Demystifying a Possible Relationship between COVID-19, Air Quality and Meteorological Factors: Evidence from Kuala Lumpur, Malaysia

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ABSTRACT

Air pollution is the culprit to yearly millions of deaths worldwide, deteriorating human health. What is not yet clear is the impact of environmental factors on susceptibility to getting infected by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The study aimed to determine associations between air quality, meteorological factors, and COVID-19 cases in Kuala Lumpur, Malaysia. Air pollutants and meteorological data in 2018–2020 were obtained from the Department of Environment Malaysia, while daily new COVID-19 cases in 2020 were obtained from the Ministry of Health Malaysia. Data collected were statistically analyzed using the Statistical Package for Social Sciences (SPSS). There were significant differences between PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, O_3, and solar radiation in 2019 and 2020 since movement control order (MCO) was implemented on 18 March 2020. Spearman's correlation test showed that COVID-19 cases were positively correlated with PM_{10} ($r = 0.131$, $p < 0.001$), $PM_{2.5}$ ($r = 0.151$, $p < 0.001$), SO_2 ($r = 0.091$, $p = 0.003$), NO_2 ($r = 0.228$, $p < 0.001$), CO ($r = 0.269$, $p = 0.001$), and relative humidity (RH) ($r = 0.106$, $p = 0.001$), whereas ambient temperature (AT) was negatively correlated with COVID-19 cases ($r = –0.118$, $p < 0.001$). Further, multiple linear regression suggested that NO_2 and AT ($R^2 = 0.071$, $p < 0.001$, $f^2 = 0.08$) were the most significant air pollutant and meteorological factors with weak contribution that influenced the incidence of COVID-19 cases in Kuala Lumpur. In general, better air quality, lower RH, higher AT, along with the targeted approach implemented thus far, have proven to curb the spread of this virus infection in Malaysia. This study supports future research in studies documented to understand the potential of transmission, survival, and infection of SARS-CoV-2.

Keywords: SARS-CoV-2; Lockdown; Air pollution; Traffic; Tropical country.

INTRODUCTION

Coronavirus disease (COVID-19) outbreak was initially declared from Wuhan, China, on 31 December 2019. It began as a collection of cases of pneumonia with an unclear origin in late 2019. Then, a new coronavirus called SARS-CoV-2 was identified to be the source of the pneumonia cases (Zheng, 2020). The World Health Organization (WHO) had designated COVID-19 as a worldwide pandemic on 11 March 2020, following a report on 118,319 cases and 4,292 deaths at the global level (WHO, 2020a). A pandemic is an outbreak that has expanded widely across a large number of people through many countries and continents. Although this novel virus is closest to the coronavirus found in animals, COVID-19 has been confirmed to have transmitted from human-to-human and has drawn significant attention globally, not only in China (Hsiao *et al.*, 2020).

China was once ranked number one for several weeks in the worldwide COVID-19 chart for both positive cases and death associated with COVID-19 (Xu *et al.*, 2020). This rank was during the invasion of SARS-CoV-2 type A, which was the closest to coronavirus found in bats and pangolins, and SARS-CoV-2 type B, which was a variation of coronavirus most common in Wuhan, China (Forster *et al.*, 2020). The type B variant also mutated slowly in China but rapidly outside China. A few weeks later, and until now, the United States of America (USA) reached the top of the chart for both positive cases and deaths associated with COVID-19 (WHO, 2020b). The third genome of this coronavirus is defined as SARS-CoV-2 type C, which is the 'daughter' of type B, one mutation different to parent variation, and spread to Europe via Singapore (Forster *et al.*, 2020). While China slows down in reporting daily new positive cases of COVID-19, other countries worldwide have been battling against the

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continual new cases and deaths associated with COVID-19.

New data confirms the improvement in air quality over the USA and Europe after the enforcement of lockdown policies and travel restrictions. The rapid reduction in air pollution is beneficial to both the environment and human beings. The National Aeronautics and Space Administration (NASA) released several satellite images, which showed changes in major cities in the US; these cities had high concentrations of NO_2 in 2019 and now become cities with a large outbreak of COVID-19 (Holcombe and O'Key, 2020). Some of these cities include New York City and Los Angeles. Besides NASA, European Space Agency shared images of the European countries, which were captured by Tropomi, a satellite that monitors several atmospheric gases, including NO_2 (European Space Agency, 2020). The differences are noticeable in the cities which are badly affected by the coronavirus pandemic, such as Madrid, Spain and Milan, Italy. Apart from these countries, other countries with lockdowns and movement restrictions have seen air pollution levels plummet across areas that are usually surrounded by air pollution due to massive industrial activities and vehicular emissions, such as China (Xu *et al.*, 2020). Therefore, the theory of highly polluted regions leads to higher COVID-19 cases is also applicable in Malaysia.

Although the better air quality eases those who are suffering from breathing problems, most people will be more susceptible to illness after years of inhaling polluted air. As previous research has shown, air pollution lowers the immunity and ability to fight off infections (Kamaruddin *et al.*, 2015; Suhaimi *et al.*, 2017; Awang *et al.*, 2019; Sopian *et al.*, 2020). Therefore, people with underlying medical conditions would possibly have challenges to fight the coronavirus. As the number of COVID-19 infections has exceeded 5.8 million with death tolls of about 363 thousand globally as of end-May 2020 (WHO, 2020b), researchers are rushing against time to unravel the complexity of this novel virus and evaluate the associated short-term and long-term effects. In summary, although many factors have been shown to affect the incidence of COVID-19, this study was performed to explore the influence of poor air quality and meteorological factors in Kuala Lumpur, Malaysia, on SARS-CoV-2 potential of transmission, survival, and infection.

METHODS

Study Location

Kuala Lumpur lies between 3°8′52″N and 101°41′43″E. This capital city of Malaysia consists of a land area of 243 km^2 with the highest population density of 7328 persons km^{-2} (DOS Malaysia, 2019).

Data Collection

Air pollutants and meteorological data from 11 March 2018 to 21 April 2020 in Batu Muda Station, Kuala Lumpur were obtained from the Department of Environment (DOE) under the Ministry of Environment and Water, Malaysia. The meteorological data included relative humidity (RH), ambient temperature (AT), wind speed (WS) and solar radiation (SR), while air pollutants data comprised of particulate matter with

≤ 10 µm diameter (PM_{10}), particulate matter with ≤ 2.5 µm diameter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO). Meanwhile, the data set on daily COVID-19 cases in Malaysia were obtained from the Crisis Preparedness and Response Centre, Ministry of Health, Malaysia (available at https://kpkesihatan.com/). The data on new COVID-19 cases were analysed against the concentrations of air pollutants collected between the years 2018 and 2019, when no COVID-19 case was reported. This method was previously described by Travaglio *et al*. (2020) to represent long-term exposure to air pollutants. However, instead of using annual average of daily measurements for each air pollutant, we used daily average concentrations to match with the meteorological factors, which also used daily average measurements.

Data Analysis

Statistical analysis was done using SPSS version 23. A descriptive analysis was executed for all the data. If the data were normally distributed, paired-samples t-test was used to analyze for a statistically significant difference between two related sample means. On the other hand, the Wilcoxon signed-rank test was used to analyze a paired sample that violated the normality assumption. Spearman's correlation test was used to assess the relationship between air pollutants, meteorological factors, and daily COVID-19 cases, since the data were not normally distributed. Then, multiple linear regression was used to examine the relationship between new COVID-19 cases with predictor variables.

RESULTS AND DISCUSSION

COVID-19 in Malaysia

Malaysia is one of the countries in the world with a high recovery rate of 81.55% and a low fatality rate of 1.48%; as of 30 May 2020, COVID-19 has infected 7,762 people in Malaysia (Ministry of Health Malaysia, 2020a). The COVID-19 cases in Malaysia have been detected among patient under investigation (PUI) with histories of travelling to affected countries or attending mass gathering events, close contacts with positive cases, and sporadic cases in the community through patients with severe acute respiratory infection (SARI) and influenza-like-illness (ILI) who had no contact with positive cases or history of travelling overseas.

Fig. S1 shows a brief chronology of COVID-19 cases in Malaysia at a glance. During the first wave of the pandemic, Malaysia managed to contain and bring down the new case numbers to zero for ten days in a row (17–26 February 2020). However, when the second wave of COVID-19 appeared in the country, the number of cases since then has risen to more than 1000. The Malaysian government announced a nationwide movement restriction to flatten the infection curve in the country. Under the MCO, all sectors were closed except essential services. Kuala Lumpur has been an area with the most reported active COVID-19 cases in Malaysia. Active cases are total confirmed cases minus deaths and recoveries. Starting 4 May 2020, Malaysia is under Conditional MCO (CMCO), which legally permits freedom of movement within states and operation of businesses.

In Malaysia, laboratory tests to detect the viral Ribonucleic Acid (RNA) for SARS-CoV-2 in the patient's body are conducted at both government and private health laboratory facilities. Although these tests are time-consuming, they are highly specialized. Accurate test results are important to manage COVID-19 patients effectively. Fig. 1 shows an increase of active COVID-19 cases that were reported in Kuala Lumpur on the day before MCO started with 106 cases (Ministry of Health Malaysia, 2020b). Then, the total cumulative cases were 1037 on 21 April 2020 (Ministry of Health Malaysia, 2020c). Out of these 1037 cases, there were 18 deaths (86%) among patients who had chronic diseases. Meanwhile, there were 3 deaths (14%) among patients who had a travel history to affected countries. The chronic diseases included heart disease, hypertension, diabetes, stroke, dementia, and kidney disease; some patients had a combination of at least two chronic diseases. Table S1 shows the distribution of deaths among COVID-19 cases in Kuala Lumpur as of 21 April 2020. There is no definite explanation as to how COVID-19 patients with a history of chronic diseases have a higher rate of mortalities. However, SARS-CoV-2 may cause multi-organ failures (Zaim *et al.*, 2020) and worsen the conditions of these immunocompromised patients.

Variations in Concentrations of Air Pollutants and Meteorological Factors

Airborne pathogens are partially subjected to ambient environmental factors, such as atmospheric pollutants, RH, temperature, and SR (Merow and Urban, 2020). These viruses could bind to air particles; thus, this condition helps them to remain airborne longer and enable them to reach the lungs, causing severe respiratory symptoms, increase health complications and even lead to fatality (Rabi *et al.*, 2020). Meanwhile, other factors, such as traffic density,

meteorological conditions, and industrial activities, could contribute to the air pollutants concentration (Nicolás *et al.*, 2020; Xu *et al.*, 2020).

The unforeseen consequence of the economic shutdown to a near-halt due to the COVID-19 outbreak is granting clear skies in places that are well-known for their poor air quality. As of 30 April 2020, there was a 26% increase in good Air Pollutant Index (API) days throughout Malaysia since MCO started. MCO does not only reduce the spread of COVID-19 among the community members but also reduce the environmental pollution due to reduction in anthropogenic activities. The evidence is most prominent in Klang Valley, with the densely populated Kuala Lumpur in its vicinity. Similar findings have been described before (Mohd Nadzir *et al.*, 2020). Table 1 shows general observations on air quality in Klang Valley and other capital cities since MCO was implemented as reported by DOE Malaysia (Department of Environment Malaysia, 2020a).

Table 2 shows a summary of hourly air pollutants and meteorological data starting from 18 March 2019 at 12 a.m. until 21 April 2019 at 11 p.m., and the same period for 2020. This 5-week duration represented MCO in Malaysia with 18 March 2020 that marked the starting of MCO Phase 1. Only data from Batu Muda station is discussed in detail because its location covers the largest localities with high COVID-19 cases in Kuala Lumpur. A paired-samples t-test (effect size, *d*) was used to compare the mean concentration of normally distributed parameters (PM_{10}, $PM_{2.5}$, O_3, RH, and WS) between these two years. In contrast, a Wilcoxon signed-rank test (effect size, *r*) was used to correctly interpret non-normally distributed parameters (SO_2, NO_2, CO, AT, and SR) between these two years.

On average, all six air pollutant variables had lower concentrations during the period in 2020 than the same
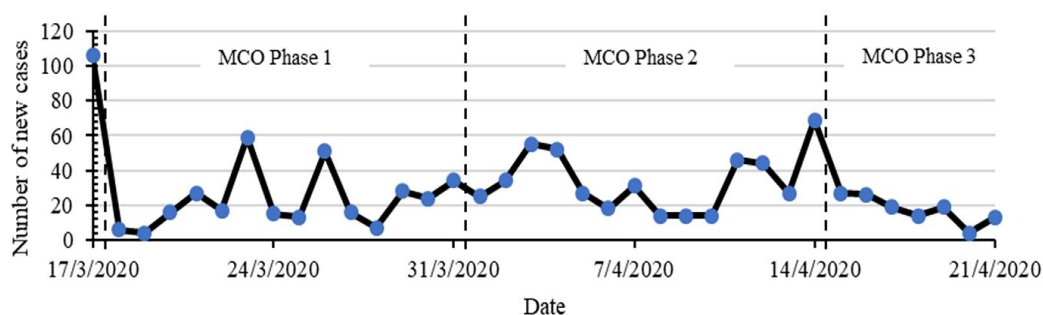

Fig. 1. Daily COVID-19 reported cases in Kuala Lumpur from 17 March 2020, to 21 March 2020.

Table 1. Analysis of Air Quality during MCO

Air Quality Monitoring Stations	Air Pollutants	Percentage of Reduction
Klang Valley:	NO_2	49%–68%
Batu Muda, Cheras, Putrajaya, Petaling Jaya,	SO_2	6%–26%
Shah Alam, Klang and Banting	CO	21%–48%
	$PM_{2.5}$	17%–36%
Other Capital Cities:	NO_2	43%–63%
Pulau Pinang, Ipoh, Kuantan, Seremban, Melaka,	SO_2	2%–48%
Pasir Gudang, Kuching and Kota Kinabalu	CO	1%–27%
	$PM_{2.5}$	3%–35%

Table 2. Descriptive statistics and differences analysis of air pollutants and meteorological data

Variables	Year	Min	Max	Mean	SD	Median	IQR	t or Z	p	d or r
PM_{10} (µg m^{-3})[a]	2019	8.035	100.1	35.19	12.98	33.41	17.16	–7.753	< 0.001*	1.71
	2020	2.334	64.30	25.25	8.861	25.09	11.11			
$PM_{2.5}$ (µg m^{-3})[a]	2019	5.622	68.53	26.29	10.92	24.748	15.25	–5.597	< 0.001*	1.10
	2020	0.248	57.99	20.25	8.427	20.063	10.12			
SO_2 (ppb)[b]	2019	0.016	3.098	0.876	0.502	0.894	0.813	–3.128	0.002*	0.53
	2020	0.007	1.646	0.548	0.362	0.459	0.385			
NO_2 (ppb)[b]	2019	1.801	50.50	17.29	8.060	16.35	10.81	–5.159	< 0.001*	0.87
	2020	0.099	22.26	5.873	3.994	5.024	5.143			
O_3 (ppb)[a]	2019	0.033	77.54	16.02	16.45	10.63	22.19	4.191	< 0.001*	0.84
	2020	0.026	65.81	19.46	15.02	16.35	22.65			
CO (ppm)[b]	2019	0.103	2.122	1.016	0.298	0.976	0.357	–4.112	< 0.001*	0.70
	2020	0.557	1.576	0.879	1.401	0.865	0.164			
RH (%)[a]	2019	41.12	98.00	76.11	15.11	79.12	26.20	0.047	0.963	0.00
	2020	42.58	98.00	80.49	13.71	84.57	17.77			
AT (°C)[b]	2019	23.02	36.37	28.94	3.528	28.04	6.405	–0.737	0.461	0.13
	2020	23.65	36.94	28.06	3.095	26.91	3.905			
WS (m s^{-1})[a]	2019	0.000	8.618	1.181	1.191	0.875	0.624	–1.993	0.054	0.50
	2020	0.000	8.323	1.039	1.151	0.712	0.648			
SR (W m^{-2})[b]	2019	0.000	886.8	164.2	250.5	0.000	321.7	–4.291	< 0.001*	0.73
	2020	0.000	784.4	134.7	207.5	0.000	233.8			

a = paired t-test, b = Wilcoxon signed rank test, *significant at $p < 0.05$.

period in 2019. These differences were statistically significant (*t* or *Z*) at $p < 0.05$, which showed the effectiveness of MCO in reducing the polluted air. PM_{10}, $PM_{2.5}$, NO_2, and O_3 showed a large effect size ($d \geq 0.80$ or $r \geq 0.80$), while SO_2 and CO showed a medium effect size ($r \geq 0.50$). On the other hand, all meteorological variables had no statistically significant difference (*t* or *Z*) at p < 0.05 except for SR, which showed a medium effect size ($r \geq 0.50$).

When comparing all the six air pollutants with the new Malaysia Ambient Air Quality Standard for 2020 (Department of Environment Malaysia, 2020b), none of these pollutants had exceeded the standard (PM_{10} = 100 µg m^{-3} for 24 hours, $PM_{2.5}$ = 35 µg m^{-3} for 24 hours, SO_2 = 95 ppb for 1 hour, NO_2 = 149 ppb for 1 hour, O_3 = 92 ppb for 1 hour, CO = 26.19 ppm for 1 hour). Fig. 2 shows the weekly average concentration of air pollutants and meteorological data from 18 March to 21 April 2019 versus the same period in 2020, and % change compared with the previous week for 2020. Week 1 of MCO was from 18 to 24 March 2020, while Week 2 of MCO was from 25 to 31 March 2020; both Week 1 and Week 2 were MCO Phase 1. Week 3 of MCO was from 1 to 7 April 2020, while Week 4 of MCO was from 8 to 14 April 2020; both Week 3 and Week 4 were MCO Phase 2. Week 5 of MCO was from 15 to 21 April 2020; Week 5 was MCO Phase 3. By using the mean of air pollutants and meteorological data on Week 1 of MCO, the figure shows that all air pollutants except O_3 showed a similar lower trend during MCO than the same period during 2019. However, there was no similar trend for meteorological factors. RH, AT, and WS showed no apparent difference between the same period in those two years. Meanwhile, SR showed a lower trend during MCO than the same period during 2019.

Fig. 3 shows the weekly average concentration of air pollutants and meteorological data starting from 1 January to 21 April 2020 (16 weeks). What is striking in this figure is that the first week of MCO (Week 12) and the second week of MCO showed a sharp decrease in all air pollutants except for O_3. This decrement was due to more O_3 formation and less O_3 degradation in warm and sunny conditions, and less NO_2 from reduced traffic density in Kuala Lumpur. Our findings were in line with a previous study that also reported lower levels of measured pollutants (PM_{10}, $PM_{2.5}$ and CO) during the MCO period in an urban area of Klang Valley, Malaysia (Mohd Nadzir *et al.*, 2020). As for meteorological factors, the first week of MCO showed a decrease in all variables except for RH, which was due to the monsoon season that is expected to continue until May 2020. The climate of Malaysia is categorized as hot and humid throughout the year because its location is near to the equator. There are two monsoon wind seasons; Southwest Monsoon from May to September and Northeast Monsoon from October to March. These monsoon seasons bring in more rainfall with higher RH, lower SR, and lower AT on average than hot seasons. Kuala Lumpur experienced the transitional period of intermonsoon season during the study period (March–April).

Relationship between COVID-19, Air Pollutants and Meteorological Factors

The incubation period of SARS-CoV-2 is between 2 to 14 days (CDC, 2020). Assuming the time between virus transmission and infection confirmation required on average seven days, daily average meteorological data from seven days earlier was compared with newly confirmed cases of the MCO day (e.g., 11 March meteorological data was paired with 18 March newly confirmed cases). Besides, there is a relationship between long-term exposure to air pollution, COVID-19 infection and fatality in European
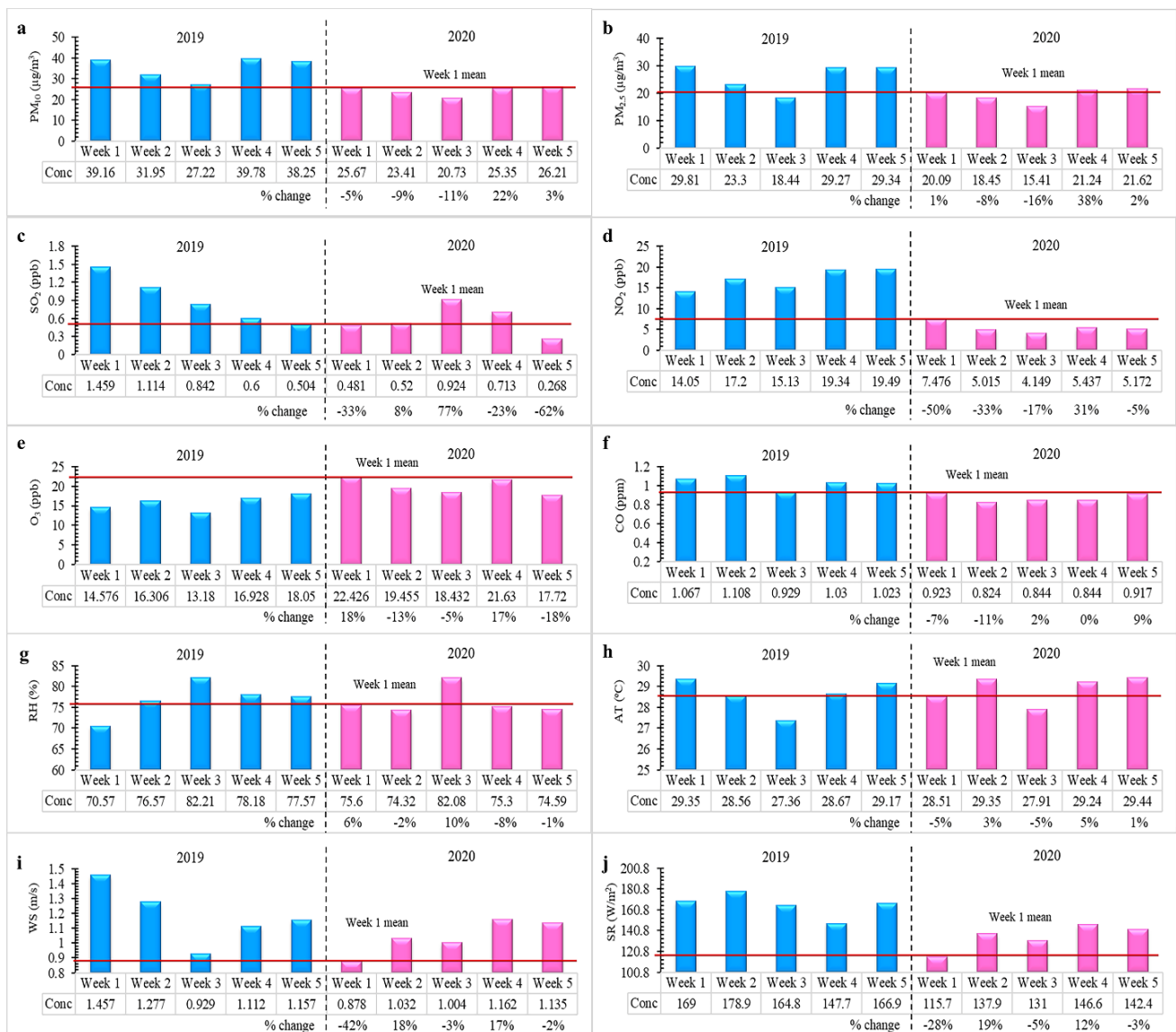
Fig. 2. (a) PM_{10} (µg m^{-3}), (b) $PM_{2.5}$ (µg m^{-3}), (c) SO_2 (ppb), (d) NO_2 (ppb), (e) O_3 (ppb), (f) CO (ppm), (g) RH (%), (h) AT (°C), (i) WS (m s^{-1}), and (j) SR (W m^{-2}) in Kuala Lumpur from 18 March to 21 April for both 2019 and 2020.

countries (Ogen, 2020). Hence, daily average air pollutant data in 2018 and 2019 from the same period in 2020, which preceded the MCO days by one week, were used for comparison (e.g., 11 March to 14 April 2018 and 11 March to 14 April 2019).

A bivariate correlation coefficient (*r*) was calculated to assess the size and direction of the linear connection between air pollutants and meteorological data with COVID-19 cases. Instead of Pearson's correlation test, Spearman's correlation test was used due to all the parameters not normally distributed. Table 3 shows that among air pollutant variables, only O_3 had no significant correlation with COVID-19 cases. On the other hand, among meteorological variables, both WS and SR had no significant correlation with COVID-19 cases. There were weak significant positive correlations between PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and RH with COVID-19 cases, while AT was negatively correlated at a weak level with COVID-19 cases. Thus far, the effects of outdoor air

pollution concentrations, meteorological factors, and MCO on COVID-19 infections were statistically significant.

Next, these statistically significant variables at the univariate level were analyzed further at the multivariate level using multiple linear regression. The stepwise method was applied, which inserted two out of seven variables (PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, RH and AT) in the final model. Table 4 shows two variables to represent air pollutant and meteorological factors, which were significantly associated with new COVID-19 cases in Kuala Lumpur. Results from multivariate level analysis using multiple linear regression revealed that NO_2 and AT were the most significant air pollutant and meteorological factors that influenced the incidence of COVID-19 cases in Kuala Lumpur, which are portrayed in Eq. (1).

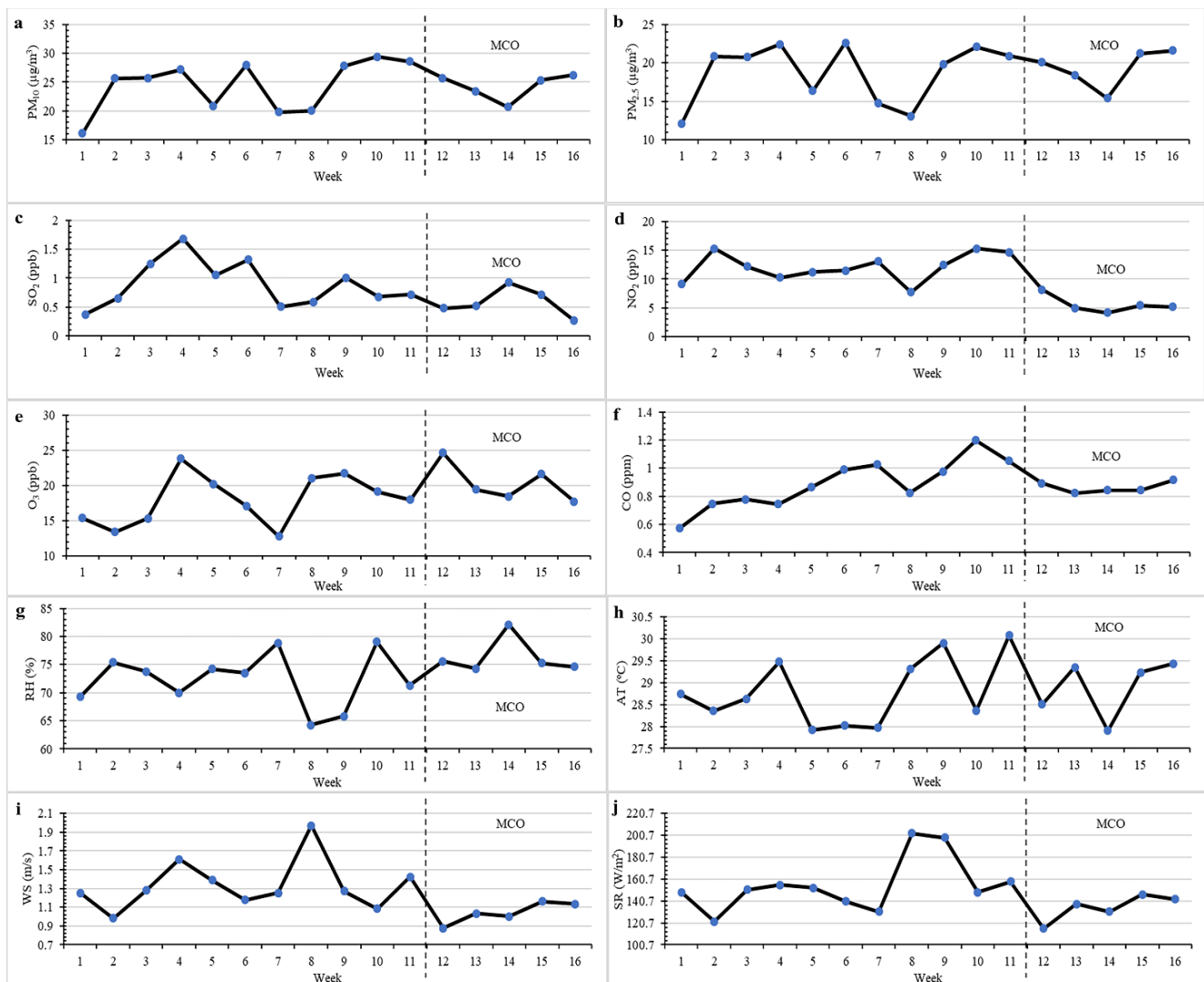$$New\ COVID\text{-}19\ Case = 47.49 + 0.462(NO_2) - 0.327(AT) \tag{1}$$

Fig. 3. (a) PM_{10} (μg m^{-3}), (b) $PM_{2.5}$ (μg m^{-3}), (c) SO_2 (ppb), (d) NO_2 (ppb), (e) O_3 (ppb), (f) CO (ppm), (g) RH (%), (h) AT (℃), (i) WS (m s^{-1}), and (j) SR (W m^{-2}) in Kuala Lumpur from 1 January to 21 April 2020.

Table 3. Spearman's correlation tests between hourly air pollutants and meteorological data with new COVID-19 cases in Kuala Lumpur.

Variables	r	p
PM_{10} (μg m^{-3})	0.131	< 0.001*
$PM_{2.5}$ (μg m^{-3})	0.151	< 0.001*
SO_2 (ppb)	0.091	0.003*
NO_2 (ppb)	0.228	< 0.001*
O_3 (ppb)	0.015	0.626
CO (ppm)	0.269	0.001*
RH (%)	0.106	0.001*
AT (℃)	−0.118	< 0.001*
WS (m s^{-1})	−0.059	0.062
SR (W m^{-2})	−0.017	0.585

*Correlation is significant at the 0.01 level (2-tailed)

For every unit (1 ppb) increase in NO_2, COVID-19 cases will increase by 0.462, provided that AT remains unchanged. Similarly, for every unit (1 ℃) increase in AT, COVID-19

cases will decrease by 0.327, provided that NO_2 remains unchanged. For both models, the beta values were significant at the 0.05 level. VIF values were below 5, which indicated that there was no problem with multicollinearity. There was a significant direct linear relationship between NO_2, and AT with COVID-19 cases ($p < 0.001$). 7.1% of variance in new COVID-19 cases can be explained by NO_2 and AT, $R^2 = 0.071$, $F(5, 834) = 12.67$, $p < 0.001$. A combined effect of this magnitude can be considered small ($f^2 = 0.08$), hence we could not evince on the large contribution of NO_2 and AT in COVID-19 cases. Many factors are partly responsible for the incidence of COVID-19 cases, which are not discussed in this study.

NO_2 is a good indicator of vehicle emissions (Ismail *et al.*, 2019). The traffic density substantially decreased in Kuala Lumpur during the MCO, hence improving the air quality, including NO_2. Earlier studies have shown that prolonged exposure to NO_2 causes a reduction in lung function (van Zoest *et al.*, 2020) and lung inflammation (Jalaludin *et al.*, 2014; Kamaruddin *et al.*, 2019), which ultimately lead to an

Table 4. Multiple linear regression for associations between NO_2 and AT with new COVID-19 cases in Kuala Lumpur.

Independent Variables	B (SE)	Standardized Coefficients	p	95% CI	VIF
Constant	47.49 (5.639)	–	< 0.001*	36.42–58.56	–
NO_2	0.462 (0.098)	0.196	< 0.001*	0.269–0.656	1.565
AT	–0.327 (0.161)	–0.071	0.042*	–0.643 to –0.012	1.088

*Significant at $p < 0.05$, Method = Stepwise, $R^2 = 0.071$, Adjusted $R^2 = 0.065$, 95% CI = 95% Confidence Interval, B = Regression Coefficient, SE = Standard Error, VIF = Variance Inflation Factor.

activation of the immune system. Therefore, there is a possibility that those infected by COVID-19 have lower immunity to defend themselves from viral infections, especially when they encounter a chronic respiratory illness due to an initial poisoning in their bodies.

Our findings on significant positive correlations between air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2 and CO) and newly confirmed COVID-19 cases were comparable to the previous studies in China, Italy, and the USA (Pansini and Fornacca, 2020; Setti *et al.*, 2020; Zhu *et al.*, 2020). Zhu *et al.* (2020) found significant positive associations of PM_{10}, $PM_{2.5}$, NO_2 and CO, with COVID-19 confirmed cases via their generalized additive model. Although we found no significant correlation between O_3 and new COVID-19 cases, Zhu *et al.* (2020) found a positive correlation between O_3 and new COVID-19 cases. As for SO_2, we found its positive correlation with new COVID-19 cases, but Zhu *et al.* (2020) reported a contrasting finding of negative correlation with daily COVID-19 cases.

Pansini and Fornacca (2020) compiled air quality information from China, Italy, and the USA. They found significant positive correlations between COVID-19 cases and air quality variables in each country, thus providing preliminary evidence that COVID-19 cases are most often found in highly polluted areas of these countries. They reported that $PM_{2.5}$, CO and NO_2 were positively correlated with COVID-19 cases, which were in line with our findings. Unlike our non-significant positive correlation between O_3 and COVID-19 cases, they presented a relatively strong positive correlation between O_3 and COVID-19 in Italy, although China and the USA displayed a negative correlation.

Setti *et al.* (2020) reported that PM_{10} pollution could be the cause of the accelerated spread of COVID-19 infection in several regions of Northern Italy; they proposed that particulate matter was used as a carrier for the coronavirus. There was a direct relationship between the incidence of COVID-19 and the PM_{10} concentration, especially in the areas with high PM_{10} concentration in Northern Italy. Their findings agreed with our findings on the positive correlation between PM_{10} and COVID-19 cases. Before proceeding to meteorological factors, all these positive connections between air pollutant concentrations (PM_{10}, $PM_{2.5}$, SO_2, NO_2 and CO) and COVID-19 cases discussed here also support the theory that fewer intra-city and inter-city movement after the MCO in Malaysia contributes to reducing the infection rate in the country. Moreover, it is evident from these findings that exposure to air pollution over time influences the incidence of COVID-19 cases.

What follows is an account of meteorological factors. The influence of temperature and humidity on incidence of COVID-19 may be credible in countries with a low percentage of imported cases because there were high occurrences of SARS-CoV-2 being transmitted in the community. Malaysia is such a country with higher cases from local community transmissions with 7287 (93.9%) cumulative local cases compared to 475 (6.1%) imported cases as of 30 May 2020 (Ministry of Health Malaysia, 2020a). SARS-CoV-2 is predicted to survive better in drier air, which means lower humidity environment. However, we observed a weak positive correlation between RH and new COVID-19 cases ($r = 0.106$, $p = 0.001$), which were in line with a review that pointed out that immune response to viruses is less effective in surroundings with lower humidity (Moriyama *et al.*, 2020). In our study, RH ranged from 64.26% to 82.08% from 1 January–21 April 2020, which was due to the interchange between hot and monsoon season in the country. Our findings demonstrated that high outdoor humidity could promote viral spread; hence, the virus can survive for longer periods in tropical countries like Malaysia, when airborne droplets that contain the virus fall on indoor surfaces. In contrast to our results, an analysis from 166 countries found that an increase of 1% RH markedly lowers the transmission of viruses with 0.85% reduction in daily new cases of COVID-19 (95% CI: 0.51%, 1.19%), and 0.51% reduction in daily new deaths (95% CI: 0.34%, 0.67%) (Wu *et al.*, 2020). Their findings would be probably applicable to countries in winter climates such as Europe and the USA, but not for tropical countries like Malaysia, and countries in summer climates like Australia.

In the case of temperature, we observed a weak negative correlation between AT and daily new cases of COVID-19 ($r = -0.118$, $p < 0.001$), which were consistent with many findings that showed high temperature significantly reduced the transmission of SARS-CoV-2 (Şahin, 2020; Wang *et al.*, 2020; Wu *et al.*, 2020). In our study, AT ranged from 27.92°C to 30.08°C from 1 January–21 April 2020, which is typical for a tropical country. Wu *et al.* (2020) testified that an increase of 1°C of temperature substantially lowers the transmission of SARS-CoV-2. A 1°C increase in temperature had significantly decreased the daily new COVID-19 cases by 3.08% (95% CI: 1.53%, 4.63%) and decreased the daily new deaths by 1.19% (95% CI: 0.44%, 1.95%) reduction in daily new deaths. Likewise, Wang *et al.* (2020) reported that the cities in northern China, where temperatures were lower than the cities along the country's southeast coast, had higher virus transmission rates. The temperature had quite a strong effect on *R*-value with significance levels of 1% for all specifications, and an increase of 1°C in temperature lowers the *R*-value by 0.0225. On the other hand, researchers from Indonesia, a country with almost similar meteorological factors like Malaysia, presented a contrasting finding (Tosepu

et al., 2020). They reported that average temperature had a significant positive correlation with COVID-19 cases ($r = 0.392$, $p < 0.01$). With this distinct finding from Indonesia, SARS-CoV-2 could, in fact, survive in this high temperature and continue to infect hosts.

Apart from RH and AT, SR is also predicted to affect the rate of SARS-CoV-2 survival. Nevertheless, we found no significant correlation between SR and newly confirmed COVID-19 cases ($r = –0.017$, $p > 0.01$), which was in line with findings in China (Yao *et al.*, 2020). They did not support the hypothesis that sunlight can decrease the transmission of COVID-19, although the ultraviolet rays from the sun were acknowledged to help destroy common flu and cold viruses. They conducted a study between early January and early March in all the endemic cities across China and revealed that SARS-CoV-2 transmission was not affected by the variations in temperature or humidity. By contrast, a study in the USA demonstrated that lower ultraviolet rays promote the growth of SARS-CoV-2 (Merow and Urban, 2020).

Another meteorological factor that is important in the transmission of SARS-CoV-2 is WS because it can cause the dispersion of suspending particles that might carry the viruses in the air. A study in Iran proved that the COVID-19 cases were higher in provinces with low wind speed compared to provinces with high wind speed (Ahmadi *et al.*, 2020). However, our finding on the correlation between WS and newly confirmed COVID-19 cases was not significant ($r = –0.059$, $p > 0.01$).

The Influence of Preventive Strategies on COVID-19 Epidemic in Malaysia

This study has relevant significances in the control and prevention of COVID-19 in term of air pollutants and meteorological factors, aside from other aspects which are not discussed in detail, such as medical resources and interventions from various sectors. Malaysia was once on top for several weeks among the Southeast Asian countries with the highest confirmed COVID-19 cases, but now the country is entering the recovery phase, as shown in Fig. S2. The strategies of Malaysia to break the chain of infection appears to be successful so far. There are four types of zones to classify the severity of COVID-19 cases, as shown in Table S2. The government paid more attention to regions that recorded high concentrations of API before MCO was implemented, such as Klang Valley that included Kuala Lumpur. These regions are mostly big cities with a high population density in the country, so there is a higher risk of virus transmission among the community members. Besides, most of these areas were categorized as COVID-19 red zones for several weeks. As expected, Kuala Lumpur is experiencing worse COVID-19 epidemic than other regions with better air quality.

Ministry of Health Malaysia also built a temporary hospital that is equipped with basic medical facilities at Klang Valley to accommodate COVID-19 patients with no or mild symptoms in case there is a shortage of hospital beds and resources due to rising COVID-19 cases. Meanwhile, the Ministry of Housing and Local Government Malaysia has been conducting public sanitation and disinfection operations at common areas such as markets, places of worship, and public transport terminals. Besides, the government highly recommends the people to wear face masks when they are out in the public area after a study had shown that SARS-CoV-2 could survive and remain suspended in the aerosol, which means that transmissions are possible during exhalation (Lednicky *et al.*, 2020). A constant reminder is also given to stay at home, wash hands frequently and maintain social distancing. Together, all these factors have partly contributed to flattening the curve of active COVID-19 cases in Malaysia, along with several aspects that are not discussed in this study.

Several limitations also bound our study due to its exploratory nature. First, the findings reported in this study were only representing Malaysia and probably some other countries with similar air pollutants and meteorological trends like Malaysia. There is a plausible link between long-term exposure to air pollution and susceptibility to the coronavirus, but it is not certain. Second, this study might have ecological fallacy to some degree due to its ecological study design. Individual-level data for exposure to air pollutants and meteorological factors were not collected; thus, the hypotheses were generated by group-level analysis. Third, we acknowledge the presence of comorbidity factors, with 86% of deaths among COVID-19 cases in this study were among senior citizens with chronic diseases. However, this is a global issue that is facing countries affected by the pandemic because older people are generally a high-risk group for complications and deaths. Future studies are needed to address these limitations and integrate the knowledge of physics to discover the capacity of air pollutants as viral vectors either outdoors or indoors since environmental parameters are crucial in the survival and transmission of viruses in the atmosphere.

CONCLUSIONS

In conclusion, the rapid COVID-19 infection spread observed in many countries worldwide could be related to years of exposure to poor air quality, which deteriorates the health of the community in the affected areas over time. The implementation of MCO in Malaysia had significantly reduced the concentrations of air pollutants between 1% to 68% throughout the country and 5% to 50% in Kuala Lumpur. This study also suggested that SARS-CoV-2 could still spread exponentially at higher humidity and temperature, and will persist through summer, as shown by a weak positive correlation between RH and new COVID-19 cases ($r = 0.106$, $p = 0.001$), and a weak negative correlation between AT and new COVID-19 cases ($r = –0.118$, $p < 0.001$). However, effective government and public health interventions, and adequate healthcare capacity have helped to reduce the incidence of COVID-19 cases in Malaysia, along with a small effect from decreased NO_2 and increased AT ($R^2 = 0.071$, $p < 0.001$, $f^2 = 0.08$). With the underlying medical conditions, many infected patients could not win the battle against SARS-CoV-2; hence, they contribute to the fatality rate. Overall, this study demonstrates the remarkable connection between air pollution, meteorological factors, and susceptibility to COVID-19 infections in Malaysia.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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