AJAE

Open Access

Vol. 14, No. 3, pp. 253-262, September 2020
doi: https://doi.org/10.5572/ajae.2020.14.3.253
ISSN (Online) 2287-1160, ISSN (Print) 1976-6912

Research Article

Air Quality Variation in Daegu, Korea During the Outbreak of COVID-19 and its Health Risk Assessment

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Received: 6 May 2020
Revised: 10 June 2020
Accepted: 26 June 2020

ABSTRACT Coronavirus disease 2019 (COVID-19), first reported in Wuhan, China, became pandemic in less than two months, and Korea was no exception. Daegu Metropolitan City, in particular, has become the center of the explosive outbreak in Korea. In this study, we evaluated how the air quality of Daegu Metropolitan City varied when people were fighting the spread of COVID-19. In concretely, we tried to estimate the air quality variation with the trend of COVID-19 in Daegu Metropolitan City based on the measured data at hourly intervals from two air quality monitoring stations (AQMSs) (see Fig. 2). In addition, we quantitatively assessed the positive health effects of improved air quality from fighting against COVID-19. Compared to the concentration in the same period of 2019, the $PM_{2.5}$ measured at the ambient AQMS decreased by 36.7, 22.5, and 37.6% respectively in January, February, and March. Meanwhile, those at the road side AQMS were 39.9, 23.7, and 40.3% in January, February, and March, respectively. The decreasing trend was not shown in April. Along with the floating population, the concentration of NO_2 at the road side AQMS decreased from 49.9 ppb to 32.7 ppb, indicating that the reduction rate was 34.5%. The summed concentration of seven hazardous metals decreased by 27.4% in February 2020 compared to 2019. Among them, lead showed the biggest drop to 43.4% in 2002 compared to 2019. The exposure of $PM_{2.5}$, $Dose_{PM2.5}$ (μg), during 60 days of self-reflection for 10-year-old children has decreased by 29.6% compared to that in the same period of 2019. The results of adult females and males also show 27, 8% and 29.5% decrease, respectively.

KEY WORDS $PM_{2.5}$, NO_x, COVID-19, Daegu, Exposure dose of $PM_{2.5}$, Health effect

1. INTRODUCTION

Coronavirus disease 2019 (COVID-19) initially identified in Wuhan, China in December 2019 spread rapidly around the world within two weeks after the first report (Huang *et al.*, 2020).

In the case of Korea, the number of cases sharply increased after the first confirmed case report on January 20, resulting in 12,240 cases as of April 30. Especially in Daegu, just 17 days after the first case was reported on February 18, an explosive spread of over 5,100 cumulative cases occurred. In order to prevent the spread of these unexpected infectious diseases, the administrative authorities enforced vari-

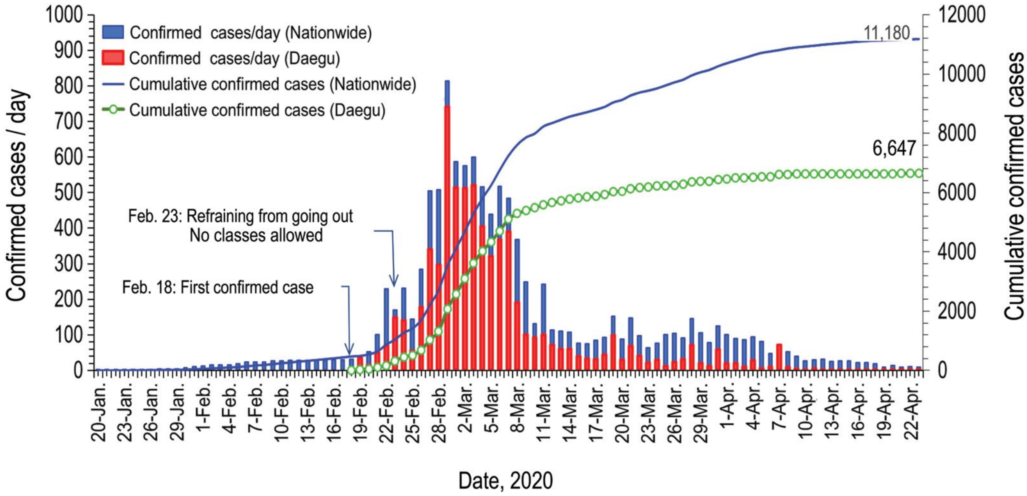

Fig. 1. Timely variation of the confirmed cases of COVID-19 per day and the cumulative status in Daegu, Korea.

ous administrative regulations from February 23. Typical regulations include refraining from going out, no classes allowed in various academies, and postponement of school opening. On March 5, 42 days after strict administrative regulations were enforced, the number of newly confirmed cases decreased to 5 cases per day.

Fig. 1 is the graph for the situation of COVID-19 spread in Daegu Metropolitan City recreated with the data of the Korea Centers for Disease Control and Prevention (KCDC) (COVID-19 status, Korea by KCDC).

Meanwhile, the global quarantine activities for the COVID-19 pandemic have affected the improvement of air quality on Earth's scale. According to the modeling results, the global carbon dioxide emissions may decrease by more than 5% in 2020 and this would be the sharpest decline since World War II (Newsweek, May 4, 2020). In addition, the satellite imagery of NASA and European Space Agency (ESA) has shown how nitrogen dioxide (NO_2) concentration has decreased drastically in every urban cities across China during COVID-19 pandemic (NASA, 2020).

In fact, it is air pollutants that are more lethal than COVID-19 in the long term. A prior study suggested that air pollution kills 7,000,000 people worldwide each year (Brauer, 2010). Even in European countries, 193,000 people died in 2012 because of airborne particulate matter (Ortiz *et al.*, 2017).

It is well known that the exposure to the particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) has been linked to chronic respiratory and cardiopulmonary diseases. Many epidemiologic studies have suggested that children and older adults are particularly susceptible to health impacts (Barnes *et al.*, 2018; Ma, 2015).

The exposure to air pollutants emitted from vehicles, especially diesel exhaust particles (DEP), can also have an adverse health effect of drivers and passengers. Moreover, it is harmful to residents living near the road and to young students at schools around the road (Barnes *et al.*, 2018).

According to the Daegu Metropolitan Government, the daily traffic volume of Sinchon-daero was 73,333 in the first week of March, when the daily confirmed cases of COVID-19 was the peak, which was 74.5% of the average of 94,374 in 2019. Also, the number of passengers using the Daegu Metropolitan Rapid Transit, which used to average 450,000 per day, dropped to 50,000 in March (Korea Economic Daily, 2020).

In the present study, we tried to estimate the air quality variation with the trend of COVID-19 in Daegu Metropolitan City, Korea. The main targets of the air quality estimation were $PM_{2.5}$ and NO_2 monitored almost real-time at two air quality monitoring stations (AQMSs) (see Fig. 1).

2. METHODS

2.1 Description of Daegu Metropolitan City

Daegu Metropolitan City, which experienced the explosive outbreak of COVID-19 in a short period of time and excellent response, is the fourth-largest after

Seoul, Busan, and Incheon with over 2.5 million residents. Daegu is also considered the third major economic city in Korea, after Seoul and Busan. The major industries of Daegu Metropolitan City are textile industry, metals and machinery, automobile component industry, mobile development, and medical care. As of May 2019, the population and area of this city are 2,489,802 and 883.54 km^2, respectively. The total number of cars registered in Daegu Metropolitan City, 2019 was 1,190,154, of which gasoline, diesel, LPG, CNG, hybrid were 561,643, 470,569, 114,533, 2,617, and 26,026, respectively (Institute of Health and Environment of Daegu Metropolitan City, 2020).

2.2 1-hour Interval $PM_{2.5}$ and NO_x Measurement at the AQMSs

In Daegu Metropolitan City, 14 ambient AQMSs and two roadside AQMSs are being operated. In this study, the target AQMSs were the Suchang-dong and Pyeongri-dong monitoring stations as the ambient AQMS and the roadside AQMS, respectively (see Fig. 2). The Suchang-dong AQMS is installed in urban areas and this AQMS measures also major heavy metals including Pb to assess the effect of nearby industrial complexes. Meanwhile, the Pyeongri-dong AQMS is being operated on the road side with a large traffic and floating population. The two AQMSs are separated by a straight-line distance of about 2.2 km. Fig. 2 illustrates the location of two AQMSs in Daegu Metropolitan City, Korea, and their views from the roof of each AQMS.

At the AQSMs, $PM_{2.5}$ is continuously measured by the β-ray absorption method (BAM) every hour. The BAM is the standard method for $PM_{2.5}$ measurement in Korea (NIER, 2009). This is a widely used air monitoring technique employing the absorption of beta radiation by solid particles extracted from air flow (Liberti, 1975).

The chemiluminescence method is being used for the one-hour interval continuous measurement of NO_2. This method uses the thermally-stabilized photodiode to detect the intensity light generated by the reaction of NO with O_3, yielding an excited state of NO_2 and O_2.

The target data of this study was about two-month measurement data monitored at two different AQMSs from January 18 to April 22, when the number of confirmed cases was reduced to one.

PM_{10} was collected at the Suchang-dong ambient AQMS in the second week of each month for five days. Then the heavy metals in PM_{10} including lead and cadmium were analyzed by an atomic absorption spectrophotometer specified in the Korean air pollution test act (Institute of Health and Environment of Daegu Metropolitan City, 2020).

The average monthly temperature, relative humidity,

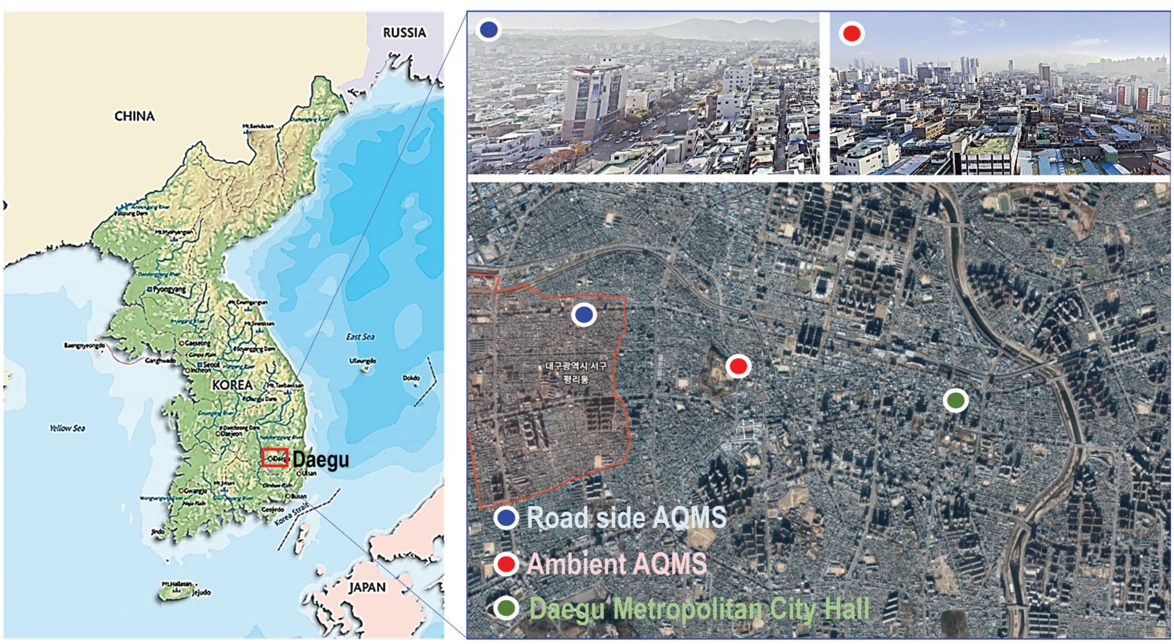

Fig. 2. The location of two AQMSs in Daegu, Korea and their views.

wind speed, and rainfall amount at the monitoring sites during the measurement period in 2020 were ranged 3.8–13.5°C, 52–61%, 2.1–2.4 m/s, and 24.5–70.4 mm, respectively. In the relative year of 2019, they were 1.7–13.5°C, 44–52%, 2.1–2.4 m/s, and 9.5–88.0 mm, respectively. There was little difference between weather factors from January to April of the two years.

3. RESULTS AND DISCUSSION

3.1 Daily Variations of $PM_{2.5}$ at AQMSs

Fig. 3 shows the daily variations of the concentration of $PM_{2.5}$ at the ambient and the roadside AQMSs with the cumulative confirmed COVID-19 cases in Daegu Metropolitan City. To better represent the time shifts in the data over the entire measurement period, the 5-day simple moving average (SMA) ($\bar{C}_{d\,SMA}$) was calculated by follows:

$$\bar{C}_{d\,SMA} = \frac{C_d + C_{d-1} + \cdots + C_{d-(n-1)}}{n} = \frac{1}{n}\sum_{i=0}^{n-1} C_{d-1}$$

where, C_d is the daily averaged data of the corresponding day, and n is the number of time periods in the average (5-day in this study). This ($\bar{C}_{d\,SMA}$) can help us distinguish between typical measurement noise and actual trend reversals.

In Fig. 3, the concentration of $PM_{2.5}$ at the ambient AQMS shows a temporary increase or decrease, but there was a slight decrease in the overall period. Especially from February 1 to February 13, the concentration dropped sharply.

Meanwhile, except for a big drop in early February, the $PM_{2.5}$ at the roadside AQMS did not show any noticeable time change except after April 16. The sharp decline after April 16 was likely to be due to the diffusion and washout by the rain accompanied by strong winds. Several temporary decreases in $PM_{2.5}$ concentration were also caused by the wet-scavenging by rainfall. The overall decline of $PM_{2.5}$ at both AQMSs might be due to the reduction of traffic volume and a partial reduction in economic activity under voluntary self-reflection. Partial reduction in economic activity can be estimated as a large decrease in the floating population as mentioned earlier.

To interpret the data of March 3 and 30, which showed an unusually distinct increase in the overall decline trend, the NOAA's backtrajectories (heights: 500, 1000, 3000 m; duration: 72 hrs) started from Daegu (35.60N; 128.36E) (Rolph, *et al.*, 2017; Stein *et al.*, 2015) were drawn in Fig. 4 with the nationwide distributions of $PM_{2.5}$ on both days.

According to the NIER (National Institute of Environmental Research) of Korea, the $PM_{2.5}$ concentration exceeded 800 μg/m^3 in northeastern China on both days, and air quality across the country was poor due to the

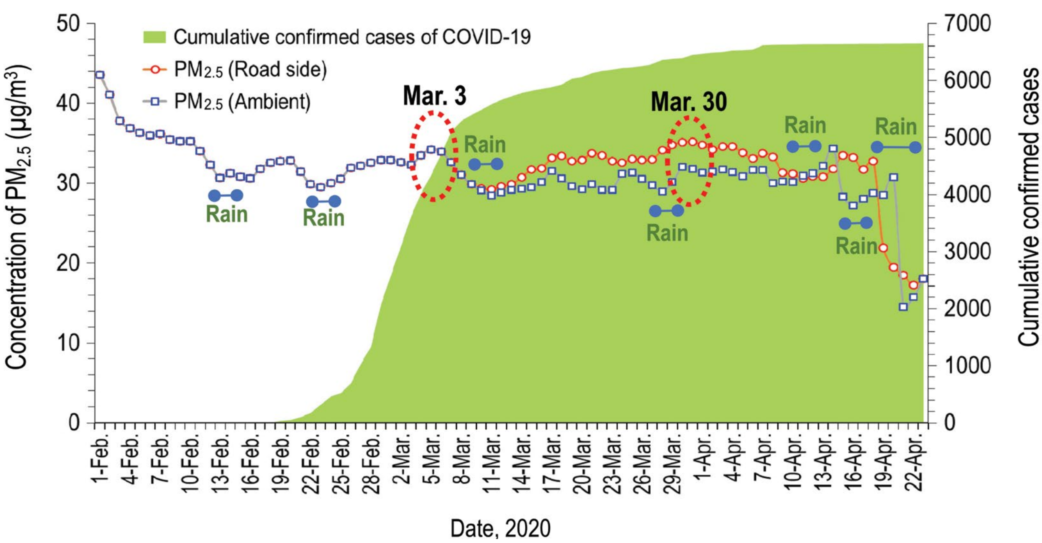

Fig. 3. Daily variations of the concentration of $PM_{2.5}$ at the ambient and road side monitoring station in Daegu, and the cumulative confirmed cases.

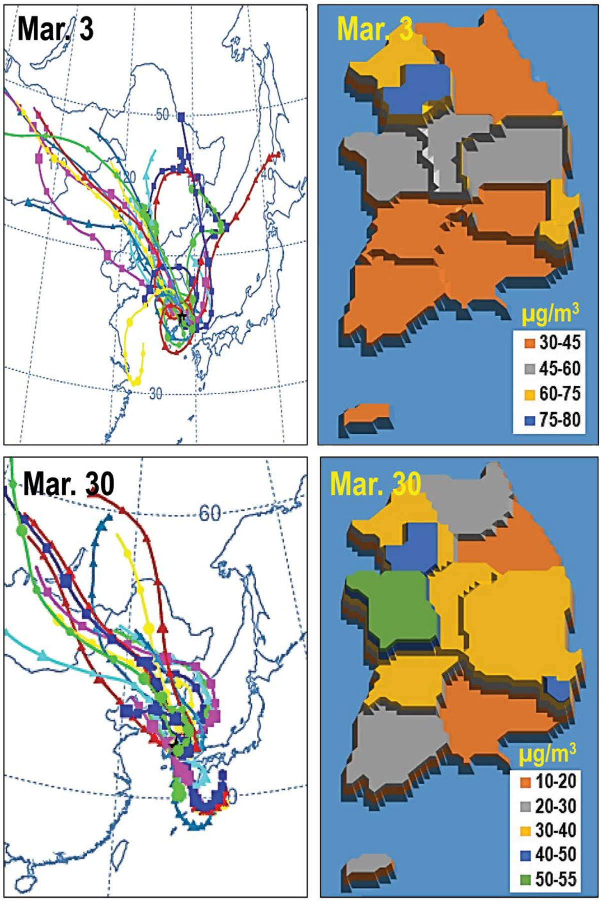

Fig. 4. The NOAA's backtrajectories started from Daegu and the nationwide distributions of $PM_{2.5}$ on Mar. 3 (top) and Mar. 30 (bottom).

influence of the northwest wind of China. The national distributions of $PM_{2.5}$ in Fig. 4 were re-produced based on the presentation of the NIER. Although the inflow amount of $PM_{2.5}$ was smaller than usual year because China also shut down the cities, it still occasionally flowed into Korea.

Fig. 5 is plotting the daily variations of the concentration of NO_2 at the ambient and road side AQMSs in Daegu Metropolitan City, and the cumulative confirmed COVID-19 cases. Unlike $PM_{2.5}$, the continuous large-scale reduction over the whole period was seen. Compared to the $PM_{2.5}$ on February 1, those at the ambient AQMA and the road side AQMS on April 22 decreased by 52.1% and 83.5%, respectively. On March 3, the NO_2 concentrations at both AQMSs were temporarily increased. This is also due to the inflow into China. Although there were occasional temporary reductions in NO_2 because of the wash-out, the overall decline might be due to the people's efforts such as reduction of traffic volume and the partial shutdown of industrial facilities under various regulations. This is the unexpected good result for our health. The U.S. Environmental Protection Agency (EPA) suggested that the short-term exposure of high NO_x can lead to irritated respiratory systems (US EPA, 2019). Based on the results of their model calculation, He *et al.* (2020) suggested that the reduction of NO_2 during COVID-19 epidemic saved 100,000 lives in China.

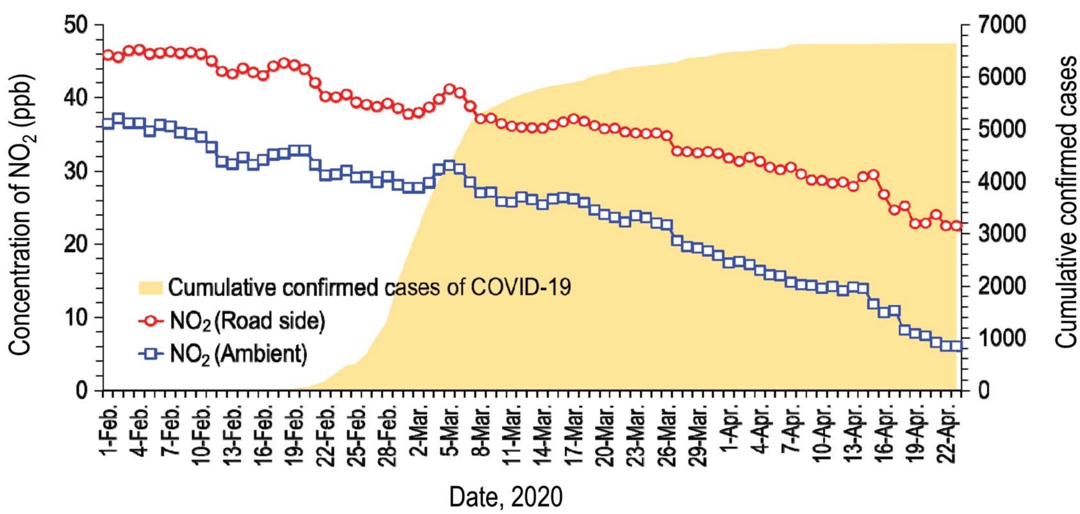

Fig. 5. Daily variations of the concentration of NO_2 at the ambient and road side monitoring station in Daegu, and the cumulative confirmed cases.

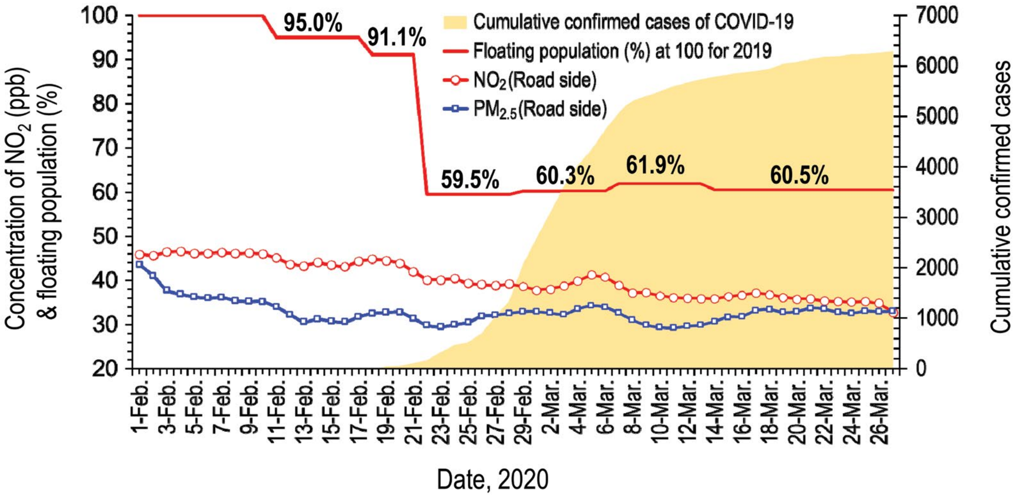

Fig. 6. Daily variations of the concentration of NO_x at the road side monitoring station in Daegu and the weekly flowing population (%) at 100 for the same period of 2019.

3.2 Variation of NO_2 and $PM_{2.5}$ Concentration by Flowing Population

Fig. 6 shows the daily variations of the concentration of NO_x at the road side AQMS in Daegu Metropolitan City and the weekly flowing population (%). The data of flowing population (%) was the result presented by the JoongAng Ilbo on March 27, 2020. The floating population (%) was calculated based on the floating population of 100 during the same period of 2019. As shown in figure, since February 1, when the number of confirmed COVID-19 cases increased to two digits in the Korea, there was a significant decrease in human movement in Daegu Metropolitan City. In particular, after February 19, when the number of confirmed COVID-19 cases in Daegu was 34, it sharply fell to 59.5%. Along with the floating population, the concentration of NO_2 at the road side AQMS also decreased from 49.9 ppb to 32.7 ppb, indicating that the reduction rate was 34.5%. The concentration of $PM_{2.5}$ also dropped from 43.6 to 32.9 $\mu g/m^3$, showing a decrease of about 24.5%.

3.3 $PM_{2.5}$ and Hazardous Metals in 2019 and 2020

Compared to the concentration in the same period of 2019, the $PM_{2.5}$ measured at the ambient AQMS was decreased by 36.7, 22.5, and 37.6% respectively in January, February, and March. Meanwhile, those at the road side AQMS were 39.9, 23.7, and 40.3% in January, February, and March, respectively. The decreasing trend was not shown in April. This is because the self-reflection mode was gradually lifted as the number of confirmed COVID-19 cases decreased to one digit on April 5.

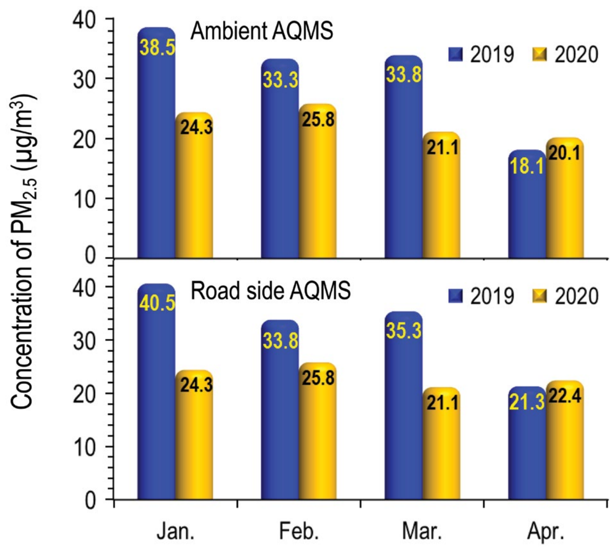

Fig. 7. Comparison of $PM_{2.5}$ measured at ambient and road side AQMSs between 2019 and 2020.

Other factors, such as meteorological conditions, also needed to be considered, but the result in Fig. 7 suggests that the citizens' self-reflection behavior due to COVID-19 temporarily improved air quality in Daegu.

Hazardous heavy metals are persistent in various environments and cause severe health problems due to their toxicity. Chronic exposure to hazardous elements is a real threat to living organisms including human being (Spiegel, 2002).

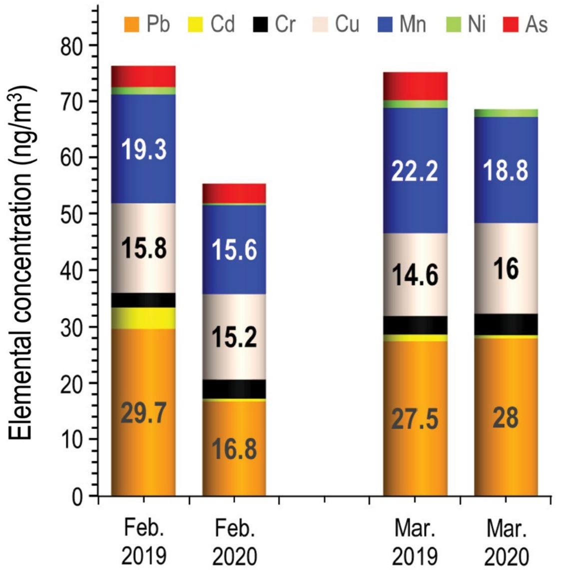

Fig. 8. Comparison of hazardous elements concentrations between 2019 and 2020 in Feb. and Mar.

The concentration of the major harmful elements (lead, cadmium, copper, manganese, nickel, and arsenic) measured by Institute of Health and Environment of Daegu Metropolitan City at the Suchang-dong ambient AQMS in February and March, 2019 and 2020 was shown in Fig. 8. The data comparison for February shows that the summed concentration of seven metals decreased by 27.4% in February 2020 compared to 2019. Among 7 hazardous elements, lead showed the biggest drop to 43.4% in 2002 compared to 2019.

Exposure to lead can cause the damage to the nervous system and give rise to impaired cognitive development and intellectual performance (Wieczorek-Dąbrowska *et al.*, 2003). Dye *et al.* (2001) suggested that the enriched metal constituents in PM induced the greatest degree of airway inflammation.

In the case of March, the total concentration was only 8.8% lower than in 2019. One thing to note is that arsenic (5 ng/m^3 in 2019) was not detected in March 2020. Arsenic is a well-known human carcinogen metal that causes lung and skin cancer (Wieczorek-Dąbrowska *et al.*, 2003).

As reported by Dai *et al.* (2015), the main sources contributing to heavy metals at urban site are the steel dust emitted from coal-fired power plant, vehicle emission, and road re-suspension dust. Of all the hazardous heavy metals, arsenic in particular is well known as harmful heavy metals emitted from coal-fired power plants (Pesch *et al.*, 2002).

The coal-fired power plant in the Daegu dyeing industrial complex rarely located in the downtown of a large city. Daegu Metropolitan City has come up with measures such as undergrounding coal storage due to the highly controversial fine dust problem, but it will still be a source of heavy metals including arsenic.

3.4 Exposure Dose of $PM_{2.5}$ during 60 Days of Self-reflection

According to Fig. 7, the difference between the concentration of $PM_{2.5}$ from January to March 2019 and that in 2020 was 12.12 μg/m^3. Ostro (2004) suggested that the proportion of deaths from the respiratory system disease could be lowered if $PM_{2.5}$ level was reduced to 3 μg/m^3.

By calculating the amount of personal exposure dose, we attempt to estimate whether the concentration of $PM_{2.5}$, which has decreased by an average of 12.12 μg/m^3 over three months, was meaningful to human health. In terms of health effects, to know how much $PM_{2.5}$ penetrate our respiratory system, namely, the exposure dose of $PM_{2.5}$ ($Dose_{PM2.5}$) is crucial.

The $Dose_{PM2.5}$ can be calculated by the below equation proposed by Löndahl *et al.* (2007).

$$Dose_{PM2.5}\,(\mu g) = C_{PM2.5} \times F_{Dep.} \times T_{Exp.} \times R_{Bre.}$$

where, $C_{PM2.5}$ are 35.9 and 23.7 μg/m^3, i.e. the average value of February and March 2019 and that of 2020, $F_{Dep.}$ is the deposition fraction in the alveolar-interstitial (AI) regions of the respiratory tract, $T_{Exp.}$ is the exposure time (h), and $R_{Bre.}$ is breathing rate (m^3/h).

The $f_{Dep.}$ is the maximum deposition efficiency in the AI region decided from the activity patterns suggested by Yamada *et al.* (2007).

Table 1 summarizes the variables and calculated results and of the $Dose_{PM2.5}$ (μg) in the AI region for 10-year children and adult females/males during 60 days of self-reflection from February to March. In this study, their daily activity patterns were classified into four categories, namely, sleep, sitting or rest, light exercise or movement, and heavy exercise. Four kinds of their daily activity patterns were set up assuming that they were mostly indoors during the period of self-reflection. The time required for each pattern is refer to Table 1.

People would have spent most of their time at home due to requests for self-reflection. Choi and Kang (2018) reported that the average indoor/outdoor (I/O) ratio

Table 1. Results and variables of $Dose_{PM2.5}$ (μg) in the AI region for 10-year children and adult females/males during 60 days of self-reflection.

	Daily activity patterns	Activity time (h)	Total exposure period (day)	$C_{PM2.5}$ (μg/m^3) in 2019	$C_{PM2.5}$ (μg/m^3) in 2020	I/O ratio[a]	$F_{dep.}$ in AI	$R_{bre.}$ (m^3/h)	$Dose_{PM2.5}$ (μg) in 2019	$Dose_{PM2.5}$ (μg) in 2020
10-year old children	Sleep	9	60	35.86	23.73	0.66	0.355	0.246	1116	739
	Sitting/Rest	4	60	35.86	23.73	0.66	0.370	0.301	633	419
	Light exrcise/movement	9	60	35.86	23.73	0.66	0.459	0.888	5209	3447
	Heavy exercise	2	60	35.86	23.73	0.66	0.510	1.610	2332	1543
Adult females	Sleep	7	60	35.86	23.73	0.66	0.356	0.252	892	590
	Sitting/Rest	14	60	35.86	23.73	0.66	0.365	0.307	2228	1474
	Light exercise/movement	2	60	35.86	23.73	0.66	0.504	0.984	1409	932
	Heavy exercise	1	60	35.86	23.73	0.66	0.550	2.130	1664	1101
Adult males	Sleep	7	60	35.86	23.73	0.66	0.412	0.360	1474	976
	Sitting/Rest	14	60	35.86	23.73	0.66	0.452	0.432	3882	2569
	Light exercise/movement	2	60	35.86	23.73	0.66	0.530	1.200	1806	1195
	Heavy exercise	1	60	35.86	23.73	0.66	0.587	2.400	2001	1324

[a]The I/O ratio referred to Choi and Kang (2018)

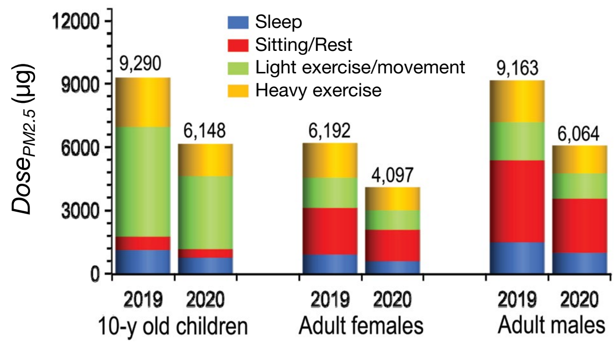

Fig. 9. Comparison between the $Dose_{PM2.5}$ (μg) in 2019 and 2020 for 10-year children and adult females/male during the period from February to March.

was 0.66 for the 14 apartment housing units located in urban areas in Korea including Daegu metropolitan city. Therefore, the indoor $PM_{2.5}$ concentration in the present study was calculated from their I/O ratio.

Fig. 9 shows the comparison between the $Dose_{PM2.5}$ (μg) in 2019 and 2020 for 10-year children, adult females, and adult male during the period from February to March. The $Dose_{PM2.5}$ (μg) for 10-year-old children was 9,290 μg in 2019 and 6,148 μg in 2020. As a result, the $Dose_{PM2.5}$ (μg) in 2020 has decreased by 33.8% compared to that in 2019. The $Dose_{PM2.5}$ (μg) of adult females and males also decreased by 2,094 μg and 3,100 μg, respectively compared to 2019.

The reason why adult females are less exposed $PM_{2.5}$ than children is because of the difference in their life style (see third column of Table 1). As Almeida *et al.* (2011) pointed out, children who are always active are vulnerable to health because their lung surface area per body weight makes them highly susceptible to $PM_{2.5}$.

4. CONCLUSIONS

In the present study, we tried to estimate the air quality variation with the trend of COVID-19 in Daegu Metropolitan City, Korea based on the data measured at two AQMSs. In addition, we quantitatively assessed the positive health effects of improved air quality from fighting against COVID-19. In fact, in numerical terms, poor air quality is taking away our lives on a much larger scale than the current COVID-19 threat (Cohen *et al.*, 2017). Although, the citizens' voluntary actions including self-reflection and proper administrative measures have caused some inconvenience to their daily lives, they can get the certainly improved air quality as unexpected positive effect of COVID-19. Therefore, we should seek an eco-friendly lifestyle for clean air quality management in the future by taking advantage of the lessons of the pandemic of COVID-19.

ACKNOWLEDGEMENT

The data of two AQMSs were the published online by Institute of Health and Environment of Daegu Metropolitan City. It was a great reference of the data discussion in this study, and the authors express their gratitude to them. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (https://www.ready.noaa.gov) used in this publication.

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