Big Data Analysis for Effects of the COVID-19 outbreak on Ambient $PM_{2.5}$ in Areas That Were Not Locked Down

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Keywords: COVID-19; SAS-cov-2; $PM_{2.5}$; low-cost sensors; domestic emission; big data

Abstract

At the end of 2019, the coronavirus COVID-19 outbreak was first observed. Also known as Severe Acute Respiratory Syndrome Coronavirus 2 (SAS-cov-2), it rapidly spread globally in the first half of 2020. COVID-19 disease was well-controlled in Taiwan without a nation-wide lockdown. Our study aimed to investigate $PM_{2.5}$ levels and patterns from $PM_{2.5}$ sensors during the COVID-19 situation in 2020 compared with those in the corresponding periods in 2019. Our sampling areas were located at industrial areas in the north and south Taiwan and were used to gather $PM_{2.5}$ data from approximately 1,500 $PM_{2.5}$ sensors every 1 or 3 minutes between January and March of 2019 and 2020. **Compared with the corresponding period of 2019 (16.3 and 32.4 μg m^{-3} in north and south Taiwan, respectively), $PM_{2.5}$ was significantly reduced by 3.70% and 10.6% in north and south Taiwan, respectively, during the COVID-19 situation from January to March in 2020 based on a big data analysis**. Similar $PM_{2.5}$ patterns were observed in the industrial areas in north and south Taiwan in 2019 and 2020. Based on our results, the decline in $PM_{2.5}$ during the COVID-19 outbreak has mainly been due to decreased domestic emissions of $PM_{2.5}$ precursors (i.e., nitrogen dioxide and sulfur dioxide) and to a lesser degree is due to reductions in transboundary transportation of $PM_{2.5}$, such as long-range $PM_{2.5}$ transport from China. $PM_{2.5}$ may be temporarily decreased during the COVID-19 outbreak, but the patterns remained similar to those in the past. Considering restrictions related to the rapid spread of the SAS-cov-2 virus during the COVID-19

episode, control of $PM_{2.5}$ emissions from local sources might help reduce the number of COVID-19 cases.

1 INTRODUCTION

Since the sudden outbreak of the COVID-19 airborne disease, which is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-cov-2) virus that initially emerged in December 2019, the World Health Organization (WHO) has reported approximately 142,057,939 confirmed cases and 3,034,210 deaths worldwide as of April 19, 2021 (Li et al., 2020d; WHO, 2021). Taiwan has experienced two waves of COVID-19 cases. The Taiwan Center for Disease Control (TCDC) announced 1,076 confirmed cases and 11 deaths by April 19, 2021 (TCDC, 2020). At that time, the TCDC announced guidelines, including wearing a mask and social distancing to help stop the spread of SARS-cov-2 virus and cellular broadcast services to advise theat-risk population and reduce potential exposure to SARS-cov-2 virus in densely populated areas starting in early February 2020. Even though the highly infectious SARS-cov-2 virus continues to spread around the world, Taiwan has successfully controlled the pandemic and minimized the impact on Taiwanese daily life through a policy of transparency and honesty about COVID-19. Unlike other regions, Taiwan is available for human activities, including industrial production without any lockdown process excluding overseas visitors.

Several reports indicated that during normal talking and breathing, individuals infected with COVID-19 could easily generate small droplets of SARS-cov-2, which are possibly transported by aerosol and remain on suspended particulate matter (PM) including $PM_{2.5}$ in the air for hours and travel over social distancing (1.5 or 2 m or 6 feet) (Anderson et al., 2020; Banik and Ulrich, 2020; Doremalen et al., 2020; Setti et al., 2020c, 2020b;; Wang and Du, 2020). Experimental results supported the existing evidence of accelerated transmission of the SARS-cov-2 virus by $PM_{2.5}$, particularly in northern Italy and in Wuhan in China (Sharma and Balyan, 2020). These small particulates carry the SARS-cov2 virus in indoor environments and diffuse it more than 10 m from the source (Setti et al., 2020a). Especially in poor indoor environments with habitual indoor burning of incense, such as in Middle Eastern countries (Amoatey et al., 2020), it is possible to spread the COVID-19 disease through heavy $PM_{2.5}$ and PM_{10} pollution. Based on the current global data, air pollution, such as that caused by $PM_{2.5}$ and PM_{10}, may be associated with COVID-19 mortality rates or incidence if population density, racial segregation, socioeconomic position, and meteorological variables, such as temperature and humidity, are not considered (Brandt et al., 2020; Jiang et al., 2020). Wu et al. (2020) revealed the positive association of $PM_{2.5}$ with COVID-19 deaths based on a 1 μg m^{-3} increase in $PM_{2.5,}$ leading to a 15% increase in mortality in the United States. Sharma and Balyan (2020) indicated that high $PM_{2.5}$ might accelerate COVID-19-related mortality based on experience with increases in air pollution-related comorbidities after humans were exposed to high levels of $PM_{2.5}$. Scientists have warned that future works need to consider whether air pollution, such as $PM_{2.5}$, directly affects COVID-19 mortality independent of population density, racial and socioeconomic segregation, cardiopulmonary disease, and meteorological conditions (Brandt et al., 2020; Jiang et al., 2020; Saadat et al., 2020).

Several reports have indicated that air quality was improved after lockdown related to COVID-19 (Bao and Zhang, 2020; Collivignarelli et al., 2020; Dantas et al., 2020; Dutheil et al., 2020; Kerimray et al., 2020; Li et al., 2020a; Li and Tartarini, 2020; Mahato et al., 2020; Nakada and Urban, 2020; Otmani et al., 2020; Saadat et al., 2020; Sharma et al., 2020; Tobías et al., 2020; Wang and Su, 2020; Wang et al., 2020a, 2020c). Notable reductions in $PM_{2.5}$, PM_{10}, SO_2, NO_2, NO, and CO were observed. The study from Ecuador was shown that the large drop of NO_2 (-68%), SO_2 (-48%), CO (-38%), $PM_{2.5}$ (-19%) was found in Quito during the first month of quarantine after COVID-19 outbreak compared with pre-COVID-19 period (Zalakeviciute et al., 2020). Ma and Kang (2020) indicated that levels of $PM_{2.5}$ and NO_2 were obviously reduced in Wuhan by 29.9% and 53.2%, respectively, after lockdown and decreased in Daequ by 20.9% and 19.0%, respectively, and Tokyo by 3.6% and 10.4%, respectively, after self-quarantine between January 23 and April 30 in 2020. Agarwal et al. (2020) revealed the average drop of $PM_{2.5}$ and NO_2 in six cities (Xiangyang, Jingzhou, Huanggang, Xiaogan, Wuhan, and Yichang) in Hubei province, China and six megacities (Delhi, Lucknow, Kolkata, Mumbai, Chennai, and Jaipur) in India by -11.3% and -48.6% for $PM_{2.5}$ and NO_2 in China as well as by -20.2% and -59.3% in India after a week of lockdown for COVID-19 issues. The Singaporean report showed the large reduction of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO by 29%, 23%, 52%, 54%, and 6%, respectively, while the increment fold of ozone (O_3) was 1.18 times after lockdown compared with pre-lockdown periods from April 2016 to May 2020 (Li and Tartarini, 2020). The decline of O_3 in the ambient air after lockdown implementation might be mainly due to lower titration O_3 by NOx (Bedi et al., 2020; Brimblecombe et al., 2020; Kumari et al., 2020b). At the same time, O_3 was significantly increased due to reductions in human and economic activities, traffic restrictions, and decreases in energy consumption during lockdowns for COVID-19 in various countries in comparison to the pre-lockdown period (Collivignarelli et al., 2020; Dantas et al., 2020; Kerimray et al., 2020; Li et al., 2020a, 2020b; Mahato et al., 2020; Nakada and Urban, 2020; Otmani et al., 2020; Sharma et al., 2020; Wang et al., 2020c). The improvement of air quality may be associated with the reduced emissions from transportation, which is related to NO_2 reductions, and the manufacturing industry, which has been linked to reductions of $PM_{2.5}$ and CO in China during the COVID-19 outbreak (Wang et al., 2020c). The effects of lockdowns due to COVID-19 on O_3 production in southern European cities (Turin, Valencia, Rome and Nice), as well as in Wuhan, China, maybe a reasonable explanation for the unpredicted decrease in NO_x emissions due to lowering ozone generation by NO (Sicard et al., 2020). Generally, the mechanism of ground-level O_3 formation and depletion is complicated to be associated with the secondary pollutants which are formed by photochemical reaction of NOx and volatile organic compounds (VOCs) due to natural sources or human activities (Bedi et al., 2020). The possible explanation for the generation of O_3 related to COVID-19 is the lower $PM_{2.5}$ loading, which decreases the sink for hydroperoxy radicals (HO_2) (Wang et al., 2020b). Meteorological interference or variations should also be taken into account in terms of their air quality impacts during this outbreak (Dantas et al., 2020; Kerimray et al., 2020; Li et al., 2020b). Kerimray et al. (2020) indicated that benzene and toluene levels in the COVID-19 period had 2-3 fold higher magnitudes compared with those in the same seasons from 2015 to 2019. These sources contribute substantially from various nontraffic-related sources, such as combined coal-fired heat and power plants and household heating systems (Kerimray et al., 2020). Long-range transport aerosols contribute to air pollution, particularly in the case of $PM_{2.5}$ and PM_{10} in receptor areas, and in turn decrease the benefits of local emission reductions related to COVIID-19 (Li et al., 2020a; Otmani et al., 2020). Obvious reductions in PM, such as emission reductions in transportation and slight reductions in industrial sources, in cities in central or southern China, did not lead to avoiding the PM loadings due to severe air pollution in northern China via long-range transport during the lockdown period (Griffith et al., 2020, Li et al., 2020a). To summarize the current global data, lockdowns or quarantining for COVID-19 have contributed to a positive impact on improvements in air quality (Nakada and Urban, 2020; Wang et al., 2020c), recovery from climate change (Rosenbloom and Markard, 2020), and attenuation of environmental impacts (Saadat et al., 2020).

The present study was focused on changes in $PM_{2.5}$ from January to March in 2019 and 2020 in selected industrial areas in the north and south Taiwan, where no lockdown or quarantine was implemented during the COVID-19 outbreak. A huge amount of data on $PM_{2.5}$ was recorded and provided by the $PM_{2.5}$ sensors in the selected areas to further examine $PM_{2.5}$ concentrations in the first quarter (from January to March) of 2019 and 2020 and evaluate the effects of $PM_{2.5}$ loading from domestic sources and transboundary transportation during the COVID-19 outbreak.

2 METHODS

2.1 Data collection from $PM_{2.5}$ sensors

The Taiwanese Environmental Protection Administration (TEPA) established 10,200 air quality sensors in Taiwan before 2020. More than 3,200 air quality micro stations are located in the the north and south Taiwan (Fig. 1) (Civil IoT Taiwan, 2020). An air quality micro station to assess $PM_{2.5}$ is set up at the height of 3 m from the ground in industrial areas to gather data following the TEPA standard. The $PM_{2.5}$ data from $PM_{2.5}$ sensors were freely announced to the public on the Civil IoT Taiwan Data Service Platform website. $PM_{2.5}$ data from air quality micro stations are generated every 1 or 3 minutes. The $PM_{2.5}$ from the network for air quality micro stations developed by the TEPA was aimed at investigating $PM_{2.5}$ emissions and levels in hotspot areas to identify and trace $PM_{2.5}$ emission sources in these regions. The hourly average $PM_{2.5}$ concentrations are calculated based on acceptable $PM_{2.5}$ data. More than 75% of all hourly average concentrations in a sensor are accepted as effective $PM_{2.5}$ data over an hour based on the TEPA standard. Based on the previous criteria, $PM_{2.5}$ micro sensor stations were selected at 609 and 891 stations for north and south Taiwan, respectively, from January to March in 2019 and 549 and 872 stations for north and south Taiwan, respectively, from January to March in 2020 (Table 1). The hourly average $PM_{2.5}$ levels were collected between January and March in 2019 and 2020. For standardization of $PM_{2.5}$ data quality and assurance of the reliability of $PM_{2.5}$ sensors, the TEPA regulates whether the data meet the standard through certified laboratory certification, field certification, and parallel comparisons between a TEPA air pollution monitor site and an air sensor. The $PM_{2.5}$ data taken from air sensors were collected daily between January and March in 2019 and 2020 for further statistical analyses. The $PM_{2.5}$ data in the cloud system were gathered and transferred to statistical software, including the Statistics Analysis System (SAS) and Microsoft Excel-based on time series before the big data analysis. More than 63,000,000 and 59,000,000 units of data on $PM_{2.5}$ from the air quality micro stations were gathered in the first quarter of 2019 and 2020, respectively.

2.2 Statistical analysis

A descriptive analysis, including mean, standard deviation (SD), median, mode, and standard error (SE), was used on the $PM_{2.5}$ data in the first stage. The probability density distribution of $PM_{2.5}$ in the first quarter of 2019 and 2020 and the difference between the probability density distribution in 2019 and 2020 were compared, where the median $PM_{2.5}$ in 2019 minus the median

$PM_{2.5}$ in the corresponding period of 2020 ($PM_{2.5/2019}$-$PM_{2.5/2020}$) were calculated. An unrotated principal component analysis (PCA) was used to determine the initial $PM_{2.5}$ conditions by replacing the original complex variables with linear combinations of major components. The unrotated PCA maximizes the sums of the root mean square (RMS) of the correlation coefficient (CV), whereas the PCA (varimax method) maximizes the variance of the squared correlation coefficients in the rotated principal components (RPCs) (Kaiser, 1958; Horel, 1981). In order to interpret $PM_{2.5}$ dependence or independence of RPCs between 2019 (pre-COVID-19 periods) and 2020 (COVID-19 outbreak), thousands of $PM_{2.5}$ data from the sensors in the industrial areas from north and south Taiwan were used. The maximum of the CV second-order moment causes the CVs to generate a wide distribution of RPCs and measurable variables. However, the factor loadings of most measurable variables were zero, and few of them presented the high loading magnitudes among the RPCs that would easily simplify the explanation of the relationship between the RPCs and the measurable variables. A time-series normalization for the $PM_{2.5}$ data was thus needed before the RPCs could be determined (Eq. (1)).

$$Z_{ik} = \frac{C_{ik}-\mu_i}{S_i} \qquad (1)$$

where Z_{ik} represents the Z score of kth time series $PM_{2.5}$ value from air quality micro station i; C_{ik} represents the kth time series $PM_{2.5}$ concentrations from air quality micro station i; μi represents the mean $PM_{2.5}$ concentrations at air quality micro station i; and Si represents the standard deviation of $PM_{2.5}$ concentrations at air quality micro station i. The association of the RPCs and Z scores could be expressed as in Eq. (2).

$$Z_{ik} = \sum_{j=1}^{n} L_{ij} P_{jk} \tag{2}$$

where L_{ij} represents the factor loadings of the j^{th} RPCs from air quality micro station i, and P_{jk} represents the k^{th} observation value of the j^{th} RPC.

All statistical analyses were tested using SAS JMP (NC, USA). The figures were drawn using SigmaPlot 14.0 software (Systat Software, Inc, CA, USA).

3 RESULTS

3.1 Hourly $PM_{2.5}$ in air quality micro stations located in the north and south Taiwan

As shown in Table 1, the median hourly $PM_{2.5}$ concentrations from the air quality micro stations (air sensors) in the industrial areas were 16.3 (2019N) and 32.4 (2019S) µg m^{-3} in the north and south Taiwan, respectively, between January and March of 2019 and were 15.7 (2020N) and 29.3 (2020S) µg m^{-3} in the north and south Taiwan, respectively, in 2020. Compared with the corresponding period in 2019, the median $PM_{2.5}$ was reduced by 3.70% and 10.6% in the north and south Taiwan, respectively, in 2020 during the pre-and post-COVID-19 outbreak. When considering the total hourly average $PM_{2.5}$ data in the big data comprising more than 5,000,000 measurements, the reduction in $PM_{2.5}$ from 2019N to 2020N was 1.70%, and that from 2019S to

2020S was 4.42%, respectively).

3.2 Probability density distribution of hourly $PM_{2.5}$ in the north and south Taiwan

The changes in the probability density distribution for hourly $PM_{2.5}$ data in the industrial areas of north and south Taiwan from January to March in 2019 and 2020 are shown in Fig. 2. A unimodal distribution was found in these four probability density distribution modes, including 2019N, 2019S, 2020N, and 2020S (Fig. 2A). The median and CV of the hourly $PM_{2.5}$ values in north Taiwan were lower than those in south Taiwan. The mode for hourly $PM_{2.5}$ decreased from 14 μg m^{-3} in 2019N to 12 μg m^{-3} in 2020N, and from 34 μg m^{-3} in 2019S to 26 μg m^{-3} in 2020S, respectively. The modes were consistent: 9.2% (2019N) and 10.2% (2020N) of the total $PM_{2.5}$ in north Taiwan, and 4.2% (2019S) and 5.1% (2020S) of the total $PM_{2.5}$ in south Taiwan. According to the air quality guidelines of $PM_{2.5}$ established by the WHO, $PM_{2.5}$ was not to exceed 10 and 25 μg m^{-3} for the annual and 24-hour means, respectively. If WHO's guideline for $PM_{2.5}$ 24-hour mean was used as the cutoff point in the hourly $PM_{2.5}$ data in the present study, the 25.1% (2019N), 23.7% (2020N), 65.3% (2019S), and 60.6% (2020S) $PM_{2.5}$ data exceeded the WHO's guideline. Evaluating the impact of COVID-19 on outdoor air, the differences in the median for hourly $PM_{2.5}$ between 2019 and 2020 (e.g., $PM_{2.5}$ on January 22, 2019 minus $PM_{2.5}$ on January 22, 2020) are shown in Fig. 2B. Although the differences in the median for hourly $PM_{2.5}$ between 2019 and 2020

(2019N-2020N and 2019S-2020S) were not consistently either positive or negative, most figures were positive and ranged from 0.0 to 5.0 μg m^{-3} (2019N-2020N) in north Taiwan and between 1.0 and 9.0 μg m^{-3} (2019S-2020N) in south Taiwan (Fig. 3).

3.3 Rate at which hourly $PM_{2.5}$ levels exceeded the $PM_{2.5}$ daily standard

Three ambient air quality standards for daily $PM_{2.5}$ (24-hour mean), 35 μg m^{-3} for Taiwan; 25 μg m^{-3} for the WHO, and 55.5 μg m^{-3} for sensitive groups (air quality index, AQI =150) on the USEPA, were chosen as the evaluation and comparison criteria to demonstrate the hourly $PM_{2.5}$ concentrations. A Pareto analysis (Cao et al., 2019) is a technique used for decision making based on the 80/20 rule, which statistically indicates that a limited number of input factors (counted hours) have the most significant impact on an outcome (exceeding rate for $PM_{2.5}$ daily standard). If the proportion of limited hours can capture the proportion of most hours during which $PM_{2.5}$ concentrations are higher than the legal standard, decision makers can capture the majority of high $PM_{2.5}$ pollution events with a few hours or days. This study was concerned with the cumulative ratios for the number of effective hours as the input, with the cumulative ratios for the numbers of hours exceeding the daily $PM_{2.5}$ standards.

For the hourly average $PM_{2.5}$ levels in 2019N (Fig. 4A), the top 10% of the hours with high concentration values explained 16.8%, 25.5%, and 37.1% of the total hours exceeding the $PM_{2.5}$

standards of 25, 35, and 55.5 μg m^{-3}, respectively, and the top 20% of the hours explained 30.6%, 38.7%, and 56.7% of the total hours, respectively. The top 20% hours in 2020N explained 31.5%, 38.2%, and 53.6% of the total hours exceeding the $PM_{2.5}$ standards of 25, 35, and 55.5 μg m^{-3}, respectively. The top 20% hours explained 56.7% and 53.6% of the total hours exceeding the $PM_{2.5}$ standards of 55.5 μg m^{-3} in 2019N and 2020N, where the cumulative rate exceeding the standard in North Taiwan decreased by 3.10% during the first quarter of 2020.

For the hourly $PM_{2.5}$ levels in 2019S (Fig. 4B), the top 10% hours explained 11.8%, 14.4%, and 25.8% of the total hours exceeding the $PM_{2.5}$ standards of 25, 35, and 55.5 μg m^{-3}, respectively; and the top 20% hours explained 23.1%, 27.1%, and 44.4% of the total hours exceeding that standard, respectively. The top 20% hours in 2020 explained 25.8%, 33.6%, and 55.7% of the total hours exceeding the $PM_{2.5}$ standards of 25, 35, and 55.5 μg m^{-3}, respectively. The top 20% hours explained 44.4% and 55.7% of the total hours higher than the $PM_{2.5}$ standards at 55.5 μg m^{-3} in 2019S and 2020S, where the cumulative rate at which the standards were exceeded in south Taiwan decreased by 11.3% during the first quarter of 2020.

The rates at which the hourly $PM_{2.5}$ levels exceeded distinct standards demonstrated the concentration profiles of high $PM_{2.5}$ levels over north and south Taiwan. The rates at which the standards of 25.0, 35.0, and 55.5 μg m^{-3} were exceeded in north Taiwan (Table 3) were 25.8%, 9.45%, and 1.05 % in 2019 and 23.6%, 9.79% and 1.56 % in 2020, respectively. The rates at which the standards of 25.0, 35.0 and 55.5 μg m^{-3} were exceeded in south Taiwan were 64.5%, 40.2%, and 13.6 % in 2019; 60.6% and 36.9%, and 11.7 % in 2020, respectively. Compared to 2019, there was a decreasing trend at which the $PM_{2.5}$ concentrations exceeded the standards for most stations during the COVID-19 period in north Taiwan; however, sporadic stations experienced an upward trend and resulted in the rates beyond the standard increasing 0.34% and 0.51% for the standard of 35 and 55.5 μg m^{-3}. The $PM_{2.5}$ concentrations showed a decreasing trend for most stations during COVID-19 period in south Taiwan, where the rate at which the standards of 25.0, 35.0 and 55.5 μg m^{-3} were exceeded decreased by 3.88%, 3.34%, and 1.91%.

3.4 Spatial changes in $PM_{2.5}$ between January and March in 2019 and 2020

The descriptive statistics for $PM_{2.5}$ and the regional changes in $PM_{2.5}$ based on the geographical statistics could not be used in the present study due to collection from more than two thousand air quality micro stations that generate thousands of units of $PM_{2.5}$ data in each station. Therefore, the RPCs were used to explain the spatial characteristics of the median hourly average $PM_{2.5}$ in our selected areas. Three factors, including eigenvalues, explained variances, and factor loadings, were mainly used to determine the number of principal components. The RPCs of the hourly average $PM_{2.5}$ data were determined as shown in Table 2. The number of principal components was first determined, based on having an eigenvalue over 1.00, to be 28 and 19 RPCs in 2019 and 2020, respectively, from $PM_{2.5}$ data of north Taiwan as well as 34 and 37 RPCs in 2019 and 2020 from south Taiwan. Secondly, the number of principal components was chosen based on the explained variances being over 1% and was reduced to 7 and 8 RPCs in 2019 and 2020, respectively, from south Taiwan. In north Taiwan, both had 6 RPCs in the two years under consideration. Therefore, the number of principal components was finally determined to be 6 $PM_{2.5}$ RPCs in north Taiwan. For the hourly average $PM_{2.5}$ data in south Taiwan, the station numbers for the 7th, 8th, and 9th RPCs were 11, 11, and 2 in 2019 and 0, 12, and 0 in 2020, respectively, based on factor loadings over 0.5 (data not shown). The 7th $PM_{2.5}$ RPC in 2020 from the $PM_{2.5}$ data for south Taiwan did not reveal better correlations between the principal components and the micro air quality stations as compared with the other RPCs from the 1st to 9th RPCs. Finally, the predominant number of RPCs in the present study was determined to be 6 in the $PM_{2.5}$ stations in both north and south Taiwan after the eigenvalues, explained variances, and factor loadings were taken into consideration (Fig. 5 and 6).

Fig. 5 shows the contour maps of factor loadings for distinct RPCs in 2019 and 2020 from north Taiwan, and those from south Taiwan are shown in Figure 6 to present the main $PM_{2.5}$ contour maps. In Fig. 5A, the main $PM_{2.5}$ factor loadings in the industrial areas in 2019 were as follows: (1) The 1st RPC was in Dayuan (DY) and Kuangin (KI); (2) the 2nd RPC was focused on Taipei City and New Taipei City; (3) the 3rd RPC was located at Pingzhen (PZ); (4) the 4th RPC was in

Linkou (LK), and (5) the 5th and 6th RPCs were in Guishan (GS). The $PM_{2.5}$ factor-loading map of the 6 main RPCs in 2020 was consistent with those in 2019 except for the 5th RPC in GS due to a lower factor loading in 2020 compared with that in 2019 (Figure 5 B). As shown in Fig. 6A, the 1st RPC of the hourly average $PM_{2.5}$ factor loading in 2019 was located at downtown Kaohsiung City; the 2nd RPC was distributed in the industrial areas of Pingtung County; the 3rd RPC was in the northern part of Kaohsiung City; the 4th RPC was focused on the Pingnan (PN) industrial area, and the 5th and 6th RPCs were scattered in sporadic points in industrial areas in Kaohsiung City. For the duration of the COVID-19 outbreak in 2020, the main factor loadings for the $PM_{2.5}$ for the 1st to 4th RPCs are shown to be consistent in terms of the factor-loading map with those in 2019 from the industrial areas of south Taiwan (Fig. 6B). Various $PM_{2.5}$ factor loadings were found in the 5th and 6th RPCs between 2019 and 2020 in south Taiwan.

4 DISCUSSION

Compared with the global pandemic outbreak of the COVID-19, the spread of the SARS-cov-2 virus was prevented and controlled effectively in Taiwan by the TCDC due to encouraging the Taiwanese population to wear masks in public, practice social distancing, reduce outdoor activities, and stay away from crowded areas. Taiwan was one of the few countries in the world without a lockdown required during the COVID-19 outbreak. Even with the absence of a lockdown in Taiwan during the COVID-19 outbreak, artificial activity was limited, which led to a reduction in air pollution based on the results of the present study. In Table 1, it can be seen that the median hourly average $PM_{2.5}$ levels were slightly decreased from 16.3 (2019N) to 15.7 (2020N) $\mu g\ m^{-3}$ in north Taiwan and from 32.4 (2019S) to 29.3 (2020S) $\mu g\ m^{-3}$ in south Taiwan. The reduction in $PM_{2.5}$ between January and March of 2019 and the corresponding duration in 2020 was 1.70% and 4.42% in the north and south Taiwan, respectively. Our findings were consistent with those from the previous report announced by the TEPA (Liang and Tsai, 2020) indicating that nation-wide average $PM_{2.5}$ collected at the national-scale air pollution monitoring sites was reduced from 21.4 $\mu g\ m^{-3}$ between October 2018 and March 2019 to 19.8 $\mu g\ m^{-3}$ in the corresponding period from 2019-2020 ($PM_{2.5}$ attenuated by 7.1%) in Taiwan. Han et al. (2020) assessed improvements in $PM_{2.5}$ quality in Seoul, Korea, which didn't execute a lockdown, before and after implementing social distancing during the COVID-19 outbreak and found a 10.4% reduction. Ma and Kang (2020) also revealed that the decline in daily $PM_{2.5}$ in the month before and after social distancing implementation without a lockdown was 20.9% in Daegu and 3.6% in Tokyo, respectively. According to the two previous reports for Korea and the results of the present study (Han et al., 2020; Ma and Kang, 2020), implementation of social distancing and self-quarantining by the government legislation resulted in significantly obvious $PM_{2.5}$ decline in the regions and cities being investigated, including Taiwan, Korea, and Japan, without a mandatory lockdown. This was probably due to a lower $PM_{2.5}$ emissions in unlocked down regions due to limited anthropogenic activities, such as industrial production, transportation, and economic activities. The reduction could also have been related to the meteorological conditions discussed earlier (Lolli et al., 2020). Due to the global spread of the SARS-cov-2 virus, most countries were under mandatory lockdown conditions to introduce precautionary measures including limitations on travel, public gatherings, and a mandatory 14-day quarantine period for suspected or confirmed patients and overseas travellers, to help prevent the spread of COVID-19. The precautionary measures taken during lockdown facilitated temporary improvements in air quality particularly in highly polluted countries (e.g., China, India, and Italy), where $PM_{2.5}$ levels were significantly and dramatically decreased by at least 25% (Bedi et al., 2020; Li et al., 2020a; Li et al., 2020c; Kumar et al., 2020a; Şahin, 2020; Shakoor et al., 2020; Srivastava et al., 2020; Zoran et al., 2020).

According to Fig. 5 and 6, the spatial patterns of 6 main PCs in 2019 and 2020 were overlapped. The intensity of PCs in 2019 was slightly higher than in 2020 from the north and south Taiwan, as shown in Table 1 and Fig. 2 and 3, indicating that $PM_{2.5}$ levels between January and March in 2019 had significantly and slightly higher magnitudes than those in the corresponding periods of 2020 in the north and south Taiwan. Liang and Tsai (2020) revealed that $PM_{2.5}$ in Taiwan is associated with transboundary transportation of $PM_{2.5}$, weather type, meteorological conditions, and precursors of $PM_{2.5}$, but $PM_{2.5}$ levels from transboundary transportation in 2020 were reduced by

0.31 μg m^{-3} compared with those in the corresponding period in 2019 (Please see the supplemental materials and Fig. S1). This finding indicated that the main reason for the improvement in air quality due to $PM_{2.5}$ in 2020 was related to the decline of $PM_{2.5}$ precursors, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), probably due to limitations on artificial and economic activities, but the improvement was slightly linked to transboundary transportation of $PM_{2.5}$, weather type, and meteorological conditions (Liang and Tsai, 2020) (Please see the supplemental materials and Fig. S2 and S3). Therefore, the long-range $PM_{2.5}$ transport from China (transboundary transportation) had minor effects on reductions in $PM_{2.5}$ during the COVID-19 outbreak in Taiwan. Reductions in $PM_{2.5}$ from local emissions were mainly associated with the decline in $PM_{2.5}$ during the COVID-19 situation (Please see the supplemental materials and Fig. S1, S2, and S3). Inversely, Han et al. (2020) indicated that synoptic conditions and the decline in aerosol optical depth from eastern China to the Korean Peninsula led to improvements in air quality, including $PM_{2.5}$, in Seoul during the COVID-19 outbreak, which might have been due to declines in domestic emissions and reductions in long-range transboundary transportation of air pollutants. According to our findings, $PM_{2.5}$-related air quality was temporarily improved during the COVID-19 outbreak mainly from reduced levels of NO_2 and SO_2 from local emissions via limitations placed on human activities. $PM_{2.5}$ levels have a significantly positive association with the number of cases and mortalities associated with the SAS-cov2 virus. It is reiterated that $PM_{2.5}$ control and reductions in $PM_{2.5}$

emissions, especially those from local sources, are very important to reducing COVID-19 case numbers.

5 CONCLUSIONS

COVID-19 spread was well controlled and limited in Taiwan by TCDC from January 20, 2020 to the present through a policy including community prevention, border quarantining, and medical responses. Taiwan is a region that was able to avoid a mandated lockdown during the COVID-19 outbreak. Air quality of $PM_{2.5}$ in the industrial areas of north and south Taiwan was slightly improved by 1.70% and 4.42% in north and south Taiwan, respectively, from January to March of 2020 as compared with those from the corresponding time of 2019 by big data analysis. The $PM_{2.5}$ spatial patterns, analyzed with a large amount of measured data, between January and March of 2020 were similar to those in the corresponding period in 2019, indicating that a reduction in $PM_{2.5}$ emissions was observed due to implementation of social distancing and limitations placed on human and economic activities. The decline of $PM_{2.5}$ during COVID-19 outbreak was mainly due to demostic $PM_{2.5}$ reduction in Taiwan and minor from long-range transport and transboundary transportation of air pollutants reduction.

Declaration of competing interest

The authors declare no conflict of interest including financial interests and personal relationships.

Acknowledgements

This study was financially and partially supported by a grant from the Ministry of Science and Technology (MOST 109-2221-E-020-009-MY3). We thank the staff of JS Environmental Technology and Energy Saving Co. Ltd., Kaohsiung, Taiwan for assisting with the acquisition of $PM_{2.5}$ big data.

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Table 1. Hourly average levels of $PM_{2.5}$ from air quality micro stations between January and March in 2019 and 2020 located in the industrial areas from northern and southern Taiwan

Year	2019		2020	
Region	North (2019N)	South (2019S)	North (2020N)	South (2020S)
$PM_{2.5}$ sensor stations	609	891	549	872
Effective data for hourly average $PM_{2.5}$ concentration	97.7%	99.5%	95.6%	97.3%
Median $PM_{2.5}$ levels ($\mu g\ m^{-3}$)	16.3	32.4	15.7	29.3

[a] $PM_{2.5}$ sensor stations were selected based on the standard of Taiwanese Environmental Protection Administration. The hourly average $PM_{2.5}$ concentrations in a sensor were included in the present study for at least 75% or higher of acceptable effective data for hourly average $PM_{2.5}$ concentrations. Stations which effective data for hourly average $PM_{2.5}$ concentrations were lower than 75% were excluded.

[b] Effective data for hourly average $PM_{2.5}$ concentration meant the hourly average $PM_{2.5}$ concentration was followed by the regulation from Taiwanese Environmental Protection Administration, indicating that the data from a sensor in an hour ($PM_{2.5}$ level was generated each 1 or 3 minutes) at least was provided for 75% or higher of acceptable measured data before the calculation.

Figure 6. Loading values of 6 rotated principal components in $PM_{2.5}$ levels from $PM_{2.5}$ sensors of the industrial areas from southern Taiwan between January and March in 2019 and 2020