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Analysis of the Similarity in the Ozone Concentration Distribution among Cities and Counties in Gyeonggi-do Using Cluster Analysis

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Abstract – This study analyzed the ozone concentration distribution across cities and counties in Gyeonggi-do (Province) from 2012 to 2021 to propose an ozone alert zone framework tailored to regional characteristics. Ozone concentration values were calculated using data from 69 urban air monitoring stations in Gyeonggi-do, and hierarchical clustering analysis was applied to divide the area into four clusters. Most clusters in Gyeonggi-do were delineated by high mountain ranges, indicating that geographical characteristics play a significant role in shaping ozone concentration patterns. These findings underscore the limitations of the current PM10-based ozone alert system and emphasize the need for zoning based on regional ozone concentration patterns.

Key words: Ozone alert, Hierarchical clustering analysis, Regional ozone distribution, Gyeonggi-do

1. Introduction

High concentrations of ozone in the atmosphere are among the air pollutants that can have significant impacts on human health and the environment [1,2]. Atmospheric ozone is primarily formed through the catalytic action of ultraviolet radiation on nitrogen oxides (NOx) and volatile organic compounds (VOCs). Consequently, ongoing research focuses on technologies to reduce NOx and VOC emissions at the source stage [3-7]. In addition, ozone concentrations are determined by various influencing factors, including meteorological conditions, regional characteristics, and the long-range transport of NOx and VOCs [8-10].

Gyeonggi-do, the province closest to Seoul, the capital of Republic of Korea, consists of an industrial and traffic-dense southwest region and a mountainous and rural northeast region [11-13]. It also records the highest total emissions of NOx and VOCs in the country [14]. Naturally, Gyeonggi-do has recorded the highest number of ozone alert issuance days and occurrences in Korea over the past decade [15]. In 2023, ozone alerts were issued for the first time in March, and the total issuance days surged from 24 in the previous year to 37 [16]. This emphasizes the growing importance of managing ozone concentrations in Gyeonggi-do.

To effectively manage ozone concentrations, Republic of Korea operates ozone alert zones for each local government, and various studies using statistical techniques have been conducted to establish efficient zoning systems and analyze ozone concentration distributions. Heo and Kim conducted hierarchical cluster analysis based on air pollutants and meteorological data in Seoul, categorizing the pollutant distribution characteristics into six distinct types [17]. Do and Jung divided Busan into five clusters using hierarchical clustering with the average linkage method [18]. They compared the differences in ozone concentrations between coastal and urban areas in Busan using Ward's method [19]. Kim et al. performed k-means clustering analysis, categorizing the ozone concentration distributions into transport-dominant, emission-dominant, and suburban areas [20]. The Gyeonggi-do Institute of Health and Environment conducted cluster analysis based on the number of exceedances of air quality standards for particulate matter (PM10) and ozone concentrations in various cities and counties within Gyeonggi-do, dividing the ozone alert zones into four regions [21].

To this day, the ozone alert zones in Gyeonggi-do are defined based on PM10 distribution, considering practical factors such as administrative boundaries, population distribution, and monitoring station locations [22]. However, PM10 and ozone exhibit different behaviors and originate from distinct sources, resulting in differing regional patterns [23,24]. Therefore, the current ozone alert zones in Gyeonggi-do suggest that regional similarities in ozone concentrations are not adequately reflected. This study aims to analyze the similarities in ozone concentration distributions across cities and counties in Gyeonggi-do to identify regional characteristics and provide a foundational basis for establishing effective ozone alert zones.

2. Methodology

2-1. Data collection

The ozone concentration data were obtained from the final annual

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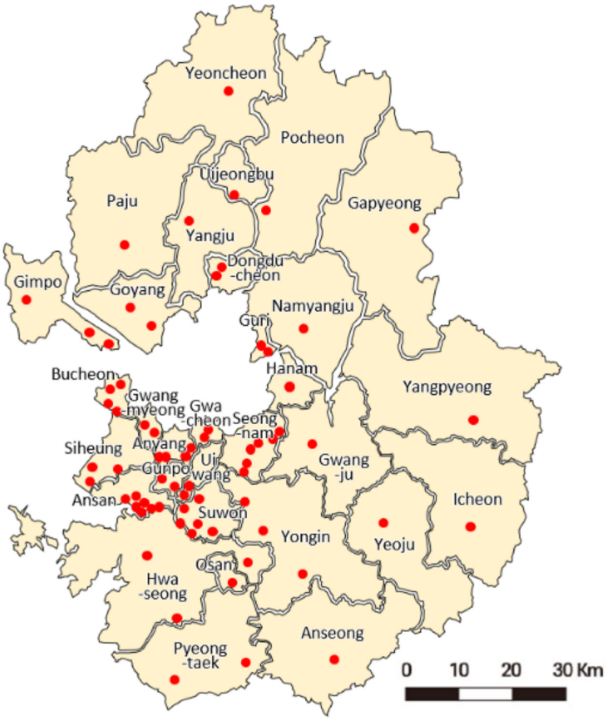

Fig. 1. Site map of air pollution monitoring sites in Gyeonggi-do.

validated measurement data provided by Air Korea, managed by the Korea Environment Corporation [25]. The analysis period spans 10 years, from 2012 to 2021, focusing on data from May to September, when ozone alerts are most frequently issued. To ensure the reliability of the 10-year dataset, hourly ozone measurement data from 69 monitoring stations in Gyeonggi-do, which have been in operation since before 2013, were used. Fig. 1 shows the locations of the monitoring stations. Data validity was ensured using only the ozone concentration records from days with at least 75% of measurements available and limiting the analysis to the period from April to October, when ozone alerts are typically issued. The ozone precursors were analyzed using NOx and VOCs emission statistics provided by the Clean Air Policy Support System(CAPSS), based on 10 years of data measured from 2012 to 2021 [26]. And the area and population data for each city and county in Gyeonggi-do were obtained from the statistical information provided by the Korean Statistical Information Service(KOSIS) [27,28].

2-2. Regional ozone distribution

For cities and counties with more than two monitoring stations, the Regional Ozone Distribution (ROD) formula was applied to calculate a representative ozone concentration value for cluster analysis. The ROD, proposed by Pont and Fontan, helps correct potential errors in the means caused by outliers at individual stations and more effectively reflects regional trends [29,30]. The ROD is calculated by standardizing the highest concentration from each station at each hour. The standardized value, $Z_n(i)$, can be obtained using Eq. (1), where $Z(i)$, $m(i)$, and $\sigma(i)$ are the daily maximum ozone concentration, mean, and standard deviation for station i, respectively, and n represents the date. The average $Z_n(i)$ values for the monitoring stations within each city or county were then calculated using Eq. (2), and the ROD was determined by adding the standard deviation σ and mean m of the maximum ozone concentration.

$$Z_n(i) = \frac{Z(i) - m(i)}{\sigma(i)} \tag{1}$$

$$ROD_n = \left(\frac{\sum_{i=1}^{k} Z_n(i)}{k}\right) \times \sigma + m \tag{2}$$

In this study, the ROD for each city and county was calculated from 2012 to 2021, and its reliability was validated by correlation analysis of the ROD trends and the annual $Z(i)$ values from individual monitoring stations.

2-3. Clustering analysis

Hierarchical cluster analysis was conducted to examine the similarity in the ozone concentration trends across cities and counties in Gyeonggi-do. Agglomerative clustering was used for the clustering method with the Euclidean distance for similarity measurement and average linkage for data connection. The analysis was performed using the hclust package in R. As the number of clusters is subject to the researcher's discretion, four clusters were identified based on the dendrogram, grouping the regions with similar ozone concentration trends. Furthermore, the geographical characteristics of each cluster were analyzed using the digital elevation model provided by the National Geographic Information Institute.

3. Results and Discussion

3-1. Validation of ROD reliability

The ROD was calculated using data from 69 urban air monitoring stations in Gyeonggi-do to compute the representative values that remove local outliers in ozone concentration distribution. Table 1 lists the annual average correlation coefficients between the ROD values and the data from the individual monitoring stations for each city and county from 2012 to 2021. In most cases, the correlation coefficients were above 0.999, indicating substantial similarity in the ozone fluctuations across monitoring stations within each city or county. Hence, the ROD effectively captures the regional trends in the ozone concentration.

3-2. Similarity analysis of ROD

In Fig. 2(a), Gyeonggi-do is initially divided into two primary clusters: the first cluster (Cluster 1) includes cities such as Bucheon, Anyang, Seongnam, Yongin, and Pyeongtaek, while the second cluster (Cluster 2) consists of cities like Gimpo, Goyang, Namyangju, Yeoju, and Anseong. When the clustering is expanded by one level (Fig. 2(b)), a subgroup separates from Cluster 2, forming a distinct cluster that includes Gimpo, Goyang, Namyangju, and Pocheon. In

Table 1. Mean correlation coefficients between ROD and each monitoring site by cities and counties in Gyeonggi-do from 2012 to 2021

Cities/counties	Year									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ansan	0.9998	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999
Anseong	-	-	-	-	-	-	-	-	-	-
Anyang	0.9999	0.9999	0.9999	0.9999	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Bucheon	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999	0.9998	0.9998	0.9999
Dongducheon	-	-	-	-	-	-	-	-	-	-
Gapyeong	-	-	-	-	-	-	-	-	-	-
Gimpo	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
Goyang	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9999
Gunpo	1.0000	0.9999	1.0000	0.9999	1.0000	1.0000	0.9999	1.0000	1.0000	1.0000
Guri	0.9999	0.9999	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Gwacheon	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	1.0000	1.0000	0.9999
Gwangju	-	-	-	-	-	-	-	-	-	-
Gwangmyeong	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	1.0000	1.0000	0.9999
Hanam	-	-	-	-	-	-	-	-	-	-
Hwaseong	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9999
Icheon	-	-	-	-	-	-	-	-	-	-
Namyangju	-	-	-	-	-	-	-	-	-	-
Osan	-	-	-	-	-	-	-	-	-	-
Paju	-	-	-	-	-	-	-	-	-	-
Pocheon	-	-	-	-	-	-	-	-	-	-
Pyeongtaek	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999
Seongnam	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999
Siheung	0.9999	0.9999	0.9999	0.9999	0.9999	1.0000	0.9999	0.9999	0.9999	0.9999
Suwon	0.9999	0.9996	0.9999	0.9999	0.9999	0.9998	0.9999	0.9999	0.9999	0.9999
Uijeongbu	0.9999	0.9999	0.9999	0.9999	1.0000	0.9999	0.9999	1.0000	0.9999	0.9999
Uiwang	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Yangju	-	-	-	-	-	-	-	-	-	-
Yangpyeong	-	-	-	-	-	-	-	-	-	-
Yeoju	-	-	-	-	-	-	-	-	-	-
Yeoncheon	-	-	-	-	-	-	-	-	-	-
Yongin	1.0000	0.9999	1.0000	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999

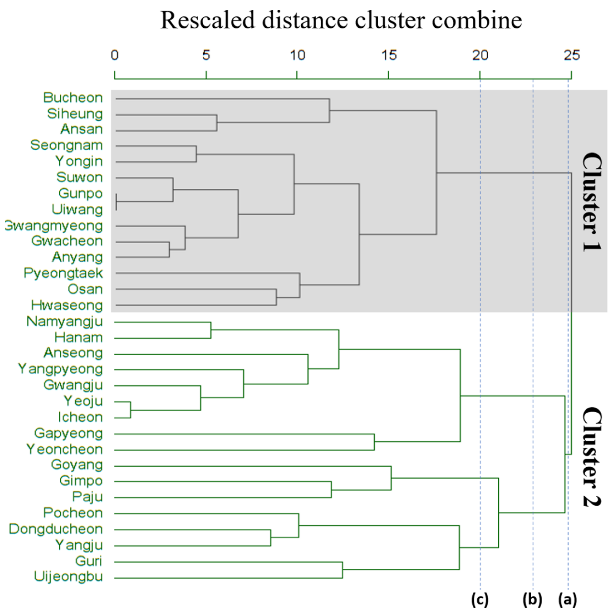

Fig. 2. Dendrogram of hierarchical clustering analysis based on ROD values for cities and counties in Gyeonggi-do from 2012 to 2021.

Fig. 2(c), Gimpo, Goyang, and Paju form their own subgroup, while Cluster 2 undergoes further segmentation.

As the clustering continues to expand, Cluster 2 becomes even more fragmented, with Yeoncheon and Gapyeong forming a separate subgroup, followed by Guri and Uijeongbu forming another subgroup. In contrast, Cluster 1 remains relatively stable and shows minimal further subdivision. This suggests that the cities in Cluster 1 exhibit a higher degree of similarity in ozone concentration patterns compared to those in Cluster 2. However, considering the current number of air pollution alert zones operated in Gyeonggi-do, this study focuses on analyzing between 2 to 4 clusters in greater detail to align with the existing air quality management framework.

Fig. 3 visually represents the ozone cluster distribution on a map based on the previously presented dendrogram. When the ROD values are classified into two clusters, as shown in Fig. 3(a), Gyeonggi-do is divided into 14 cities in the southwest (Cluster 1) and 17 cities in the remaining regions (Cluster 2). Cluster 1 includes cities with industrial complexes and ports, exhibiting annual average NOx emissions exceeding 10^7 kg yr^{-1} (Fig. 4(a)) and VOCs emissions exceeding $10^{6.5}$

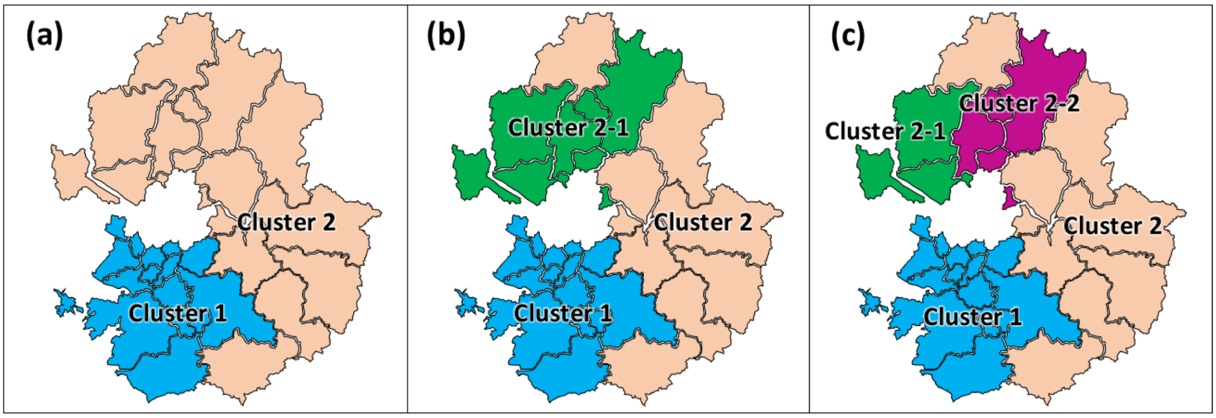

Fig. 3. Distribution of hierarchical clustering results based on rod values for cities and counties in Gyeonggi-do from 2012 to 2021 with (a) 2, (b) 3, and (c) 4 clusters.

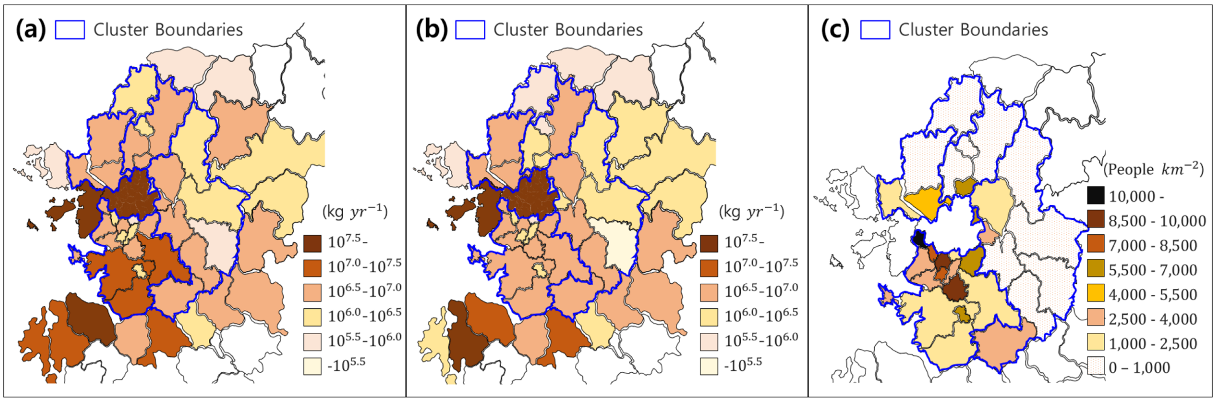

Fig. 4. Annual average emissions of (a) NOx and (b) VOCs in Gyeonggi-do from 2012 to 2021 and (c) population density distribution in 2021.

kg yr^{-1} (Fig. 4(b)). Additionally, many cities in Cluster 1 have a high population density exceeding 7,000 people km^{-2} (Fig. 4(c)) and the southwesterly summer winds influencing this area contribute to their classification in the same cluster [31].

When the number of clusters is expanded to three, Cluster 2 splits into a new subgroup, forming Cluster 2-1, which includes Gimpo, Goyang, Paju, Guri, Yangju, Uijeongbu, Dongducheon, and Pocheon (Fig. 3(b)). As shown in Fig. 4, these cities are close to Seoul, have high population density, and exhibit NOx and VOCs emissions around $10^{6.5}$ kg yr^{-1}. When expanded to four clusters, Cluster 2-1 further subdivides, creating Cluster 2-2, which includes Guri, Yangju, Uijeongbu, Dongducheon, and Pocheon (Fig. 3(c)). While Cluster 2-2 shares some similarities with Cluster 2-1, it includes areas with VOCs concentrations below 10^6 kg yr^{-1}. These cities also have lower population density and reduced industrial activity, justifying their classification into a separate group.

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In conclusion, the similarity in ozone concentration distribution in Gyeonggi-do can be broadly categorized into high-concentration industrial and densely populated areas in the southwest and the remaining less-industrialized areas.

3-3. Analysis of geographical characteristics of clusters

Fig. 5 overlays the four clusters classified by cluster analysis onto the digital elevation model of Gyeonggi-do. Cluster 1 forms a gentle plain extending from east to west and borders Cluster 2 along a mountain range extending from Namhansanseong Provincial Park to Taehwasan, with elevations ranging from 560 to 641 meters. Cluster 2 consists mostly of mountainous areas. Within this cluster, Cluster 2-1 features a gentle plain towards the west, which is likely why it was separated first. Cluster 2-2, on the other hand, is bordered by Bukhansan and Dobongsan to the west, with elevations ranging from 739 to 836 meters, and by Cheonmasan and Baekunsan to the east, with elevations reaching up to 1,000 meters. As such, the boundaries of each cluster are largely shaped by mountainous terrain, a pattern

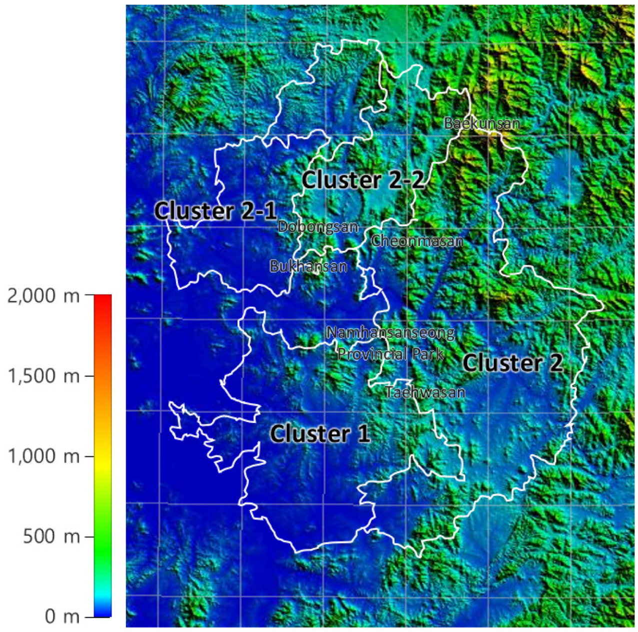

Fig. 5. Digital elevation model of Gyeonggi-do with four clusters defined by hierarchical clustering analysis results.

similar to that observed in Seoul [32].

However, Kang and Kim [33] pointed out that topographic elevation itself may not directly affect air pollutant concentrations. Therefore, future research should comprehensively consider factors such as topographical features, population density, meteorological conditions, and the long-range transport of ozone precursors when analyzing cluster boundaries.

4. Conclusions

This study analyzed the ozone concentration distribution across cities and counties in Gyeonggi-do from 2012 to 2021 to propose an ozone alert zone classification that reflects the regional characteristics. The ROD values were calculated using the data from 69 urban air monitoring stations in Gyeonggi-do, and four clusters were identified through hierarchical cluster analysis.

The southwestern region, characterized by high NOx and VOCs emissions and high population density, was classified into a single cluster (Cluster 1), while regions with low population density and relatively fewer pollution sources formed a separate cluster (Cluster 2). As the number of clusters increased, subdivisions primarily occurred within Cluster 2, which consists mainly of mountainous terrain. It was observed that mountain ranges formed natural boundaries for each cluster, indicating that clusters are largely shaped by topographical features.

These findings suggest that the distribution of ozone concentrations is influenced by geographical factors, population density, and industrial activities, underscoring the need to establish ozone alert zones that reflect the geographical characteristics of Gyeonggi-do.

However, this study has limitations, as it did not consider seasonal factors and meteorological conditions such as wind and rainfall, which also significantly influence ozone concentrations. Future research should comprehensively analyze the effects of industrial activities and traffic within clusters, assess pollutant transport from neighboring regions, and clarify the role of geographical features such as mountainous terrain in air pollution to provide more accurate and reliable results.

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