Poll Res. 41 (1) : 30-37 (2022)

ISSN 0257–8050
DOI No.: http://doi.org/10.53350/PR.2022.v41i01.003

STATISTICALLY IDENTIFYING THE PATTERN CHANGE IN THE NITROGEN DIOXIDE (NO_2) POLLUTION IN SEOUL AFTER THE COVID-19 PANDEMIC

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(Received 26 July, 2021; Accepted 24 August, 2021)

ABSTRACT

Nitrogen dioxide (NO_2) is a reddish-brown, highly reactive gas generated by oxidation of nitrogen monoxide in the atmosphere. It is widely recognized that NO_2 is a toxic air pollutant as well as being one of the causative substances of secondary ultrafine dust such as particulate matter 2.5 (PM2.5). Our previous work (Chang and Lee, 2021) presents the recent change of PM2.5 and PM10 in Seoul before and after the COVID-19 pandemic. In this paper, we compare the average NO_2 densities in Seoul before and after the COVID-19 pandemic. Our analysis has produced the following results: (i) the average NO_2 density in Seoul has decreased significantly in the first half of 2020 compared to that before the COVID-19 pandemic; (ii) the average difference in the NO_2 density in Seoul between the period from October 2020 to June 2021 and that from October 2019 to June 2020 is not statistically significant. In contrast to discussing average values only, as was done in a report by the Ministry of Environment in the Republic of Korea, our analyses have produced statistically valid results. Our results could be partly interpreted as the effect related to the partial resumption of economic activity in Seoul after the first half of 2020. We also make comments on the implications of our findings, which are not discussed in our previous work (Chang and Lee, 2021).

KEY WORDS: Nitrogen dioxide (NO_2), NO_2 pollution before/after the COVID-19 pandemic, Statistical pattern recognition

INTRODUCTION

Nitrogen dioxide (NO_2) is a reddish-brown, highly reactive gas that is generated by oxidation of nitrogen monoxide in the atmosphere (U.S. Environmental Protection Agency (EPA), 2018; UK Air Pollution Information System, 2019; Greenpeace India Report, 2021; Indoor Quality Air [IQAIR]). Studies suggest that NO_2 could be harmful to human health and associated with several diseases. Long-term exposure to NO_2 can lead to an increase in the incidence of acute respiratory diseases, lung cancer, respiratory stimulation, bronchitis, pulmonary edema; increased blood pressure; and loss of consciousness (American Lung Association; GreenFacts; Institute of Occupational Medicine; U.S. EPA; UK Air Pollution Information System; Greenpeace India Report, 2021). NO_2 not only affects human health but can also cause air pollution. NO_2 is widely recognized as a toxic air pollutant and is one of the causative substances of secondary ultrafine dust such as particulate matter 2.5 (PM2.5) (see Material and Methods for details). Our previous work (Chang and Lee, 2021) presents the recent change of PM2.5 and PM10 in Seoul before and after the COVID-19 pandemic.

In this paper, we compare the average NO_2 densities in Seoul before and after the COVID-19 pandemic. Our analysis has produced the following results: (i) the average NO_2 density in Seoul has reduced significantly in the first half of 2020 compared to that before the COVID-19 pandemic; (ii) the average difference in the NO_2 density in Seoul between the period from October of 2020 to

June 2021 and that from October of 2019 to June 2020 is not statistically significant.

In contrast to discussing average values only, as was done in a report by the Ministry of Environment in the Republic of Korea, our analyses have produced statistically valid results. Our results could be partly interpreted as an effect related to the partial resumption of economic activity in Seoul after the first half of 2020. We also make comments on the implications of findings, which are not discussed in our previous work (Chang and Lee, 2021).

The rest of this article is organized as follows: In Material and Methods, we summarize our review of related works, and their implications and limitations. In Results, we compare the average differences in the average NO_2 density in Seoul during the period from January 2020 to June 2021 and that from January 2019 to June 2020 in Seoul. In the Discussion, we discuss the implications of the results, including comments on the implications of our findings.

MATERIAL AND METHODS- REVIEW OF RELATED WORK

Review of literature on Nitrogen dioxide (NO_2)

We summarize the properties, hazards, derivation, environmental effects, and environmental limit of Nitrogen dioxide in Table 1 (U.S. EPA, 2018; UK Air

Table 1. Properties, hazards, environmental effects, and environmental limit of NO_2

Properties	• A red-brown gas or yellow liquid; becomes a colorless solid at -11.2 °C, which exists in varying equilibrium with other oxides of nitrogen as the temperature is varied. • Melting point (liquid): -9.3 °C, Boiling point (gas): 21 °C, Density: 1.880 g/L, Odor: Chlorine-like, Specific heat: 1.0 cal/g (solid), 0.477 cal/g (liquid), The specific heat of a gas varies greatly with temperature due to dissociation. Noncombustible. • NO_2 acts as a precursor to generate ozone (O_3) by reacting with volatile organic compounds in the atmosphere. • The greenhouse effect of NO_2 is 260 times higher than that of carbon dioxide (CO_2), even at a lower concentration in the air. NO_2 is one of the causative substances of secondary fine dust. NO_2 causes greater damage to the human body than nitrogen monoxide (NO). The toxicity of NO_2 is 5 to 10 times that of NO.
Hazard	• Highly toxic; inhalation may be fatal. Tolerance, 5 ppm in air. Can react strongly with reducing materials, Oxidizer. • When a person is exposed to high concentrations of nitrogen dioxide for a long period of time, the incidence of acute respiratory diseases in children and the elderly increases, and even lung cancer occurs. In addition, respiratory stimulation and bronchitis occur, and mucous membranes are severely stimulated, and in severe cases, pulmonary edema and increased blood pressure appear, causing loss of consciousness.
Derivation	A typical example of reactions involving NO: When heated above 600 °C, it dissociates into NO and oxygen (O_2). NO_2 typically arises via the oxidation of nitric oxide (NO) by O_2 in air. The reaction formula is $2NO_2\,(g) \leftrightarrows 2NO\,(g) + O_2(g)$ At elevated temperatures, nitrogen (N_2) combines with O_2 to form NO: $O_2\,(g) + N_2\,(g) \rightarrow 2NO\,(g)$ Nitric oxide (NO) released into the atmosphere reacts rapidly with O_2 to form NO_2.
Environmental effect	Gases such as NO and NO_2 are oxidized in the atmosphere to nitric acid (HNO_3). When these substances dissolve in water, they become strong acids, which are substances that cause acid rain.
Environmental limits	Air quality criteria on the density of pollutants, including NO_2, are proposed by various organizations such as the World Health Organization, EU, United States Environment Protection Agency, and Occupational Safety and Health Administration in the US, etc. The annual maximum NO_2 density recommended by the World Health Organization is 40 µg/m. According to the Occupational Safety and Health Administration in the US, the permissible exposure limit for NO_2 in homes and offices should not exceed 5 ppm (9 mg/m^3). NO_2 levels as low as 0.1 ppm cause respiratory discomfort in vulnerable population such as asthmatics. See Ambient Air Quality Criteria (AAQC) for details on international standards.

Pollution Information System, 2019; Ministry of Environment; Occupational Safety and Health Administration; Greenpeace India Report, 2021; American Lung Association; Green Facts, Institute of Occupational Medicine).

Implications: We can see from Table 1 that NO_2 is widely recognized as a toxic air pollutant as well as one of the causative substances of secondary ultrafine dust.

Known results from the Institute of Health and Environment in Seoul

According to the report of the Institute of Health and Environment in Seoul (2020), the main cause of NO_2 generation in Seoul in 2019 was exhaust gas emitted from automobiles. In proportion to the rapid increase in automobiles in Seoul, the level of NO_2 pollution is also increasing.

In Table 2, the largest portion (53%) of ultrafine dust (PM2.5) in Seoul in 2019 was ions such as ammonium nitrate (NH_4NO_3), secondary particles generated by conversion of gaseous precursors in the atmosphere. Among the ions, the proportion of specific gravity of nitrate ions (NO_3^-) generated by the reaction of NO_2 emitted from automobiles was 45% (Institute of Health and Environment in Seoul, 2020). It is reported that the amount of secondary fine dust accounts for about two-thirds of the total amount of ultrafine dust generated in the metropolitan area including Seoul (Atmospheric environment report (2010-2021).

Implication: We can see that the findings also suggest the need for research on NO_2, which has a significant impact on producing nitrate ions (NO_3^-).

Known statistics (Table 3) from the Ministry of Environment in the Republic of Korea

Remark : The Fine Dust Seasonal Management System in the Republic of Korea is a system to alleviate the intensity and frequency of occurrence of high-density ultrafine dust and reduce damage to public health through stronger emission reduction and management measures (Ministry of Environment). It was implemented during the period from December 1 of 2020 to March 31 of 2021. It may be remarked that high density of fine dust in Seoul occurs frequently in January, February, March, October, November and December (Air Korea).

Implications: The Ministry of Environment's results in the Republic of Korea are based on the average rate of change compared with that in the previous year, which is a simple method and easy to understand. However, they do not give us detailed information about whether the difference is statistically significant. In contrast to discussing average values only, as was done in a report by the Ministry of Environment in the Republic of Korea, our analyses have produced statistically valid results. See Results for details.

Review of articles that present some changes in average NO_2 density worldwide *before/ after* the *COVID-19 pandemic*

We summarize the articles that present the changes in average NO_2 density worldwide before/after the COVID-19 pandemic in Tables 4-6.

- **References that present the change in NO_2 density worldwide *before COVID-19 pandemic***
- **References that present a significant decrease in NO_2 density worldwide *after* the *COVID-19 pandemic***

Other references related to NO_2

According to a Greenpeace India Report, Hyderabad's NO_2 pollution increased by 69% between April 2020 and April 2021 despite strict lockdown. Meng *et al.* (2021) discuss the effects of urban functional fragmentation on NO_2 variation with anthropogenic-emission restriction in China. Meng *et al.* (2021) estimated the weekly excess all-cause mortality during COVID-19 and effect of air pollution and human activies on mortality variations. Ogen (2021) studies the relationship between long-term exposure to NO_2 and coronavirus fatality. Braun *et al.* (2021) discuss the impact of second-hand smoke on NOx and the concentrations of its main components NO and NO_2

Table 2. Component of PM2.5 in Seoul in 2019 (Institute of Health and Environment in Seoul, 2020)

Component of PM2.5 in Seoul 2019	Percentage
Ion (Nitrate, Sulfate, Ammonium)	53%
Carbon (Organic carbon compound, Inorganic carbon)	32%
Silicon	13%
Metal	2%

Table 3. Known statistics in the Ministry of Environment in the Republic of Korea (2021).

	Known statistics
Ministry of Environment in the Republic of Korea (May 25, 2021)	• Mentioned that the average concentration of ultrafine dust and the number of good and bad days in the Republic of Korea improved with implementation of the seasonal management system. • Study period: December 1 of 2020 to March 31 of 2021. • The national average concentration of ultrafine dust during the second seasonal management system was 24.3 μg/m^3, with 35 good days and 20 bad days. It is about 16% improvement compared to the average density of 29.1 μg/m^3, for the last 3 years. **Remark 1.** In the report of Ministry of Environment, ultrafine dust pollution level is defined as follows: Daily average density / Grade: 0-15 μg/m^3 — Good 16-35μg/m^3 — Normal 36μg/m^3 - 75μg/m^3 — Bad 76μg/m^3 or more — Very bad • The amount of time that the public was exposed to bad ultrafine dust was reduced, and the time that good ultrafine dust lasted increased compared with the last 3 years. • The frequency of the occurrence of bad ultrafine dust day decreased (28% ^{o}C 19%), and the incidence of good ultrafine dust increased (21% ^{o}C 33%). • The emission of air pollutants related to ultrafine dust has been reduced by 121,960 tons, which is about 13% of the level before the implementation of the seasonal management system. • In the case of Seoul, the concentrations of NO_2 and elemental carbon (EC), two major pollutants that are directly emitted from the combustion of automobile fuel, have been reduced. See the report in Ministry of Environment (2021) for details.

Table 4. References that present the change in NO_2 density worldwide *before* the *COVID-19 pandemic*

References	Main results
NASA (2005-2016)	• States that NO_2 is an indicator of pollution sources in its website 'Air Quality - Observations from Space'. The animation in the NASA website shows the changes in NO_2 worldwide from 2005 to 2016 from data of the Ozone Monitoring Instrument (OMI), a Dutch-Finnish instrument, on the NASA Aura satellite.
ESA (European Space Agency)	• % Reports the change in NO_2 worldwide based on observations from the Copernicus Sentinel-5P satellite.

% **Reference showing that NO_2 density worldwide deteriorated to pre-pandemic levels**

in a small interior. They present substantial increases in NOx concentrations when smoking only one cigarette.

Implications: NASA and ESA pollution monitoring satellites detected significant decreases in NO_2 density worldwide in the first half of 2020. However, as the economic activities of countries gradually resumed in the second half of 2020, some changes in air quality around the world, including China and the Republic of Korea, have been observed. Readers are referred to OECD report (2021), Greenpeace India, and Material and Methods in this paper for details on the seriousness of NO_2 air pollution.

RESULTS

In this section, we present the main results and their interpretations. According to AirKorea and AirVis, most of the ultrafine dust warning alarms in Seoul were issued in January, February, March, October, November, and December. In July, August, and September, there were almost no alarms (AirKorea). According to the Ministry of Environment in the Republic of Korea, the amount of secondary fine dust generated by chemical reactions of gaseous substances with other particles in the air accounts for about two-thirds of the total fine dust generation

Table 5. References that present a significant decrease in NO_2 density worldwide *after* the *COVID-19 pandemic*

References	Main results
NASA and ESA (2020)	• NASA and ESA pollution monitoring satellites have detected significant decreases in NO_2 density over China. % Air pollution in Wuhan and other Chinese metropolitan areas has deteriorated significantly over the past three months (NASA Earth Observatory, 2020).% Study subject and period: NO_2 concentrations from January 1 to 20 and those from February 10 to 25 after containment
Bauwens, M *et al.* (2020)	• Air pollution caused by NO_2 in northern China, Western Europe, and the United States had decreased by 60% relative to late 2019 and early 2020.% The occurrence of PM2.5 in northern China decreased by 35% and NO_2 by 60% compared with before. Overall, NO_2 air pollution in China decreased by 40%, and in Western Europe and the United States, decreased by 20%–38%.% Satellite measurements of NO_2 and ultrafine dust concentrations in China, Korea, Italy, Spain, France, Germany, Iran, and the United States from January 2020 to April 2020 were compared with average concentrations in the same period before.
Misra *et al.* (2021)	• Detected Nitrogen oxide concentrations and emission changes during COVID-19 restrictions in Northern India.
Restrepo (2021)	• Detected a drastic decrease in NO_2 concentration in transportation usage in New York City.

Table 6. References showing that NO_2 density worldwide deteriorated to pre-pandemic levels

References	Main results
Financial Times (2020)	% Paris, Brussels and Milan experience big rises in NO_2 levels compared with recent lows. NASA (2020)
.	% As economic activity resuming, the levels of NO_2 over China have returned to near normal.- Study period: February 10- May 12, 2020
ESA (2021)	% Air quality improved in 86% of cities in 2020 even in China, where air pollution was high, but it has deteriorated to pre-pandemic levels in 2021.

in the metropolitan area including Seoul. For these reasons, we will analyze the average NO_2 density during two time periods: January 2020 to June 2020 and October 2020 to June 2021. The average NO_2 density during the two time periods will be compared against those of the previous year.

Known Statistics in AirKorea and AirVisual: Tables 7-8

We present the average NO_2 densities in Seoul for the period from January 2020 to June 2020 and that from January 2019 to June 2019 in Table 7 (AirKorea; Seoul Metropolitan Air Quality Information):

We present the average NO_2 densities in Seoul during the period from October 2020 to June 2021 and that from October 2019 to June 2020 in Table 8 (AirKorea, Seoul Metropolitan Air Quality Information):

Statistical reasoning and analysis

We first make statistical comparisons of two data sets: (i) average NO_2 density in Seoul during the period from January 2020 to June 2020 and (ii) average NO_2 density in Seoul during the period from January 2019 to June 2019. The following hypotheses are set for the average NO_2 density in Seoul:

Table 7. Monthly average NO_2 density in Seoul during the period from October 2020 to June, 2021 and that from October 2019 to June 2020 (unit: ppm)

	2020	2019
OCT	0.025	0.025
NOV	0.030	0.034
DEC	0.032	0.035
	2021	2020
JAN	0.031	0.034
FEB	0.030	0.032
MAR	0.032	0.028
APR	0.022	0.021
MAY	0.019	0.020
JUN	0.019	0.019

H_0 (Null hypothesis): Average NO_2 density in Seoul from January 2020 to June 2020 $\geq$ average NO_2 density in Seoul from January 2019 to June 2019

H_1 (Alternative hypothesis): Average NO_2 density in Seoul from January 2020 to June 2020 < average NO_2 density in Seoul from January 2019 to June 2019

Since two time series are correlated (see the correlation coefficient in Table 9), and each month's data is paired with the other's, a pairwise test was used to compare the differences between the two populations (Chang and Lee, 2020). Under the assumption that the null hypothesis is true, we first made statistical comparisons between data during the period from January 2020 to June 2020 and data during the period from January 2019 to June 2019. The following (Table 9) is the result of the pairwise comparison test (significance level of test = 0.01) using Excel (2016):

As can be seen from Table 9, we have drawn the following conclusion: The null hypothesis that the two population groups have the same mean is rejected because the p-value is 0.00220952217, which is less than 0.01 significance level. There is strong evidence that the average NO_2 density in Seoul in 2020 from January 2020 to June 2020 was less than that in Seoul in 2019 from January 2019 to June 2019, and the reliability of this conclusion is 0.99.

We carried out a similar analysis and obtained the following (Table 10) for the statistical comparisons between data during the period from October 1, 2020 to June 31, 2021 and data during the period from October 1, 2019 to June 31, 2020.

Although there are some months (November, December, January, February and May) when the average NO_2 density decreased (see Table 8), the average decrease is not large enough to lead to the rejection of the null hypothesis. That is, the null hypothesis that the two population groups have the same mean is not rejected because the p-value is 0.156079973, which is greater than 0.01 significance

Table 8. Pairwise comparison test result (significance level = 0.01)
- Comparison period: Jan 2020 to Jun 2020 vs Jan 2019 to Jun 2019
t-test results
Pairwise comparison test

	Density of NO_2 JAN 2020 to JUN 2020	Density of NO_2 JAN 2019 to JUN 2019
Average	0.0256666667	0.031
Sample variance	4.26667E-5	4.64E-5
No. of observations	6	6
Pearson's correlation coefficient	0.921468533	
Difference between two means	0	
d.f.	5	
t statistics	-4.914360935	
P(T<=t) one-sided	0.00220952217	
t statistics	3.364929997	
P(T<=t) two-sided	0.00441904435	
t statistics two-sided	4.032142983	

Table 9. Pairwise comparison test result (significance level = 0.01)
- Comparison period: October, 2020 to June, 2021 vs October, 2019 to June, 2020
t-test results
Pairwise comparison test

	Density of NO_2 OCT 2020 to JUN 2021	Density of NO_2 OCT 2019 to JUN 2020
Average	0.026666667	0.027555556
Sample variance	3E-05	4.22778E-05
No. of observations	9	9
Pearson's correlation coefficient	0.928950467	
Difference between two means	0	
d.f.	8	
t statistics	-1.07871978	
P(T<=t) one-sided	0.156079973	
t statistics	2.896459446	
P(T<=t) two-sided	0.312159946	
t statistics two-sided	3.355387331	

level. There is not enough evidence that the average NO_2 density of Seoul from October 2020 to June 2021 was less than that in Seoul from October 2019 to June 2020, and the reliability of this conclusion is 0.99.

DISCUSSION

In this paper, we compare the average NO_2 density in Seoul after the COVID-19 pandemic with that before the COVID-19 pandemic. Our analysis has produced the following results (with significance level = 0.01): (i) the average NO_2 density in Seoul has decreased significantly in the first half of 2020 compared to that before the COVID-19 pandemic; (ii) the average difference in the NO_2 density in Seoul between the period from October of 2020 to June 2021 and that from October 2019 to June 2020 is not statistically significant.

In contrast to discussing average values only, as was done in a report by the Ministry of Environment in the Republic of Korea, our analyses have produced statistically valid results. Our results could be partly interpreted as the effect related to the partial resumption of economic activity in Seoul after the first half of 2020.

Based on our findings, we have drawn the following recommendations

% It is necessary to establish a real-time monitoring system that tracks major sources of NO_2 in Seoul. Some of related research topics include investigation of the degree of damage caused by the amount of NO_2, development of eco-friendly materials that meet international environmental limits, development of economical and commercially available catalytic converter technology for internal combustion engine cars, establishment of infrastructure necessary for supplying eco-friendly vehicle power sources, etc.

% The ultrafine dust (including NO_2) density levels and their relative decrease vary greatly from city to city (e.g., Seoul, Yeongdong, Baekryeong Island, Ulleung Island, etc.). Therefore, when the fine dust seasonal management system announces its monthly report regarding the effect of their policy, it should provide individual measures (e.g, percent decrease of NO_2 density) for each city rather than aggregate values (such as the national average concentration of ultrafine dust).

ACKNOWLEDGEMENT

This research was supported by Hankuk University of Foreign Studies Research Fund.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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