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Comparison Study on Particulate Matter (PM2.5 and PM10) Pollution in Seoul from October 2021 to May 2022 via Statistical Reasoning

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Abstract: Our previous studies (Chang & Lee 2020, 2021) presented observations on the recent changes in particulate matter (PM2.5 and PM10) pollution in Seoul after the COVID-19 pandemic. This paper derives updated results for the particulate matter pollution in Seoul after considering recent data, specifically the data during the period from October 2021 to May 2022. Although the Government of the Republic of Korea has recently implemented the third seasonal fine dust management system to reduce the intensity and frequency of fine dust by taking stronger emission reduction and management during the period from December 2021 to March 2022, our analysis suggests that the average differences in the monthly average concentration of ultrafine dust in Seoul during the period from October 2021 to May 2022 and that from October 2020 to May 2021 are not statistically significant. Our study shows statistically comprehensive results compared to the studies that limit their discussions to average values, as presented in a report by the Ministry of Environment, the Republic of Korea. We make brief comments on the implications of our findings, and suggestions in the context of climate change and carbon reduction policy.

Keywords: Particulate matter, air pollution, statistical significance, climate change

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1. Introduction

According to the 2021 World Air Quality Report published by AirVisual, a global air pollution research institute, none of the cities in the Republic of Korea met the new PM2.5 annual guideline established by the World Health Organization (WHO) on September 22, 2021. The report mentions that the Republic of Korea experiences increased air pollution around Seoul and areas with high concentrations of manufacturing and industrial sites, as well as sand and dust storms from the Gobi Desert. These dust storms have become more frequent and extreme because of drought and increasing temperatures due to climate change (World Air Quality Report, 2021). Additionally, new aerosols created by sea fog have been shown to result in increased PM2.5 concentrations not only along the western coast of the Republic of Korea but even further inland in the Seoul Metropolitan Area (World Air Quality Report, 2021).

Fine dust, which contains a lot of sulfur and organic carbon, scatters sunlight and acts in the direction of lowering the earth's temperature. However, substances such as soot, which are black soot particles, can act in a way that increases the earth's temperature by absorbing solar radiation (US Environmental Protection Agency 2022). See Organization for Economic Cooperation and Development's (OECD) report (2020), Intergovernmental Panel on Climate Change (IPCC) Report (2021), Greenpeace (2021a, 2021b) for details on the issues related to particulate matter (PM) pollution and climate change.

The report published by World Bank in 2022 estimates that the global cost of health damages associated with exposure to air pollution is $8.1 trillion, equivalent to 6.1% of the global GDP. People in low- and middle-income countries are most affected by mortality and morbidity from air pollution (World Bank 2022). In February 2021, the Center for Clean Air Research (CREA), commissioned by Greenpeace, announced the economic and health costs of air pollution from fossil fuel combustion in 2018. According to the announcement, the environmental cost due to air pollution totaled $2.9 trillion for one year, accounting for 3.3% of the world's GDP, and about $8 billion per day.

Our previous studies (Chang & Lee 2020, 2021) presented observations on the recent changes in particulate matter (PM2.5 and PM10) pollution in Seoul after the COVID-19 pandemic. This paper derives updated results for the particulate matter pollution in Seoul after considering recent data, specifically the data from October 2021 to May 2022. It should be remarked that high concentrations of fine dust occur frequently in Seoul every year from winter to early spring due to seasonal factors, and domestic and foreign influences (Ministry of Environment in the Republic of Korea). Although the Government of the Republic of Korea has recently implemented the third seasonal fine dust management system to reduce the intensity and frequency of fine dust by taking stronger emission reduction and management during the period from December 2021 to March 2022, our analysis suggests that the average differences in the monthly average concentration of ultrafine dust in Seoul from October 2021 to May 2022 and that from October 2020 to May 2021 are not statistically significant. Our study shows statistically comprehensive results compared to the studies that limit their discussions to average values, as presented in a report by the Ministry of Environment, Republic of Korea. Based on our findings, we make suggestions for policy directions that may resolve climate change and carbon reduction simultaneously. Considering that the starting point to solve net zero (OECD, 2021, Chang & Lee (2022b): pp.46-54) and ultrafine dust problem at the same time is 'fossil energy reduction', synergy effects could be expected if policies of the Governments of the Republic of Korea and China are efficiently planned and implemented cost-effectively based on 'fossil energy reduction'. See Conclusion for details. For successful monitoring and solution of environmental-friendly pollution control technologies, continuous update of research findings on the recent change in major health-damaging air pollutants (such as PM 2.5 and PM10) is of utmost importance (Chang & Lee 2022a). The updated information on the change in major health-damaging air pollutants promotes an exchange of knowledge and communication between researchers, scientists, policy-makers, government agencies, and professionals (Chang & Lee 2022a).

The rest of this article is organized as follows: In Method, we summarize our review of related works and their implications; in Findings and Discussions, we derive updated results from Chang and Lee (2020, 2021) and present statistical comparisons of the two data sets: (i) monthly average concentration of particulate matter (PM2.5 and PM10) in Seoul during the period from October 2021 to May 2022 and

(ii) monthly average concentration of particulate matter (PM2.5 and PM10) in Seoul during the period from October 2020 to May 2021. In the Conclusion, we present a brief discussion of the implications of the results.

2. Method

In Methods, we present the average number of yellow dust days in Seoul by season, histories of fine dust alerts during the study period, air quality criteria of particulate matter (PM2.5 and PM10), the main source of PM emissions, and classification of the sources of PM emission in Seoul and their interpretations, which update Chang and Lee (2020, 2021).

Known Statistics from the Meteorological Agency in the Republic of Korea

According to the report by the Meteorological Agency in the Republic of Korea, the number of yellow dust days is defined as the number of days that the yellow dust was reported. See Table 1.

Table 1: Average number of yellow dust days in Seoul by season

Year	Spring (Mar-May)	Summer (Jun-Aug)	Autumn (Sep-Nov)	Winter (Dec-next Feb)
2022	4	NA	NA	NA
2021	12	0	0	0
2020	2	0	3	2
2018-2022	4.6	0	2.2	0.6
2013-2022	4.9	0	1.3	1.2

Table 2: Average number of yellow dust days in Seoul by month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	0	0	2	2	0	NA	NA	NA	NA	NA	NA	NA
2021	2	0	5	2	5	0	0	0	0	1	2	0
2020	0	1	0	1	1	0	0	0	0	1	2	0
2018-2022	0.6	0.2	1.0	1.2	2.4	0	0	0	0	0.4	1.8	0
2013-2022	0.5	0.6	2.0	1.2	1.7	01	0	0	0	0.2	1.1	0.1

Remark 1. In Tables 1–2, the number of occurrences of yellow dust does not mean the number of days of the occurrence of yellow dust in places of origin, such as China and Mongolia, but the number of cases of yellow dust affecting the Korean Peninsula (Meteorological Agency in the Republic of Korea).

As we can see from Tables 1–2, most yellow dust days occur in Seoul in January, February, March, April, May, October, November and December. We thus make a statistical comparison of the two data sets: (i) monthly average concentration of particulate matter (PM2.5 and PM10) in Seoul during the period from October 2021 to May 2022 and (ii) monthly average concentration of particulate matter (PM2.5 and PM10) in Seoul during the period from October 2020 to May 2021.

We summarize the histories of fine dust alerts and ultrafine dust alerts during the study period in Table 3.

Table 3. Histories of fine dust alerts during the study period (AirKorea and AirVisual)

Type of alerts	Period
Fine dust alerts	• April 27, 2022 06:00–23:00 • March 5, 2022 01:00–04:00 and 08:00–12:00 • November 19, 2021, 21:00 – November 21, 2021, 24:00
Ultrafine dust alerts	• February 11, 2022, 23:00 – February 13, 2022, 21:00 • January 8, 2022, 22:00 – January 10, 2022, 21:00 • December 15, 2022, 16:00 – December 17, 2021, 02:00 • November 19, 2022, 19:00 – November 11, 2021, 24:00

In this paper, we paid attention to the causes of the fine dust alert on April 27, 2022, and the ultrafine dust alert during the period from January 8, 2021 to Jan 10 2021 in Table 3, and summarized their causes in the following Table 4.

Table 4. Alerts and their causes

Alerts	Cause
Fine dust alert on April 27, 2022	It was analyzed that the increase in fine dust concentration in Seoul was caused by yellow dust from the Inner Mongolia Highlands in northeastern China (Seoul Institute of Health and Environment Report 2022).
Ultrafine dust alert during the period from Jan 8, 2022 to Jan 10, 2022.	On January 9, a high concentration of ultrafine dust was observed centered on Shandong Peninsula in China. As high-concentration pollutants in China flowed into the Korean Peninsula via the westerly wind on January 8, the amount of ultrafine dust in Baengnyeong Island, Seoul and the mid-western region in the Republic of Korea was observed to increase. Additionally, the high concentration of ultrafine dust in Seoul and the midwestern region continued as the domestic atmosphere in the Republic of Korea was stagnant (Seoul Air Environment Annual Report, 2022).

Remark 2. The Seoul Institute of Health and Environment issued a fine dust advisory as of 6:00 am on April 27, 2022, as the average hourly concentration of fine dust (PM-10) lasted more than 150 $\mu g/m^3$ for

2 hours. It should be remarked that an ultrafine dust advisory is issued when the hourly average ultrafine dust concentration is 75 ㎍/㎥ or higher for 2 hours (Ministry of Environment in Republic of Korea). On January 8, 2022, the hourly average ultrafine dust concentration in the 25 autonomous districts of Seoul was 79 ㎍/㎥ at 9:30 pm and 82 ㎍/㎥ at 10 pm.

Air Quality Criteria of PM

We summarized the air quality criteria of PM stated in the US EPA, WHO, US CDC, and Ministry of Environment in the Republic of Korea in Tables 5–8.

Table 5. National Ambient Air Quality Standards (40 CFPR part 50) for PM (EPA)

Pollutant	*primary secondary*	*Average Time*	*Level*	*Form*
PM2.5	primary	1 year	12.0 μg/m^3	annual mean, averaged over 3 years
	secondary	1 year	15.0 μg/m^3	annual mean, averaged over 3 years
	primary and secondary	24 hours	35.0 μg/m^3	annual mean, averaged over 3 years
PM10	primary and secondary	24 hours	150 μg/m^3	Not to exceeded more than once per year on average over 3 years

Table 6. Recommended short-term (24-hour) AQC level and interim targets for PM2.5 established in WHO (2022)

Recommendation	*PM2.5*
Interim target 1	75 μg/m^3
Interim target 2	50 μg/m^3
Interim target 3	37.5 μg/m^3
Interim target 4	25 μg/m^3
AQC level	15 μg/m^3

Table 7. Recommended short-term (24-hour) AQC level and interim targets for PM10 established in WHO (2022)

Recommendation	*PM2.5*
Interim target 1	70 µg/m^3
Interim target 2	50 µg/m^3
Interim target 3	30 µg/m^3
Interim target 4	20 µg/m^3
AQC level	15 µg/m^3

Table 8. Air quality criteria of PM established in the Ministry of Environment, the Republic of Korea.

Pollutant	*Type of average used*	*National standard*	*Seoul standard*
PM2.5	Yearly average 24-hour average	15 µg/m^3 35 µg/m^3	15 µg/m^3 35 µg/m^3
PM10	Yearly average 24-hour average	50 µg/m^3 100 µg/m^3	50 µg/m^3 100 µg/m^3

As the pollution prevention technologies improve, air quality criteria should be more stringent than those presented in Table 8.

The main source of PM emissions and classification of PM emission sources in Seoul

We summarize the main source of PM emissions and the classification of PM emission sources in Seoul in Table 9.

Table 9. Main sources of PM emissions and classification of PM emission sources in Seoul

Type of sources	*Definitions*	*Examples*
Primary sources	Sources that cause particle pollution on their own	Wood stoves, forest fires, unpaved roads, etc.
Secondary sources	Sources that let off gases (such as SO_2 and nitrogen oxides [NO_x]) that can form ultrafine dust (such as PM2.5) from chemical reactions	Power plants, coal fires, industries, automobiles, etc.
Either primary or secondary	Sources that can be either primary or secondary	Factories, cars, trucks, construction sites, etc.

Table 10 summarizes the classification of PM emission sources in Seoul (Ministry of Environment in the Republic of Korea).

Table 10. PM (PM10 and PM2.5) emission source classification in Seoul (2018)

Emission source classification	*PM10*	*PM2.5*
Road transport pollution source (e.g., Diesel vehicle, Automobile exhaust gas)	585472 ton/year	538624 ton/year
Scattering dust	12573062 ton/year	1640468 ton/year
Non-road transport pollution source (e.g., Heavy construction equipment (fork cranes, bulldozers, etc.), agricultural machinery, ships, etc.)	1648189 ton/year	1516333 ton/year
Non-industrial combustion	166529 ton/year	136746 ton/year
Area sources contaminant	38891 ton/year	35002 ton/year
Waste disposal	8213 ton/year	6386 ton/year
Energy industry combustion	7729 ton/year	7729 ton/year
Bio-combustion	101288 ton/year	91576 ton/year
Manufacturing combustion	626 ton/year	507 ton/year
Total	15129999 ton/year	3973381 ton/year

Remark 3. Scattering dust in Table 10 is a generic term for dust that is directly discharged into the atmosphere without a specific exhaust port (Ministry of Environment in the Republic of Kore). It occurs frequently in the construction industry, cement, coal, and earth and sand industries (Ministry of Environment in the Republic of Korea). Note that it is generated through chemical reactions in the atmosphere with substances emitted during the combustion of fossil fuels such as automobile exhaust gas, coal, oil, etc (Ministry of Environment in the Republic of Korea).

We can see that the findings in Table 10 suggest the following:

(i) The primary source (83.10%) of PM10 emissions source in Seoul was scattering dust. It was followed by a non-road transport pollution source, which amounted to 10.893%.

(ii) The primary source (41.286%) of PM2.5 emissions source in Seoul was scattering dust. It was followed by a non-road transport pollution source, which amounted to 38.162%.

It should be remarked that the primary source of PM emission source differs by region and city in the Republic of Korea.

Table 11 summarizes the main results in the third seasonal fine dust management system in the Republic of Korea.

Table 11. Summary of the main results in the third seasonal fine dust management system in the Republic of Korea (2022)

<table>
<tr><th>Organization</th><th>Main results</th></tr>
<tr><td>Ministry of Environment in the Republic of Korea

April 5, 2022</td><td>• Mentioned that the national average concentration of ultrafine dust in the Republic of Korea improved with the implementation of the 4th seasonal management system, compared to that during the 3rd seasonal management system.

• Study period: December 2021 to March 2022

• National average concentration of ultrafine dust in the Republic of Korea during the study period was 23.3μg/m^3, with 18 good days and 40 bad days. It is about a 4% improvement compared to the average density of 24.3 μg/m^3, during the 3rd seasonal management system.

• The emission of air pollutants related to ultrafine dust has been reduced by 132,846 tons by implementing the strategy for reducing the operation of coal power plants and the operation of class 5 vehicles.

<table>
<tr><td>Substances</td><td>Amount of reduction (ton)</td></tr>
<tr><td>Emission of ultrafine dust</td><td>6,800 tons</td></tr>
<tr><td>Sulfur oxide</td><td>4,659 tons</td></tr>
<tr><td>Nitrogen oxides</td><td>62,070 tons</td></tr>
<tr><td>Volatile organic compounds</td><td>22,957 tons</td></tr>
</table>
• See the report by the Ministry of Environment (2022) for details.</td></tr>
</table>

The Fine Dust Seasonal Management System in the Republic of Korea aimed to alleviate the intensity and frequency of occurrence of high-density ultrafine dust and reduce damage to public health by implementing stronger emission reduction and management measures than usual. It was implemented from December 1 of 2021 to March 31 of 2022. Note that the Ministry of Environment's results in the Republic of Korea are based on the average rate of change compared with that of the previous year, which is a simple and easily comprehensible method. However, it does not provide detailed information about the statistical significance of the difference. In contrast to discussions limited to average values, as was done in the report by the Ministry of Environment, the Republic of Korea, our analyses produced statistically valid results. See the Findings and Discussion section of this paper for details.

3. Findings and Discussions

In this section, we present the main findings, their interpretations and discussions.

Known statistics in the atmospheric environment of Seoul

The monthly average concentrations of fine dust and ultrafine dust in Seoul from October 2021 to May 2022 are presented in Tables 12 and 13 (Atmospheric environment of Seoul, 2021–2022).

Table 12: The monthly average concentrations of ultrafine dust (PM2.5) in Seoul from October 2021 to May 2022 (unit: μg/m³)

	Year 2021	*Year 2020*
Oct	13	17
Nov	26	24
Dec	23	27

	Year 2022	*Year 2021*
Jan	29	21
Feb	25	29
Mar	21	32
Apr	22	19
May	17	20

Table 13: The monthly average concentrations of fine dust (PM10) in Seoul from October, 2021 to May, 2022 (unit: μg/m³)

	2021	*2020*
Oct	26	33

Nov	45	42
Dec	39	42

	2022	*2021*
Jan	43	38
Feb	40	48
Mar	41	66
Apr	45	41
May	33	60

Statistical reasoning and analysis

In this section, we present statistical comparisons of the two data sets: (i) monthly average concentration of PM2.5 in Seoul during the period from October 2021 to May 2022 and (ii) monthly average concentration of PM2.5 in Seoul during the period from October 2020 to May 2021. The following hypotheses are set for the monthly average concentration of PM2.5 in Seoul:

H_0(Null hypothesis): Average monthly concentration of ultrafine dust (PM2.5) in Seoul during the period from October 2021 to May 2022 ≥ Average monthly concentration of fine dust (PM2.5) in Seoul during the period from October 2020 to May 2021.

H_1 (Alternative hypothesis): Average monthly concentration of ultrafine dust (PM2.5) in Seoul during the period from October 2021 to May 2022 < Average monthly concentration of ultrafine dust (PM2.5) in Seoul during the period from October 2020 to May 2021.

The basic principle of the analysis presented in this paper is same as that of the statistical control chart. We define the difference between the monthly average concentration of PM 2.5 in Seoul in a specific year and the monthly average concentration of PM2.5 in Seoul in the previous year in a specific year as the error (or natural variability or the chance causes of variation). Under the assumption that H_0 is true, the error (natural variability) is assumed to follow a normal distribution with a mean 0 and a finite variance that is greater than 0, which is an implicit assumption of our study.

Since two-time series are correlated, and each month's data is paired with each other, a pairwise test was used to compare the average differences between the two populations (Chang & Lee, 2020, 2021). Under the assumption that the null hypothesis is true, the average monthly concentrations of fine dust (PM2.5) in Seoul are compared between the period from October 2021 to May 2022 and from October 2020 to May 2021. The following is the result of the pairwise comparison test (significant level of test = 0.01) using Excel (2016):

Table 14: Pairwise comparison test result (significant level of test= 0.01) t-test results: Pairwise comparison test

	PM2.5 from Oct 2021 to May 2022	*PM2.5 from Oct 2020 to May 2021*
Average	22	23.625
Sample variance	26	27.98214
No. of observations	8	8
Pearson's correlation coefficient	0.381335553	
Difference between two means	0	
d.f.	7	
t statistics	-0.795161746	
P(T<=t) one-sided	0.226316688	
t statistics one-sided	2.997951567	
P(T<=t) two-sided	0.452633376	
t statistics two-sided	3.499483297	

Source: Author's findings

As can be seen from Table 14, the null hypothesis that the two population groups have the same mean is not rejected because the p-value is 0.226316688, which is greater than the 0.01 significance level. There is not enough evidence that the average monthly concentration of fine dust (PM2.5) in Seoul during the period from October 2021 to May 2022 was less than that in Seoul from October 2020 to May 2021, and the reliability of this conclusion is 0.99.

Remark 4. As mentioned in Table 4, we paid attention to the causes of the fine dust alert on April 27, 2022, and the ultrafine dust alert during the period from January 8, 2022 to January 10, 2022. As we can see in Table 12, the monthly average concentrations of ultrafine dust (PM2.5) in Seoul in April 2022 and January 2022 are greater than those in Seoul in April 2021 and January 2021. To check whether the causes in Table 4 affect the decision in Table 14, we removed the data of April and January in Table 12 and compared the average difference between the two populations with the data of April and January removed. According to our analysis, the null hypothesis that the two groups have the same mean was rejected at the significance level of 0.05, which suggests that the causes of the fine dust alert on April 27, 2022, and ultrafine dust alert during the period from January 8, 2022 to January 10, 2022 are influential causes that led to our conclusion in Table 14. Due to the lack of space, the comparison results with the data of April and January removed are not being presented, but are available from the authors on request.

We carry out a similar analysis, and obtain the following table for the concentration of PM 10 in Seoul:

Table 15: Pairwise comparison test result (significant level of test = 0.01) t-test results: Pairwise comparison test

	PM10 from Oct 2021 to May 2022	*PM10 from Oct 2020 to May 2021*
Average	39	46.25
Sample variance	42.5714285714286	127.071428571429
No. of observations	8	8
Pearson's correlation coefficient	0.0796347733732121	
Difference between two means	0	
d.f.	7	
t statistics	-1.63174633762644	
P(T<=t) one-sided	0.0733764728997153	
t statistics one-sided	2.99795156686853	
P(T<=t) two-sided	0.146752945799431	
t statistics two-sided	3.49948329735049	

Source: Author's findings

As can be seen from Table 15, the null hypothesis that the two population groups have the same mean is not rejected because the p-value is 0.0733764728997153, which is greater than the 0.01 significance level. There is not enough evidence that the concentration of fine dust (PM10) in Seoul from October 2021 to May 2022 was less than that in Seoul from October 2020 to May 2021, and the reliability of this conclusion is 0.99.

Remark 5. Based on the argument similar to Remark 4, we compare the average difference between the two populations with the data of April and January removed. According to our analysis, we conclude that the causes of the fine dust alert on April 27, 2022, and the ultrafine dust alert during the period from January 8, 2022 to January 10, 2022 are influential causes that led to our conclusion in Table 14. Due to the lack of space, the comparison results with April and January removed are not being presented, but are available from the authors on request.

4. Conclusion

In this paper, we compared the average monthly concentration of ultrafine dust in Seoul during the period from October 2021 to May 2022 with that from October 2020 to May 2021 via statistical reasoning. According to our analysis (with significance level =0.01), there is not enough evidence that the average monthly concentration of ultrafine dust in Seoul during the period between October 2021 to May 2022 and that from October 2020 to May 2021 are statistically significant. We make supplementary comments on our conclusion based on the alerts and their causes during the study period in Table 4. As stated in Section 4, high frequencies and intensities of ultrafine dust originating from alerts in Table 4 naturally affect the key statistics in our statistical reasoning and lead to a rational conclusion: The average differences during the periods between October 2021 to May 2022 and October 2020 to May 2021 are not statistically significant. Note that our conclusion is valid only for October 2021 to May 2022.

Based on our findings, the following suggestions can be recommended: Considering that the starting point to solve net zero and ultrafine dust at the same time is 'fossil energy reduction', synergy effects could be expected if the policies of the Governments of the Republic of Korea and China are efficiently planned and implemented cost-effectively based on 'fossil energy reduction'. Specific measures may include the following:

• Establishment and implementation of government and corporate policies/regulations for the reorganization of the domestic industrial structure for fossil energy reduction.

• Development of a digital platform for reducing fossil energy that can be realized gradually in the domestic environment.

• Digital transformation of the domestic industrial structure and supply chain based on 4th industrial revolution technologies (such as Artificial Intelligence, Big Data, Robots, Drones, Augmented Reality, Internet of Things, Block-chain Technology, etc), improvement of the efficiency of energy, transition to renewable energy (such as solar energy, solar heat, wind power, hydropower, marine renewable energy, geothermal power, bio-energy, etc) generation, and reforestation business.

• Enhanced international environmental cooperation.

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