$

SO$_2$ showed increasing concentrations from the beginning of the

Fig. 1. Daily 24 h averages of a). PM$_{10}$, b). PM$_{2.5}$, c). SO$_2$, d). NO$_2$, e). O$_3$ and f). CO concentration of major cities in Malaysia.
year 2020 until the early part of the MCO and then decreasing concentrations after the first few days of the MCO in Kota Kinabalu city (Fig. 1c). A similar trend was also recorded at Kuantan with a sudden drop in SO$_2$ concentrations in the middle of the MCO period. The opposite trend was exhibited at Johor Bahru where a steady increase in SO$_2$ concentrations was recorded from the beginning of 2020 which continued during the MCO period. Kuala Lumpur and Seremban both had fluctuating concentrations before the MCO while during the MCO no clear reduction of concentration was observed. As listed in Table S3, the highest mean concentration of SO$_2$ both before and during the MCO was from Johor Bahru with concentrations of 1.60 ppb and 1.88 ppb respectively. The average daily SO$_2$ concentrations during the MCO were 0.9 times lower (an average reduction of 39%) than before the MCO at all cities (except Johor Bahru and Kuching), with significant differences ($r < 0.05$) between concentrations before and during the MCO. The result of the DiD model (Table S4) suggested that Seremban, Kota Kinabalu, Alor Star, Kuantan had reduced SO$_2$ concentration after MCO had been established.

Hourly SO$_2$ average concentrations were observed to be higher before the MCO compared to during the MCO at Alor Star, Ipoh, Kota Kinabalu, Kuala Lumpur and Seremban (Fig. 3a). A clear distinction of hourly average SO$_2$ concentrations before and during the MCO were observed at Seremban, where the highest concentration before the MCO was recorded between 06:00 to 12:00. Johor Bahru had higher hourly SO$_2$ concentrations during the MCO compared to before the MCO but the other cities had the opposite pattern, with higher hourly SO$_2$ concentrations before the MCO compared to during the MCO period. Monthly concentrations of SO$_2$ showed decreases at Kota Kinabalu, Kuantan and Seremban while other cities had either increases or constant trends in the monthly concentrations of SO$_2$.

SO$_2$ concentrations were expected to decrease due to reduced industrial activities in Malaysia during the MCO, while the increase in concentrations at Johor Bahru suggest that the nearby coal-fired power plant influenced SO$_2$ concentrations as they were observed to be higher here for both before MCO and during MCO compared to other cities. SO$_2$ concentration can further transported to other places from industries and power plant that have massive emission of SO$_2$ (Shen et al., 2017). Sharma et al. (2020) reported that increased SO$_2$ concentrations in 2020 during the lockdown may be due to coal-fired powered plant contributions while Tobias et al. (2020) suggested the rising SO$_2$ concentrations were from shipping emissions. Mahato et al. (2020) reported only small changes in SO$_2$ concentrations compared to other air pollutants after the lockdown event in Delhi, India during the COVID-19 pandemic. This was likely to be due to the location of Delhi as it is inland and would generally experience low SO$_2$ concentrations. Compared to other studies, higher reduction of SO$_2$ than this study was observed (Nakada and Urban, 2020; Sulaymon et al., 2021; Tobias et al., 2020; Yuan et al., 2021) which suggested that the different levels of SO$_2$ during the regular day without lockdown could be unlikely due to

![Fig. 2. Variation of a). PM$_{10}$ and b). PM$_{2.5}$ before MCO and during MCO calculated for hourly, weekday and monthly concentration.](image-url)
different intensity and source of SO₂ concentration, which in turns provide different percentages of reduction. Furthermore, the effect of strengthened air pollution regulation during the APEC Meeting and the Victory-day Parade in Beijing; and World Internet Conference in Jiaxing which had reported reduction of 56.5% and 7.1% which suggested effectiveness of stringent regulation to reduced air pollution (Li et al., 2017; Shen et al., 2017).

3.2.3. NO₂

All cities showed decreasing concentrations of NO₂ during the MCO, except for Alor Star which had peak concentrations during the MCO (Fig. 1d). Some cities, for instance Kota Bharu, Kota Kinabalu, Kuantan and Kuching, showed small variations in concentrations with no obvious peak in concentrations either before or during the MCO. Kuala Lumpur had fluctuations in NO₂ before the MCO with a minimum value of 0.01 ppb and maximum value of 42.9 ppb, while during the MCO the minimum value was 0.008 ppb and maximum value was 22.2 ppb (Table S3). The result from DiD model (as shown in Table S4) had negative values for all cities except for Kota Bharu, Johor Bahru and Alor Star, which indicated no significant impact of MCO towards NO₂ concentration in these cities.

The calculated hourly and weekday trends of NO₂ clearly showed that higher concentrations were observed before the MCO compared to during the MCO, except for Alor Star and Kota Bharu (Fig. 3b). Almost all cities had peak concentrations between 06:00 and 12:00 while another peak was observed at night (18:00 to 23:00) for Ipoh, Johor Bahru, Kota Kinabalu, Kuala Lumpur, and Seremban. Decreases in the calculated average monthly concentrations of NO₂ were observed in Alor Star, Ipoh, Johor Bahru, Kuala Lumpur and Seremban. Higher NO₂ concentration during lockdown were observed by Bao and Zhang (2020), Nakada and Urban (2020), Sulaymon et al. (2021) and Tobias et al. (2020) compared to the MCO period in this study indicating that NO₂ concentration may depend on the specific sources and local contribution.

Significant decreases in NO₂ concentrations after the implementation of the MCO were caused by the reduced number of motor vehicles on the roads as human activities were reduced. Reduced concentrations of NO₂ were clearly observed in Kuala Lumpur and Seremban. These cities are close to each other and usually have high numbers of motor vehicles used to commute between these cities on a normal day. Moreover, a significant peak of NO₂ was observed on the March 13 for Kuala Lumpur and Seremban, a date that marked the beginning of a school holiday in Malaysia and thus unusual traffic movements were suggested to be due to family activities such as visiting home towns and tourism activities. A similar result was obtained by Tobias et al. (2020) where peak concentrations before the lockdown and significant variations in NO₂ were suggested to be due to reduced emissions from combustion process, road traffic, power generation and shipping. A study by Dantas et al. (2020) reported a reduction of NO₂ concentrations in the city of Rio de Janeiro, Brazil where NO₂
was suggested to be decreased due to the decrease of 80% of the vehicle movements and other factors, for instance transport of air masses and meteorological parameters. Ogen (2020) assessed the levels of NO$_2$ over Europe using TROPOMI data which indicated that high NO$_2$ concentrations are often associated with downward airflows providing increased NO$_2$ near to the earth’s surface and this combined with topographic structures and atmospheric conditions means NO$_2$, along with other air pollutants, was not dispersed.

3.2.4. O$_3$

The mean concentrations of O$_3$ before the MCO in the studied cities were in the sequence Alor Star > Ipoh > Seremban > Kuantan > Kuala Lumpur > Johor Bahru > Kota Bharu > Kota Kinabalu > Kuching while the sequence during the MCO was Alor Star > Seremban > Ipoh > Kuala Lumpur > Kuantan > Johor Bahru > Kota Kinabalu > Kota Bharu > Kuching (Table S3). No clear trend in O$_3$ concentrations was observed during either period (before and during the MCO) for all cities (Fig. 1e). However, similar trends of O$_3$ were observed for Kuala Lumpur and Seremban where the highest peak concentration was observed at the end of January 2020 before the MCO period and another peak was seen in the early part of the MCO. Only Ipoh, Kuantan, Kota Bharu and Kuching had reduced O$_3$ concentrations after the implementation of the MCO with an average percentage reduction of 0.8%. The $t$-test indicated that no significant difference ($r > 0.05$) was observed for O$_3$ concentrations before and during the MCO period, while DiD model result (Table S4) indicated that only Kuala Lumpur and Ipoh had reductions of O$_3$ during the MCO period.

Hourly average of O$_3$ concentrations clearly showed similar trends before and during the MCO in all cities, with increasing concentrations after 06:00 until 12:00 and then rapid decreases after 12:00 for all cities except for Seremban which had highest peak concentrations in the late afternoon (17:00) (Fig. 4a). For weekday average concentrations, only Kota Bharu had higher O$_3$ concentrations before the MCO on all days of the week compared to before the MCO. Monthly average concentrations showed decreases during the MCO in April for Alor Star, Kuala Lumpur, Kuantan, and Seremban while other cities had increasing or stable O$_3$ concentrations during the MCO period.

This study found that O$_3$ concentrations were not affected by the MCO and this is suggested to be due to the continuous production of O$_3$ via photochemical reactions. O$_3$ is a component of photochemical smog and formed through a reaction involving NOx and VOCs in the presence of sunlight where both NOx and VOCs are suggested to originate from traffic (Zhang et al., 2011). With the reduction in O$_3$ precursors such as NOx, O$_3$ concentration will increase with the added effect of titration ($\text{NO} + \text{O}_3 = \text{NO}_2 + \text{O}_2$) (Mahato et al., 2020). Agreeing with the result from this study, Li et al. (2017) had also found that higher O$_3$ concentration after regulatory approached to reduced air pollutants in Beijing. Comparisons of O$_3$ concentrations before and after seasonal

![Fig. 4. Variation of a), O$_3$ and b), CO before MCO and during MCO calculated for hourly, monthly and weekday concentration.](image-url)
holidays conducted in China and Taiwan showed higher O3 concentrations were observed during the holiday period due to the NO titration effect (Chen et al., 2019; Tan et al., 2009; Xu et al., 2017). A study by Tan et al. (2009) on the holiday effect in China reported higher O3 concentrations during the Chinese New Year holiday compared to non-Chinese New Year holiday periods which was thought to be due to factors such as carry forward emissions, NO titration and the effect of dust storms.

3.2.5. CO

The average mean concentration of CO in all cities before the MCO period was 0.53 ppm which is about 0.94 times higher compared to the mean concentration during the MCO period (Table S3). Significant differences in CO concentrations before and during the MCO for all cities were seen using a t-test (r < 0.05) with an average reduction of 1.2%. The CO concentrations in Kuala Lumpur recorded a large range, between 0.55 ppm and 1.57 ppm during the MCO while range concentrations between 0.07 ppm and 2.75 ppm were observed before the MCO, with a small reduction of 1.1% after the MCO was implemented. The two highest peaks were observed in the second week of February 2020 and March 2020 for 24 h average CO concentrations in Kuala Lumpur with concentrations above 1.2 ppm while several other peaks were also observed during the January 1, 2020 to the April 17, 2020 (Fig. 1f). Based on Table S4, the negative value of DD was only observed for Kuala Lumpur and Kuching (significance at 1%), which suggested a reduced CO concentration with not a much difference for CO concentration during the MCO period compared to the previous year.

For hourly CO variation, peak concentrations were observed between 06:00 to 12:00 before the MCO in Seremban, Kuala Lumpur, Johor Bahru, Kuching, Alor Star and Ipoh. Moreover, only Alor Star and Kuching had higher hourly concentrations during the MCO compared to before the MCO (Fig. 4b). For weekday averages, all days in the week had similar concentrations with no obvious peaks. Monthly variations of CO indicated decreasing monthly concentrations for Alor Star and Kuching during the MCO. Before the MCO, Kuala Lumpur recorded a rapid increase in concentrations from January 2020 to March 2020.

The reduced concentrations of CO can be attributed to restricted movement after the MCO was implemented, particularly due to reduced vehicle emissions. CO emissions are strongly related to local emission sources, particularly road traffic where higher CO concentrations have been recorded in high traffic areas (Azhari et al., 2018; Jang et al., 2017). A study by Mahato et al. (2020) recorded a reduction in CO of 36.84% in the megacity of Delhi, thought to be due to factors such as carry forward emissions, NO emissions and the incomplete combustion of fuel. CO and NO2 were observed to have a moderate relationship with both PM10 and PM2.5, suggesting these pollutants have similar sources.

3.4. Health risk assessment

The hazard quotient (HQ) values for non-carcinogenic exposure to air pollutants are reported in Table 1. Overall, higher HQ values for all pollutants were observed before the MCO compared to during the MCO except for PM2.5 and O3. The total HQ value is indicated by the hazard index (HI) which recorded a reduction of 11% for PM10 and SO2, 81% for NO2 and 3% for O3 and an increase of 3% for PM2.5 and 10% for O3 during the MCO. Among all pollutants, the highest HQ values were observed for PM2.5 at Kuala Lumpur both before the MCO (4.37E-02) and during the MCO (4.53E-02) while Kuala Lumpur also recorded the highest total HQ value for air pollutants with values of 7.43E-02 (before the MCO) and 1.19E-01 during the MCO. The sequence of non-carcinogenic exposure was PM2.5 > PM10 > O3 > NO2 > CO > SO2 before the MCO while during the MCO it was PM2.5 > PM10 > O3 > NO2 > CO > SO2.

The results for HQ and HI were lower than the acceptable limit of 1.0, indicating that there is no significant non-carcinogenic risk from air pollutant exposure either before or during the MCO. Higher HQ values for PM2.5 compared to other pollutants clearly indicate the greater non-carcinogenic risk posed by fine particles, while the population of Kuala Lumpur are exposed to a higher risk from air pollutants compared to other cities. Non-carcinogenic health risks in Kuala Lumpur showed a HI value of 0.28 for an adult during a non-haze day in Kuala Lumpur while the inhalation of O3 was shown to pose a health risk to the population in Kuala Lumpur (Sulong et al., 2017). A study by Othman et al. (2020) had higher HQ values for O3 rather than PM2.5 in outdoor air which is inconsistent with this study. This could be due to the strong outdoor sources such as traffic and human activities. Studies on human health risks are usually performed based on inhalation, ingestion and dermal routes for metals and exposure calculations can be different based on exposure duration, time, frequency and body weight. Moreover, calculation of the excess risk of the population described by Sharma et al. (2020) was attempted but due to low 24 h concentrations of all air pollutants compared to the Standard 2020 for air pollutants implemented under the Malaysia Ambient Air Quality Standard, no excess health risk of air pollutants was suggested.

With the result of this study, clear policies on vehicle emission and improving of current standard of fuel are needed for example in city of Kuala Lumpur with high population thus mitigating the emission of fine PM and health risk area crucial.

4. Conclusion and policy implication

In this study, the impact of the MCO due to the COVID-19
Overall, the highest reduction in air pollutants was observed for NO$_2$ with an average percentage of 40%. Reductions of more than 50% NO$_2$ after the MCO was implemented were recorded at Kuala Lumpur (54%), Ipoh (58%), Seremban (50%), Kuantan (54%) and Kota Kinabalu (62%). PM$_{2.5}$ showed an increase in concentrations of between 0.10 and 2.90 $\mu$g/m$^3$ after the MCO at Kuala Lumpur, Alor Star, Ipoh, Seremban, Johor Bahru and Kota Bharu. On top of that, the concentrations of the six criteria air pollutants after the implementation of the MCO were significantly different to those before ($r < 0.05$) except for O$_3$. No non-carcinogenic risk exposure was recorded either before or during the MCO with HQ values of $<1.0$ in all cities. However, higher health risks from air pollutants were observed in Kuala Lumpur compared to other cities.

From the results obtained, this study provided evidence that the Malaysian Government’s initiatives to reduce the transmission of
the COVID-19 pandemic have a significant impact on the air pollutants concentration in Malaysia. Moreover, it can be said that reduced human outdoor activities, vehicle emissions and coal-fired power plant emissions play significant roles in achieving cleaner air. The results of this study can also help the respective government body to identify the concentration of air pollutants in each of the cities as a benchmark for and consideration of emission standards for air pollutants. Hence, Malaysia needs to design systematic policies based on pollution sources and characteristics in each city with the use of cleaner alternative and new vehicle technology, as most of the cities had air quality improvement with reduced vehicle numbers during the MCO period. In addition, each local authority can have its mitigation measures to reduce the air pollution concentration to be implemented on a small scale, which may eventually be expanded to a larger scale.

Further studies on the effects of meteorology on air pollutant concentrations are highly recommended in order to further evaluate the variation of air pollutants for the pre-MCO, MCO and post-MOC periods. There are uncertainties in identifying the source contribution of air pollutants in each city which are lack of chemical composition and other air pollution data, such as volatile organic compound (VOC), insufficient vehicle numbers data and the industries that operated during the MCO period. Despite the associated uncertainty, the results of this study have shown that the MCO is a mitigation strategy to reduce the transmission of COVID-19 but has also had an impact on air pollutant concentrations in city areas. Even though most of the air pollutants concentrations were reduced during the MCO period, O3 still had showed not much different concentration that needs further investigation.

CRediT authorship contribution statement

Murnira Othman: Conceptualization, Formal analysis. Mohd Talib Latif: Writing - review & editing.

Declaration of competing interest

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

Acknowledgement

This study was supported by University Kebangsaan Malaysia under research grant GUP-2018-109. Special thanks to Academy of Science Malaysia (ASM) for encouragement on COVID-19 studies in Malaysia and Malaysian Department of Environment (DOE) for the air quality data permission. Thank you to Dr. Rose Norman for proofreading this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.125992.

References

Abdullah, S., Mansor, A.A., Napi, N.N.L.M., Mansor, W.N.W., Ahmed, A.N., Ismail, M., Ramly, Z.T.A., 2020. Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. Sci. Total Environ. 729, 1–5, 139022.

Accarino, G., Lorenzetti, S., Aloisio, G., 2021. Assessing correlations between short-term exposure to atmospheric pollutants and COVID-19 spread in all Italian territorial areas. Environ. Pollut. 268, 1–11, 115714.

Aloi, A., Alonso, B., Benavente, J., Cordera, R., Echaniz, E., Gonzalez, F., Ladasa, C., Lezama-Romaneli, R., Lopez-Parras, A., Mazzey, V., Perucci, L., Prieto-Quintana, D., Rodriguez, A., Sanudo, R., 2020. Effects of the COVID-19 lockdown on urban mobility-empirical evidence from the city of Santander (Spain). Sustainability 12, 1–12.

Amato, F., Pandolfi, M., Escrig, A., Querol, X., Alastuey, A., Pey, J., Perez, N., Hopke, P.K., 2009. Quantifying road dust resuspension in urban environment by Multilinear Engine: a comparison with PMF2. Atmos. Environ. 43, 2770–2780.

Azhari, A., Latif, M.T., Mohamed, A.F., 2018. Road traffic as an air pollutant contributor within an industrial park environment. Atmos. Pollut. Res. 9, 680–687.

Bao, R., Zhang, A., 2020. Does lockdown reduce air pollution? Evidence from 44 cities in northern China. Sci. Total Environ. 713, 1–18.

Carslaw, D.C., 2015. The DepurG Manual-Open-Source Tools for Analysing Air Pollution Data. King’s College London. Manual for Version 1.1-4.

Chen, P.Y., Yan, P.H., Chou, C.C.K., Lin, Y.S., Chen, W.N., Shiu, C.J., 2019. Impacts of holiday characteristics and number of vacation days on “holiday effect” in cities. Atmos. Environ. 202, 133–140.

Conticini, E., Frediani, B., Caro, D., 2020. Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? Environ. Pollut. 261, 114465.

Dantas, G., Siciliano, B., Boscaro, B., Cleyton, A., Arbilla, G., 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. Sci. Total Environ. 725, 1–10, 139085.

Donato, F., Zani, C., 2019. “Risk is in the air”: polyvalent aromatic hydrocarbons, metals and mutagenicity of atmospheric particulate matter in a town of Northern Italy (Respira study). Mutat. Res. Genet. Toxicol. Environ. Mutagen 128, 1–9.

Gallayrous, G., Kious, P., Papatheodorou, S., Woodcock, J., Tainio, M. 2020. The long-term mortality impact of restricting cycling and walking during high air pollution days on all-cause mortality: Health impact Assessment study. Environ. Res. 184, 1–11, 109590.

Hanedar, A., Alp, K., Kaynak, B., Av, E., 2013. Toxicity evaluation and source apportionment of Polycyclic Aromatic Hydrocarbons (PAHs) at three stations in Istanbul, Turkey. Sci. Total Environ. 488–489, 437–446.

He, G., Pan, Y., Tanaka, T., 2020. The short-term impacts of COVID-19 lockdown on urban air pollution in China. Nat. Sustain. 3, 1005–1011. https://doi.org/10.1038/s41893-020-0581-y.

Hossain, M.S., Ahmed, S., Uddin, M.J., 2021. Impact of weather on COVID-19 transmission in south Asian countries: an application of the ARIMA model. Sci. Total Environ. 761, 143315. https://doi.org/10.1016/j.scitotenv.2020.143315.

Jang, E., Do, W., Park, G., Kim, M., Yoo, E., 2017. Spatial and temporal variation of urban air pollutants and their concentrations in relation to meteorological factors at four sites in Busan, South Korea. Atmos. Environ. 143, 1–11, 105072.

Kalmba-Drozdz, M., 2015. The interaction between air pollution and diet does not influence the DNA damage in lymphocytes of pregnant women. Environ. Res. 136, 295–299.

Li, X., Qiao, Y., Zhu, J., Shi, L., Wang, Y., 2017. The “APEC blue” endeavor: causal effects of air pollution regulation on air quality in China. J. Clean. Prod. 168, 1381–1388.

Liu, J., Zhou, J., Yao, J., Zhang, X., Li, L., Xu, X., He, X., Wang, B., Fu, S., Niu, T., Yan, J., Shi, Y., Ren, X., Ni, J., Zhu, W., Li, L., Luo, B., Zhang, K., 2020. Impact of meteorological factors on the COVID-19 transmission: a multi-city study in China. Sci. Total Environ. 726, 1–8.

Liu, S., Kong, G., Kong, D., 2020b. Effects of the COVID-19 on air quality: human mobility, spillover effects, and city connections. Environ. Resour. Econ. 76, 635–653.

Ma, Y., Zhao, Y., Liu, J., He, X., Wang, B., Fu, S., Yan, J., Niu, J., Zhou, J., Luo, B., 2020. Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China. Sci. Total Environ. 712, 1–7.

Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 1–23.

Maroone, M., Diab, R., 2003. Health risk assessment for sulfur dioxide pollution in South Durban, South Africa. Arch. Environ. Health 58, 763–770.

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: the world should face the reality. Environ. Int. 139, 1–3.

Nadzir, M.S.M., Ooi, M.C.G., Bakar, M.A.A., Mohtar, A.A.A, Nor, M.F.M.F., Latif, M.T., Hamid, H.H.A., Ali, S.H.M., Arif, N.M., Anuar, J., Ahmad, F., Azhari, A., Hanif, N.M., Subhi, M.A., Othman, M., Nor, M.Z.M., 2020. The Impact of Movement Control Order (MCO) during Pandemic COVID-19 on Local Air Quality in Klang Valley, Malaysia. Aerosol Air Qual. Res. 20, 1237–1248.

Nakada, L.Y., Urban, R.C., 2020. COVID-19 pandemic: impacts on the air quality of the megacity Delhi, India. Sci. Total Environ. 730, 1–23.

Ogen, Y., 2020. Assessing nitrogen dioxide (NO2) levels as a contributing factor to COVID-19 (COVID-19) fatality. Sci. Total Environ. 726, 1–5, 138605.

Othman, M., Latif, M.T, Yee, C.Z., Norshariffudin, L.K., Azhari, A., Halim, N.D.A., Alias, A., Sofwan, N.M., Hamid, H.H.A., Matsumi, Y., 2020. PM2.5 and ozone in office environments and their potential impact on human health. Ecotox. Environ. Saf. 194, 1–9.

Panis, L.L., Provost, E.B., Cox, B., Louwies, T., Laeremans, M., Standaert, A., Dons, E., Holmstock, L., Nawrot, T., De Boever, P., 2017. Short-term air pollution exposure decreases lung function: a repeated measures study in healthy adults. Environ. Health 16, 1–7.

Road Transport Department Malaysia, 2020. Open data: total motor vehicles by type and state. http://www.datagov.my/data/ms_MY/dataset/jumlah-kenderaan-bermotor-mengikut-jenis-dan-negeri-total-motor-10
vehicles-by-type-and-state/resource/0b2aa265-d000-4148-bb88-9191ae1aaf3d. (Accessed 8 May 2020).

Sarnat, J.A., Marmur, A., Klein, M., Kim, E., Russell, A.G., Sarnat, S.E., Mulholland, J.A., Hopke, P.K., Tolbert, P.E., 2008. Fine particle sources and cardiorespiratory morbidity: an application of chemical mass balance and factor analytical source-apportionment methods. Environ. Health Perspect. 116, 459–466.

Sarma, S., Zhang, M., Anshika, Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 1–8, 138878.

Shen, L., Wang, H., Li, S., Zhang, X., Yuan, J., Tao, S., Zhang, G., Wang, F., Li, L., 2017. Influence of pollution control on air pollutants and the mixing states of aerosol particles during the 2nd World Internet Conference in Jiaxing, China. J. Clean. Prod. 149, 105362.

Sun, Z., Yang, L., Bai, X., Du, W., Shen, G., Fei, J., Wang, Y., Chen, A., Chen, Y., Zhao, M., Sulong, N.A., Latif, M.T., Khan, M.F., Amil, N., Ashfold, M.J., Wahab, M.I.A., Chan, K.M., Sahani, M., 2017. Source apportionment and health risk assessment among age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. Sci. Total Environ. 601–602, 556–570.

Sun, Z., Yang, L., Bai, X., Du, W., Shen, G., Fei, J., Wang, Y., Chen, A., Chen, Y., Zhao, M., 2019. Maternal ambient air pollution exposure with spatial-temporal variations and preterm birth risk assessment during 2013–2017 in Zhejiang Province, China. Environ. Int. 133, 1–10.

Tan, P.H., Chou, C., Chou, C.C.K., 2013. Impact of urbanization on the air pollution “holiday effect” in Taiwan. Atmos. Environ. 70, 361–375.

Tan, P.H., Chou, C., Liang, J.Y., Chou, C.C.K., Shiu, C.J., 2009. Air pollution “holiday effect” resulting from the Chinese New Year. Atmos. Environ. 43, 2114–2124.

Tanzer-Gruener, R., Li, J., Eilenberg, S.R., Robinson, A.L., Presto, A.A., 2020. Impacts of modified factors on ambient air pollution: a case study of COVID-19 shutdowns. Environ. Sci. Technol. Lett. 7, 554–559.

Tello-Leal, E., Macías-Hernández, B.A., 2020. Association of environmental and meteorological factors on the spread of COVID-19 in Victoria, Mexico, and air quality during the lockdown. Environ. Res. 110442 https://doi.org/10.1016/j.envres.2020.110442. In press.

Toibas, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 1–4, 135840.

USEPA. 2009. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment). Office of Superfund Remediation and Technology Innovation. Environmental Protection Agency, Washington D.C.

Venter, Z.S., Aunan, K., Chowdhury, S., Believeld, J., 2021. Air pollution declines during COVID-19 lockdowns mitigate the global health burden. Environ. Res. 192, 110403 https://doi.org/10.1016/j.envres.2020.110403.

Wang, C., Bi, J., Olde Rikkert, M.G.M., 2018. Early warning signals for critical transitions in cardiopulmonary health, related to air pollution in an urban Chinese population. Environ. Int. 121, 240–249.

Wang, P., Chen, K., Zhu, S., Wang, P., Zhang, H., 2020. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resour. Conserv. Recycl. 158, 1–9.

Who, Coronavirus disease (Covid-2019) situation reports, 2020. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports. (Accessed 25 April 2020).

Xu, Z., Huang, X., Nie, W., Chi, X., Xu, Z., Zheng, L., Sun, P., Ding, A., 2017. Influence of synoptic condition and holiday effects on VOCs and ozone production in the Yangtze River Delta region, China. Atmos. Environ. 168, 112–124.

Yang, C., Zhang, Y., Li, X., 2020a. Impact of gasoline upgrade policy on particulate matter pollution in China. J. Clean. Prod. 262, 1–15.

Yang, Z., Zeng, Z., Wang, X., Si, Z., Liao, W., Zamin, M., Liu, P., Cao, X., Gao, Z., Mai, Z., Liang, J., Liu, X., Li, S., Li, Y., Ye, F., Guan, W., Yang, Y., Li, F., Luo, S., Xie, Y., Liu, B., Wang, Z., Zhang, S., Wang, Y., Zheng, N., He, J., 2020b. Modified SEIR and AI prediction of the epidemics trend of COVID-19 in China under public health interventions. J. Thorac. Dis. 12, 13–174.

Yuan, Q., Qi, B., Hu, D., Wang, J., Zhang, J., Yang, H., Zhang, S., Liu, L., Xu, L., Li, W., 2021. Spatiotemporal variations and reduction of air pollutants during the COVID-19 pandemic in a megacity of Yangtze River Delta in China. Sci. Total Environ. 751, 1–9, 148520.

Zhang, Y.N., Xiang, Y.R., Chan, L.Y., Chan, C.Y., Sang, X.F., Wang, R., Fu, H.X., 2011. Source apportionment and health risk assessment among different age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. Environ. Int. 36, 375–385.

Zhang, Y., Yang, L., Zeng, Z., Gao, Z., 2011. Air pollution declines during COVID-19 lockdowns mitigate the global health burden. Environ. Res. 110403 https://doi.org/10.1016/j.envres.2020.110403.

Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ. 727, 1–7, 138704.