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Online community users' perceptions of particulate matter in South Korea through topic modeling and semantic network analysis

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ABSTRACT

In this study, we investigate public perception of particulate matter (PM) in South Korea to address the persistent high public anxiety levels surrounding this environmental issue. For this purpose, we first compared the monthly trends of PM concentrations, news articles, and online community posts. Furthermore, we performed a cross-correlation analysis between PM concentrations and online community posts, which are considered to be the most public-aware source, to examine how the public's response changes with variations in PM concentrations. Additionally, we conducted topic modeling and identified nine topics based on 2714 online community posts from January 2013 to December 2023. The results showed that public concern about PM is related to PM concentrations but media was found to play a role in amplifying it. The most prominent topic was the public's critical attribution of PM in Korea to China. Other topics included interest in PM forecasts, physical risks and personal responses to PM, requests for more active government response, and controversy over the South Korean government's PM reduction policies. In addition, the public has significant health concerns, leading to individual protective actions such as mask and air purifier purchases, possibly influenced by media and marketing strategies. There is a significant gap between public perceptions of the causes of PM and the direction and content of government policies. For instance, although the public tends to attribute PM primarily to external factors such as pollution from China, government policies appear to emphasize internal sources, such as regulating vehicle emissions. The discrepancy was found to make the public feel dissatisfied with policy implementation. This study demonstrates how the public perceives and interprets PM issues. It is also significant that we provide empirical evidence of the relationship between PM concentrations and online community posts through cross-correlation analysis. In this study we advocate for the need for policymakers to communicate PM-related information effectively to facilitate public alignment with PM reduction policies.

1. Introduction

Particulate matter (PM) is a significant environmental and social issue in South Korea. PM, also called *fine dust*, refers to dust particles with a small diameter. It is categorized into PM_{10} for particles smaller than 10 μm, known as coarse particles, and $PM_{2.5}$ for particles smaller than 2.5 μm, known as fine particles. According to the OECD (2024a), in South Korea, the concentration of $PM_{2.5}$ is higher than the OECD average and exceeds the levels observed in countries such as Germany, Japan, and the United States. High concentrations of air pollutants are known to lead to severely poor air quality, and in 2019, outdoor air pollution in South Korea was reported to cause 19 deaths per 100,000 people. This figure is higher than Japan's and New Zealand's 12 deaths, and the United States' 14 deaths (WHO, 2022). In 2019, excess deaths due to PM resulted in economic losses equivalent to 4.09 % of South Korea's GDP, which is higher than both the OECD average of 2.44 % and

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Japan's 3.05 % (OECD, 2024b).

To address PM-related issues and problems, South Korea has implemented various policies and PM management systems. Since introducing PM forecasting in 2014, the government has strengthened its policies with Comprehensive Particulate Matter Management Measures and the Seasonal Control Measure, focusing on controlling key emission sources, identifying PM causes, improving forecasting accuracy, and enhancing cooperation with other countries such as China. In fact, actual PM concentrations have shown a long-term declining trend (Yeo and Kim, 2019, 2022).

However, public perception and anxiety regarding PM have consistently worsened. According to a 2019 survey on public perceptions of PM in South Korea, 86 % of respondents answered that the annual average concentration levels of PM have increased compared to a decade ago (National Council on Climate and Air Quality, 2020). Researchers found that an estimated 4.023 trillion KRW is spent annually on PM-related expenses, with individual respondents spending an average of 20,000 KRW monthly (Hyundai Research Institute, 2019). According to Statistics Korea (2023), 64.6 % of the population nationwide reported feeling anxious about PM, higher than the 45.9 % expressing anxiety over climate change.

Many scholars have indicated that one of the reasons for public unaddressed anxiety regarding PM-related issues is the inadequacy of government communication with the public (Kim 2017; National Council on Climate and Air Quality, 2020; Three Major Academies, 2017). The primary goal of policy should be to reduce public anxiety about PM through effective communication with the public (Kim, 2017; Three Major Academies, 2018). This is because only when this is achieved can the government gain public consent, providing a foundation for policy effectiveness.

To alleviate public anxiety and ensure policy effectiveness, it is crucial to understand what perceptions the public holds about PM and what specific concerns the public has. At this point, it is necessary to consider the role of the media, which is a powerful tool for conveying information about PM and related issues to the public. For example, the framing of media reports can influence the public's perception of PM (Shapiro and Bolsen, 2018), and the framing of Korean media has been shown to distort actual PM concentrations (Kim et al., 2015a). Given this, it is important to determine whether the Korean public perception of PM is based on PM concentrations or whether other factors such as the media influence it. Understanding this may provide clues to address the gap between policy and public perception and substantially reduce public anxiety.

However, there is little research that has analyzed public perceptions of PM. Most researchers on PM have focused on analyzing its sources and suggesting reduction measures, or they have only analyzed current policies while examining how the media frames the PM issue and sets related agendas.

Recently, researchers have conducted studies on personal perceptions, behaviors, and responses, but many are survey-based studies with limited samples, often grounded in predefined frameworks or methodologies. Thus, in this study, we aim to examine the perceptions and issues surrounding PM by analyzing online community content through topic modeling and semantic network analysis. Although some researchers have used topic modeling and semantic network analysis to examine perceptions of PM, they have limited their work to specific behaviors or viewpoints, such as deriving nursing implications for strengthening health behaviors (Byun et al., 2021) or examining changes in outdoor activity perceptions among cyclists (Kim and Lee, 2019). Additionally, researchers analyzing news comments (Chung, 2021) have based their work on media framing, where opinions may be formed or temporarily biased toward specific issues. In contrast, in communities, discourse can be based on various sources beyond media reports, including personal experiences and emotional opinions. Therefore, we utilized data from online community posts that reflect the public perception because they have a wider range of topics and generate issues relatively independently. In addition, few studies have examined whether public response to PM is based on PM concentrations or news articles. In this sense, we set up the research questions, which guides this study as follows:

- What are the trends in news articles, PM concentrations, and community posts about PM?
- What is the perception structure of PM among users of Korean online communities?
- What are the main topics discussed about PM in Korean online communities?

2. Theoretical background

2.1. Trend in PM concentration and PM policies in South Korea

PM, commonly referred to as dust, includes two types: coarse particles (PM_{10}) and fine particles ($PM_{2.5}$; Ministry of Environment, 2022). The air quality standards for coarse particles (PM_{10}) are an annual average of 50 μg/m^3 or less and a 24 h average of 100 μg/m^3 or less, whereas for fine particles ($PM_{2.5}$) the standards are an annual average of 15 μg/m^3 or less and a 24 h average of 35 μg/m^3 or less (Ministry of Environment, 2022).

Although $PM_{2.5}$ concentrations in South Korea are higher than the OCED average (OECD, 2024a), the average concentrations of $PM_{2.5}$ and PM_{10} in South Korea have been decreasing over the long term as shown in Fig. 1 (Yeo and Kim, 2022). From 2001 to 2017, the frequency of high concentrations interval of PM_{10} and the frequency of consecutive high concentrations also show an overall decreasing trend (Yeo and Kim, 2019).

To improve the air quality in the heavily polluted capital region of South Korea, the Special Act on the Improvement of Air Quality in the Seoul Metropolitan Area was enacted in 2003. In 2005, a 10-year plan, the Master Plan for Seoul Metropolitan Air Quality Management, was implemented to promote comprehensive measures and systematically manage pollution sources, aiming to protect residents' health and create a pleasant living environment. Nevertheless, as PM worsened across the country, including in the capital region, the government launched the Special Committee on Particulate Matter in February 2019, followed by the establishment of the National Council on Climate and Air Quality in April 2019 to address PM issues.

The South Korean government has implemented a variety of policies in response to the growing problem of PM. If we categorize the government's policies according to their duration, long-term responses include the 8 Laws on Particulate Matter and the Comprehensive Plan for Particulate Matter Management (2020–2024), whereas short-term policies include the Emergency Reduction Measures and the Seasonal Control Measures.

First, there is a basic law on the reduction and management of PM, which is a long-term response, in the form of the Special Act on the Reduction and Management of Fine Dust and other laws that include provisions to reduce PM in the law (Special Committee on Particulate Matter, 2024). The goal of the first phase (2020–2024) of the Comprehensive Plan for Particulate Matter Management is to reduce the concentration of $PM_{2.5}$ by more than 35 % from 26 μg/m^3 in 2016 to 16 μg/m^3 in 2024. To achieve this, the following measures have been promoted: conversion to eco-friendly energy in the power generation sector, nationwide expansion of the total emission system in the industrial sector, reduction of old diesel vehicles and expansion of low-emission vehicles in the transportation sector, and international cooperation to reduce $PM_{2.5}$ in East Asia (Special Committee on Particulate Matter, 2024).

The Emergency Reduction Measures, a short-term but intense policy, is a crisis management system that is triggered when high concentrations of PM occur and implements an odd–even traffic policy for administrative and public institutions. In addition, the Seasonal Control

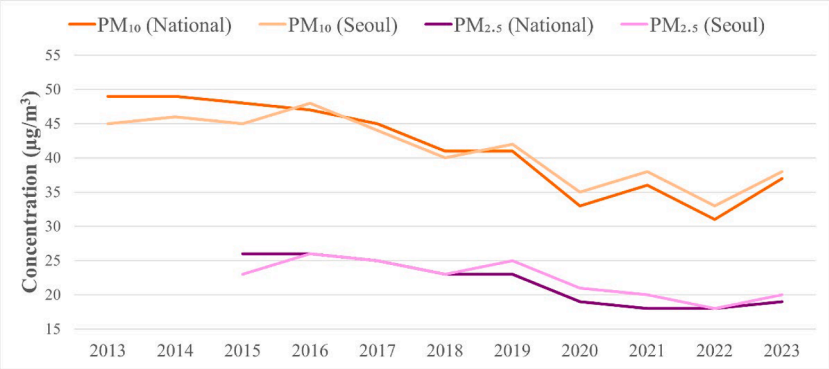


Fig. 1. Trends in $PM_{2.5}$ (2015-2023) and PM_{10} (2013-2023) concentration in South Korea and Seoul (Source: National Institute of Environmental Research, 2024, Annual Report on Ambient Air Quality).

Measure is a policy to reduce PM more intensely than usual from December to March, when PM is at a high concentration, by sector, region, and in cooperation between Korea and China. Specifically, this measure restricts the operation of Grade 5 emission vehicles that emit significant amounts of PM, reduces the operation of coal power plants, and installs air purification facilities for sensitive and vulnerable groups such as children. In addition, Korea and China have signed the Blue Sky plan for environmental cooperation, pledging cooperation in three areas: air policy and technology exchange, joint research, and technology industrialization (Comprehensive Portal for Particulate Matter, 2025). Overall, the South Korean government has established and implemented policies to reduce PM.

2.2. Review of research on PM

Research on PM can be categorized according to disciplines. Scholars of environmental engineering mainly focus on the sources of PM, chemical composition, reduction technologies, or air quality monitoring systems. In the fields of medicine and health sciences, researchers examine the effects of PM on human health and the damage to the health of vulnerable groups. Authors of social science and policy studies are interested in governments' responses to PM issues, changes in public perceptions and behaviors, and policy effectiveness analysis. Recently, how PM issues are described and understood in the public discourse has become an important research topic.

Some researchers have focused on how the media reports on PM and have examined it through content analysis (Kim et al., 2015a; Lee et al., 2021). Researchers have found a temporal discrepancy between the South Korean media coverage of PM and measured PM concentrations. This gap shows that media agenda-setting may not always align with scientific data. For example, Kim et al. (2015a) found that although the risk of PM existed before 2013, media coverage spiked after the fourth quarter of 2013. In addition, Lee et al. (2021), who compared regional and national coverage centered on Chungcheongnam-do, south of the Seoul Metropolitan Area, where the concentration of PM is particularly high, also found differences in the level of PM concentration and the frequency of media coverage. The researchers attributed this to the fact that it is more closely related to policy implementation and outcomes than PM concentrations themselves. In other words, the timing and extent to which the media sets the agenda and makes it a social issue may be independent of the actual level of PM concentration. These studies have confirmed that social discourse can be shaped by media representation of PM, rather than actual PM concentrations.

More recently, researchers have investigated media discourse and the public's understanding of PM by performing topic modeling based on big data such as news, news comments, and social media (Byun et al., 2021; Chung, 2021; Yoon and Kim, 2020). Yoon and Kim (2020) collected Korean news articles for 10 years from 2010 to 2019 and conducted an latent Dirichlet allocation (LDA) analysis. As a result, they found that the air purifier business market had expanded; there were policy discussions, such as those on limiting the operation of old diesel vehicles through the Comprehensive Plan for Particulate Matter Management; and discussions took place on ensuring the environmental rights of vulnerable groups. In addition, Byun et al. (2021), from a nursing perspective, analyzed the semantic structure before 2014–2016 and after 2017–2019 the implementation of the Comprehensive Plan for Particulate Matter Management. The common topics before and after the policy implementation were "causes of PM" and "response behaviors" in social media (Byun et al., 2021, p.74). Chung (2021) found that, in the case of news articles, the government's policy measures to reduce PM took center stage, whereas in the case of comments, the majority of comments were negative about China and the effectiveness of government policies. These studies commonly indicate that the causes of PM, response behaviors, and China were the main topics of media discussion and public perception. However, these studies have focused on text mining news articles, and few studies have directly examined public responses. Some studies have looked at news comments (Chung, 2021), but these studies are limited because the comments were written on news articles, which are likely to be directly influenced by the framing and content of the news articles. In contrast, online communities have the advantage of generating topics freely by exchanging media reports, personal experiences, and opinions.

Meanwhile, beyond identifying the content of the coverage, researchers have examined the impact of media coverage on public perception of PM based on the roles of the media in public perception (Chung, 2021; Kim et al., 2015a; 2016; Shapiro and Bolsen, 2018). In particular, the South Korean media has indicated China as the source of PM (Kim et al., 2015a; Shapiro and Bolsen, 2018), and the South Korean public seems to be influenced by the media because it tends to attribute the source of PM to China (Chung, 2021; Kim et al., 2016). In addition, unlike experts' understanding of PM based on scientific evidence, the public tends to understand the risks of PM based on emotional heuristics, such as understanding the risks of PM based on negative emotions influenced by media representation (Kim et al., 2016). As such, public perception is influenced by how the media reconstructs the issue, and it sometimes fails to thoroughly understand the issue of PM. Considering this, we compare the monthly trends of news articles and online community posts to explore the relationship between media coverage and public responses to PM.

Taken together, in previous studies, researchers have investigated how media reports on PM specifically, or how media contents and PM concentrations affect public perception or public behavior. Some authors have compared the frequency of media coverage and trends in PM concentrations (Lee et al., 2021) or sought to understand public perception through social media or comments (Byun et al., 2021; Chung, 2021). However, few researchers have examined how public perceptions

are shaped over the long term and have combined media coverage, PM concentrations, and public response trends. For this purpose, we first compare monthly trends in news articles, online community posts, and PM concentrations to examine how public responses to PM align or diverge from news reports and PM concentrations. Then, we also statistically demonstrate the relationship between PM concentrations and community posts through cross-correlation analysis. Lastly, we aim to examine how the public perceives and responds to the problem of PM by analyzing texts posted by the public voluntarily in online communities.

3. Research methods

3.1. Research subjects

To understand the general public's perception of PM, discussions related to PM on major online communities will be analyzed. Online communities play the role of a public sphere where individuals produce, share, and spread information, enabling two-way communication. With the growing influence of online communities in socio-political spheres, they also function as spaces for consumer and agenda movements (Cho et al., 2015).

Given the active voluntary sharing of opinions among users in online communities, they were deemed suitable for investigating public perceptions of PM. Additionally, to ensure representativeness and avoid bias toward specific fields or political inclinations, posts were collected from communities with diverse political orientations (Far-left: Clien, Ppomppu, Ruliweb; Progressive: 82cook, MLBPARK; Centrist: Ygosu, Inven; Far-right: Ilgan Best) and communities covering various interests such as IT (Clien), gaming (Ruliweb, Ygosu, Inven), cooking (82cook), and sports (MLBPARK). These communities are known to be actively used not only by people in their 20s and 30s but also by those in their 40s and 50s (Lee et al., 2023; Kim, 2023). When reviewing community rankings based on traffic and top post consumption metrics as of November 2023, the following were confirmed: Ruliweb (3rd), Ppomppu (4th), Inven (5th), Clien (8th), Ilgan Best (9th), Funny University (11th), MLBPARK (12th), Etoland (14th), and 82cook (15th) (Today's Best, 2025). These communities were determined to have sufficient representativeness as they are major online platforms in South Korea where active exchanges of opinions take place.

3.2. Research procedure

To address the research questions, this study analyzed the monthly trends in news articles, PM concentrations, and online posts; performed a cross-correlation analysis to examine how PM concentrations are associated with fluctuations in the volume of online posts; and applied big data analysis, including semantic network analysis and LDA topic modeling.

To understand public perceptions of PM, we first collected relevant posts about PM by entering the Korean word for 'particulate matter' in online communities in South Korea. After refining the words using text mining techniques, key terms were extracted. Based on this, a semantic network was structured, and finally, LDA topic modeling was conducted to derive key themes, which were then visualized.

3.3. Data collection

This study collected posts from 10 online communities from January 2013 to December 15, 2023. The reason for starting with 2013 is that media coverage began to increase rapidly in the fourth quarter of 2013 as the "Clean Air Conservation Act" (July 2013) and the pilot particulate matter forecasting system (August 2013), were implemented (Kim et al., 2015a, p.135). Initially, we collected 2953 posts, but some posts that had no content or repeatedly wrote the same thing without difference. These data were deleted to prevent distortion of the results. As a result, a total of 2714 community posts were collected. In addition, we obtained data on the monthly trends in news articles related to 'particulate matter' from BIGKinds (2025) (https://www.bigkinds.or.kr/) and monthly PM_{10} and $PM_{2.5}$ concentration information from the Environmental Statistics Portal (2025) (https://stat.me.go.kr/) to examine and compare the trend of news articles, PM concentrations and the number of posts.

In the time series analysis, we used 2690 online posts collected based on monthly data from January 2013 to November 2023. Full monthly data for December 2023 were unavailable, so this month was excluded. The text mining analysis identified the semantic structure and subtopics of online posts for a total of 2714 data sets from January 2013 to December 15, 2023.

3.4. Data preprocessing for cross-correlation analysis

Cross-correlation analysis of PM_{10} National, PM_{10} Seoul, $PM_{2.5}$ National, $PM_{2.5}$ Seoul, and Posts monthly data from January 2013 to November 2023 was performed in the following order. First, the data must be stationary to perform the cross-correlation analysis. Stationarity, which is necessary for analyzing time series data, is the feature that the mean and variance of the data remain constant over time. We used the Augmented Dickey-Fuller (ADF) unit root test using Python's statsmodels package to check the stationarity of the collected monthly data. Moreover, autocorrelation function (ACF) and partial autocorrelation function (PACF) were performed to determine the autocorrelation of the time series data. The Ljung-Box test (Ljung and Box, 1978) was used to determine whether the residuals are independent. To perform the cross-correlation analysis, we performed a first-order seasonal difference considering the characteristics of the data. Following differentiation, the data were checked for stationarity using the Augmented Dickey-Fuller (ADF) test, and cross-correlation was performed in the SPSS software. We used cross-correlation analysis to explore whether the number of posts responded in a time-lagged pattern to changes in PM concentrations. Considering that the increase in the number of posts occurred in April 2016, the period was divided into January 2013–November 2023 and April 2016–November 2023, respectively. The PM concentrations were log10-transformed following previous studies (see, for example, Seinfeld and Pandis, 2016), and the posts were transformed to $\log10(x+1)$ because they were zero in some periods.

3.5. Data preprocessing for text mining

Given the nature of community data, many unrefined words appeared, so a process was conducted to merge or delete words with the same meaning. For example, "Chinese government," "China," and "PRC" were standardized to "China," while profanity and repetitive, meaningless words were deleted.

3.6. Data analysis for text mining

Based on the 2714 collected community posts, this study used the program NetMiner to extract key words' TF (term frequency) and TF-IDF (term frequency-inverse document frequency). In addition, to identify relationships between words and key topics, word centrality was analyzed, the semantic network was visualized, and LDA topic modeling was conducted.

We calculated the number of words to analyze using the formula from Sun et al. (1999), based on 3978 words that were extracted for text mining, deemed meaningful, and had a frequency of 2 or more; as a result, we ultimately analyzed 63 words.

Latent Dirichlet allocation (LDA), a topic classification method developed by Blei et al. (2003), was used to categorize topics based on the likelihood of word occurrences. To determine the number of topics, we used the coherence c_v and u_mass index to examine the coherence values through simulation. However, when selecting the number of topics, it is necessary to complement the process of reviewing whether

the topics are actually well classified by the researcher for a qualitative evaluation rather than simply judging the index alone. Therefore, in this study, we ran LDA on 7 and 9 topic count candidates with high coherence values, reviewed the topic contents, and finally selected 9 topics that were judged to be well categorized. The alpha and beta hyperparameters were set to 0.1 and 0.01, respectively, based on previous research (Park and Park, 2021). After that, we checked the contents of each topic and named each topic. When naming the topics, we mainly considered the words with the highest probability, and reviewed the posts corresponding to the topic to create a title that could encompass the content.

4. Research results

4.1. Association between news and PM concentrations and public response: time-series comparison and cross-correlation analysis

We examined the data trends and performed a cross-correlation analysis on monthly data from January 2013 to November 2023. During this period, 394318 news articles related to PM were reported in Korea, and 2690 online posts were made.

To examine the trends, we compared the monthly trends of the number of news articles and posts and found that the overall trends were similar (Fig. 2). First, news articles started to increase rapidly from Q4 2013, and posts started to appear from December 2013, suggesting that they were influenced by the surge in media coverage. In sum, it seems that the public began to recognize PM because of media reports.

When the number of news articles increases or decreases, posts also tend to increase or decrease. Overall, from 2016 to 2018, the number of community posts tended to increase slightly when the number of news articles increased, especially in March 2019, when the number of news articles exploded compared to February 2019. The reason for the spike in news articles in March 2019 is that Emergency Reduction Measures were implemented from March 1 to 7, 2019, which included an odd–-even traffic policy for administrative and public vehicles in some areas. This was the first time since the Emergency Reduction Measures were implemented in 2017 that they were issued for 1 week in a row (An, 2019).

In addition, the number of news articles increased in March 2023, and the number of community posts also exploded. The reason for the increase in articles in March 2023 was the yellow dust from China, which caused a PM advisory, which is issued when the average concentration of PM_{10} per hour is 150 μg/m^3 or higher for more than 2 h, to be issued in most parts of the country on March 23–24 (National Institute of Environmental Research, 2024; Cheon, 2023). Although the average number of articles in March 2023 did not increase as overwhelmingly as in March 2019, the number of community posts increased sharply, suggesting that the public may have become aware of the danger by using weather apps in addition to news articles and become more sensitive because of government actions or past learning effects. Moreover, the number of posts tended to decrease when the number of news articles decreased. For example, from July to September 2018, the number of news articles decreased, and the number of posts also decreased.

However, we also observed months during which community posts remained high or reacted later even as the number of articles decreased at some points, suggesting that the public may be affected by a staggered response after media coverage or that the community may reproduce the issue on its own. For example, on April 12 and 13, 2023, when a PM advisory and warning was issued (National Institute of Environmental Research, 2024), the number of news articles decreased slightly in April 2023 compared to March, but the number of community posts increased. This suggests the possibility of self-generated discourse within the community spreading even as media coverage decreases. In short, although it is difficult to conclude a causal relationship between news articles and the number of communities, the timing of the spike suggests that media coverage influenced the formation of public discourse.

To explore whether the public's reaction was based on actual PM concentrations, we visualized the monthly trends of PM concentration and the number of posts (Fig. 3). The graph shows that PM concentration and post counts tend to follow similar patterns of ups and downs. For example, in November 2018 and January 2019, the number of posts increased when PM levels rose. This shows that higher PM concentrations led to an immediate public reaction, resulting in an increase in PM-related posts. In particular, the number of posts follows a similar pattern as PM concentrations increase in winter and spring and decrease in summer. In March and May 2021, the number of posts increased when PM concentrations increased, and conversely, the number of posts decreased when PM concentrations were low in June 2019 and July 2020.

To statistically confirm these similarities, we performed a cross-correlation analysis between PM concentrations and posts. Considering the increase in the number of posts from April 2016, we divided the period from January 2013 to November 2023 and from April 2016 to

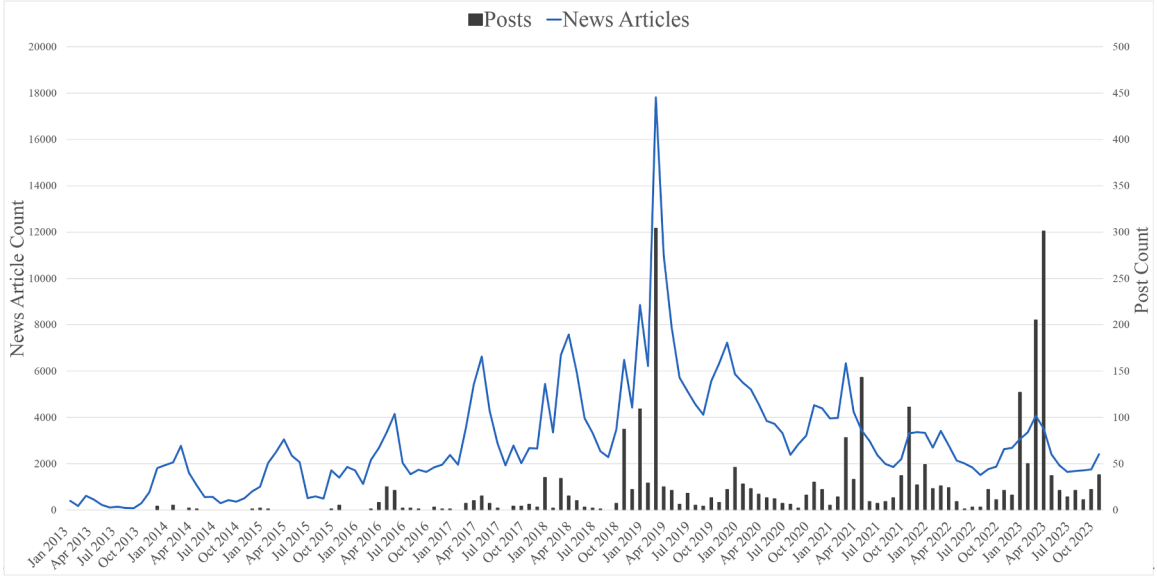


Fig. 2. Monthly trends in news articles and posts from January 2013 to November 2023.

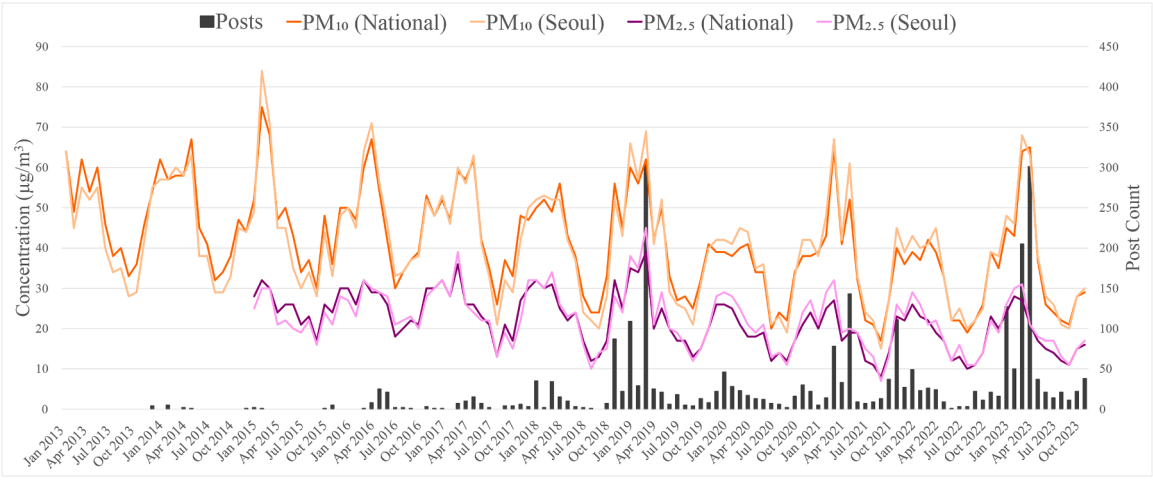


Fig. 3. Monthly trends in PM_{10} and $PM_{2.5}$ concentration and posts from January 2013 to November 2023.

November 2023 (Table 1). For clarity of interpretation, only significant correlation coefficients from lag 0 to lag 3 are reported in Table 1.

First, when analyzed from January 2013 to November 2023, the highest cross-correlation coefficient was observed at lag 0 for all PM concentrations, and these coefficients were statistically significant ($p < 0.001$). The correlation coefficient values were high in the order of $PM_{2.5}$ Seoul, PM_{10} Seoul, $PM_{2.5}$ National, and PM_{10} National at lag 0. These results suggest that an increase in PM concentration is significantly correlated with a relative increase in the number of online posts at the same time, indicating that public reactions occurred simultaneously.

In addition, the analysis covering the period from April 2016 to November 2023 showed that the cross-correlation coefficient of all PM concentrations was the highest and statistically significant ($p < 0.001$) at lag 0. During the period from April 2016 to November 2023, PM_{10} Seoul, PM_{10} National, $PM_{2.5}$ National show relatively higher correlation coefficients compared to the period from January 2013 to November 2023. In particular, the coefficient for PM_{10} Seoul was the highest at 0.618 at lag 0. This result means that the correlation between PM concentration and posts was relatively stronger.

In summary, the highest maximum cross-correlation coefficient at lag 0 suggests a concurrent response with a relative increase in the number of posts in months with higher PM concentrations compared to previous months. In addition, significant cross-correlation coefficients for lags 1 and 2 were found for some PMs, indicating a delayed response to the increase in posts one or two months following the increase in PM concentrations. To explore the reason for the higher correlation in the period from April 2016 to November 2023, the public's awareness of PM possibly increased as the media began to report on PM in 2013. Subsequently, the public responded by checking the changes in PM concentrations themselves, and this response was reflected in a rise in posts. In other words, as the public became more interested in PM, their sensitivity increased and they may have responded more directly to PM concentrations. Although we used log 10 transformations and seasonal differences to ensure stationarity, the Ljung-Box test revealed significant autocorrelation in some time series. For this reason, when interpreting the cross-correlation results, we focused on the pattern of time differences rather than the absolute value of the coefficients.

However, in some cases, the number of posts is much larger than the average monthly increase in PM concentration in Fig. 3, suggesting that factors other than concentration need to be considered. For example, in March 2019 and March 2023, the number of posts spiked more compared to the increase in PM concentration, most likely because the

Table 1
Cross-correlation coefficient for PM concentrations and posts.

Period	PM	N	cross-correlation lag time	cross-correlation coefficient	95 % Confidence interval		P-value
					Lower Confidence Limit (LCL)	Upper Confidence Limit (UCL)	
(1) 2013.01-2023.11	PM_{10} National	119[a]	Lag=0	0.487	0.307	0.667	<0.001
		119	Lag=1	0.253	0.073	0.433	<0.01
		119	Lag=2	0.277	0.097	0.457	<0.01
	PM_{10} Seoul	119	Lag=0	0.535	0.355	0.715	<0.001
		119	Lag=1	0.221	0.041	0.401	<0.05
		119	Lag=2	0.217	0.037	0.397	<0.05
	$PM_{2.5}$ National	95[b]	Lag=0	0.528	0.326	0.730	<0.001
	$PM_{2.5}$ Seoul	95	Lag=0	0.547	0.345	0.749	<0.001
		95	Lag=1	0.209	0.007	0.411	<0.05
(2) 2016.04-2023.11	PM_{10} National	80[c]	Lag=0	0.589	0.369	0.809	<0.001
		80	Lag=1	0.285	0.064	0.506	<0.05
		80	Lag=2	0.389	0.168	0.610	<0.001
	PM_{10} Seoul	80	Lag=0	0.618	0.398	0.838	<0.001
		80	Lag=2	0.293	0.072	0.514	<0.01
	$PM_{2.5}$ National	80	Lag=0	0.561	0.341	0.781	<0.001
	$PM_{2.5}$ Seoul	80	Lag=0	0.530	0.310	0.750	<0.001

[a] Out of the total of 131 data sets, cross-correlation analysis was performed on 119 data sets due to seasonal differences.
[b] Since $PM_{2.5}$ has been observed from January 2015, the number of $PM_{2.5}$ data is analyzed as 95, which is 24 less than PM_{10}.
[c] Out of the total of 92 data sets, cross-correlation analysis was performed on 80 data sets due to seasonal differences.

public reacted to the high concentration of monthly episodes due to the Emergency Reduction Measures in March 2019 and the PM advisory in March 2023. Put differently, the public reacted to PM concentration, but the government's policy implementation and media coverage of PM concentration amplified the intensity of the public's reaction.

4.2. Results of text mining on PM-related online community posts

Text mining was performed on all 2714 posts, and the distribution of posts by community is as follows (Table 2). The number of posts collected by each community was highest for Clien, 82cook, MLBPARK, and Ruliweb.

4.2.1. TF and TF-IDF analysis results

After preprocessing the community posts data, we analyzed the high frequency words. The list of the top 63 words derived is as follows (Table 3). When comparing the words extracted through TF and TF-IDF, most were consistent. However, whereas "capital" and "fine" appeared in TF, "toxic smog" and "North Korea" emerged in TF-IDF, showing some differences. Nevertheless, the top six words—"PM," "China," "South Korea," "concentration," "government," and "citizen"—were ranked the same in both analyses. These results indicate that discussions on high PM concentrations in South Korea prominently focused on the subjects of the government, citizens, and neighboring country China.

Whereas "PM" ranked first, "fine particle" ranked 23rd in TF and 22nd in TF-IDF. This suggests that the public discussed PM collectively rather than distinguishing between coarse particles and fine particles, resulting in fewer mentions of fine particles.

In addition, among the keywords, more words related to "China" were identified than other countries, indicating that China is an important target in Korea's PM problem. Specifically, "China" was ranked second, with a higher frequency than "South Korea," which was ranked third, and a higher number of China-related words such as "China," "Chinese," and "originating from China" than other countries such as "Japan," "USA," and "North Korea." In addition, words such as "factory" and "yellow dust," which are considered to be caused by China, were also identified. This indicates that when discussing PM issues, the Korean public viewed China as a central player and mentioned it more actively than other countries.

The public's understanding of the dangers of PM centered around "concentration" and physical reactions, and they were responding personally by purchasing products to protect themselves in these situations, such as "face masks" and "air purifiers." "Concentration" ranked fourth in both TF and TF-IDF, "eye" ranked 42nd in TF and 46th in TF-IDF, and "throat" ranked 44th in TF and 50th in TF-IDF. In addition, "face mask" was ranked 13th in TF and 16th in TF-IDF, and "air purifier" was ranked 35th in TF and 39th in TF-IDF. In other words, it seems that people experience physical reactions in the eye or throat area because of high concentrations of PM and use face masks when they are outside and air purifiers when they are inside because it is difficult to ventilate or go outside because of PM. This suggests that the way the public perceives the risk level of PM is centered on numerical concentrations and physical reactions and that they are willing to pay to protect themselves on a personal level and purchase related products. These results are consistent with a study that found that residents in areas with high concentrations of PM were worried about the health effects of PM based on witnessing factory smoke or experiencing health symptoms in themselves or their acquaintances (Kim et al., 2022). In other words, the public perceives the risk of PM based on the concentration of PM and

Table 3
Key high-frequency words.

Rank	Word	Frequency	Word	TF-IDF
1	PM	2,990	PM	2284.785
2	China	1,195	China	1871.154
3	South Korea	634	South Korea	1413.455
4	concentration	465	concentration	1097.866
5	government	333	government	924.501
6	citizen	330	citizen	902.779
7	air	313	solution	882.016
8	person	301	person	820.043
9	solution	291	cause	789.666
10	cause	282	air	787.855
11	vehicle	264	vehicle	764.423
12	Seoul	263	resolve	742.187
13	face mask	251	environment	731.401
14	problem	237	Seoul	728.610
15	environment	232	Moon Jae-in	703.675
16	dust	225	face mask	698.336
17	resolve	220	problem	691.032
18	Moon Jae-in	217	dust	659.125
19	outdoor	208	Chinese	646.285
20	originating from China	207	domestic	638.781
21	domestic	207	originating from China	613.659
22	factory	206	fine particle	604.721
23	fine particle	198	factory	600.644
24	sky	189	atmosphere	599.302
25	ventilation	184	ventilation	584.898
26	atmosphere	181	outdoor	566.674
27	Chinese	176	sky	561.652
28	house	174	spy	553.769
29	region	172	region	543.734
30	country	171	yellow dust	535.052
31	yellow dust	165	country	529.073
32	window	149	house	523.451
33	health	148	Ministry of the Environment	517.070
34	coal	146	health	510.871
35	air purifier	140	coal	494.121
36	news	139	window	483.168
37	Ministry of the Environment	132	research	479.558
38	COVID-19	130	news	456.088
39	the worst	129	air purifier	450.076
40	child	127	child	442.892
41	research	123	COVID-19	425.288
42	eye	120	mackerel	425.074
43	wind	118	pollutant	418.322
44	throat	115	state	412.699
45	state	115	the worst	408.927
46	mackerel	112	eye	407.438
47	Japan	110	wind	398.082
48	weather	105	reduction	390.521
49	reduction	102	Japan	380.988
50	economy	99	throat	380.772
51	pollutant	98	economy	377.372
52	spy	97	weather	355.361
53	the press	93	emission	347.492
54	policy	89	policy	345.394
55	pollution	89	the press	344.238
56	nationwide	88	toxic smog	343.778
57	the Korean Peninsula	87	pollution	342.270
58	emission	87	the Korean Peninsula	336.092
59	rain	84	nationwide	331.148
60	USA	84	USA	330.615
61	capital	77	nuclear power plant	318.638
62	fine	77	North Korea	318.196
63	nuclear power plant	76	rain	314.773

Table 2
Distribution of PM-related posts by community from January 2013 to December 15, 2023.

Clien	82cook	MLBPARK	Ruliweb	Ilgan Best	Funny University	Ppomppu	Ygosu	Inven	Etoland	Total
521	515	474	466	425	162	86	62	2	1	2714

direct physical reactions.

In addition, the words related to government and policy were identified, indicating that the government is perceived as the main actor involved in the problem of PM and that the public is particularly interested in policies to address the problem. "Government" and "citizen" are ranked equally 5th and 6th in the TF and TF-IDF rankings, respectively, whereas "solution" is ranked 9th in TF and 7th in TF-IDF, and "problem" is ranked 14th in TF and 17th in TF-IDF. "Policy" ranked 54th in TF and TF-IDF, suggesting that the public recognizes the need for government policy as well as personal action to address the problem of PM.

4.2.2. Centrality analysis

The results of the centrality analysis for the extracted key words are shown in Table 4. First, "PM," "China," and "South Korea" consistently ranked in the top three across all centralities. Excluding the topic word "PM," "China" recorded the highest centrality. This result indicates that "China" is the most connected to other words, acting as a mediator between them and playing a central role in controlling the flow of discussions within the network. Notably, among the keywords related to China, "originating from China" ranked 7th in eigenvector centrality, indicating that this word holds a highly influential position within the semantic network. That is, the public's discussion of PM in South Korea centers around "China," reflecting their perception that China has a significant impact on the PM problem. These results are consistent with findings that "originating from China" and "China" are key words in news comments on PM and that the public viewed China as the source of PM, especially during the period when the issue was surfacing (Chung, 2021). Furthermore, given the tendency of the South Korean media to point to China as the source of PM (Kim et al., 2015a; Shapiro and Bolsen, 2018), we can speculate that these results are the result of the public being influenced by media reports.

Additionally, terms that describe PM such as "air," "pollution," "fine particle," "concentration," "atmosphere," and "outdoor," along with core terms related to the causes and solutions for the PM issue, such as "cause," "problem," and "solution," were among the top 26 ranked words. This shows that these terms are highly connected within the network, playing a central role in discussions about PM. It demonstrates that the public perceives high PM concentrations as a problem and actively discusses its causes and potential solutions. These results are similar to the results of a text mining study of social media, which found that the main topics of causes and solutions were the same before and after the Comprehensive Plan for Particulate Matter Management Byun et al. (2021), suggesting that the public values identifying and solving the causes of PM problems.

Meanwhile, words such as "eye," "sky," "house," and "ventilation" ranked relatively higher in betweenness centrality, at 29th, 40th, 32nd, and 45th, respectively, compared to their rankings in degree centrality, closeness centrality, and eigenvector centrality. This indicates that although these words may not be as directly connected to other terms, they play an important role in mediating the flow of discussions within the network. Thus, we confirmed that discussions about physical and environmental changes caused by PM, as well as indoor ventilation, also significantly influence the flow of conversations within the semantic network.

4.2.3. Semantic network

To understand the position and role of words within the network, we conducted a semantic network analysis. The visualization of the network is shown in Fig. 4. The size of each node represents the frequency of the word, whereas the thickness reflects the degree of co-occurrence between words.

4.2.4. LDA topic modeling

The results of the LDA topic modeling are presented in Table 5 and Fig. 5. The main words in Topic 1 included "PM (0.091)," "face mask (0.038)," "person (0.02)," "eye (0.018)," "air (0.016)," "outdoor (0.015), " " concentration (0.014)," "throat (0.013)," and "COVID-19 (0.013)." Example community posts for this topic include, "Even with a mask on, my nose and throat burn, and I feel suffocated. Don't go outside"; "I only walked outside for a bit, but my throat is stinging . . . Why is there so much PM lately?" and "My eyes sting . . . my throat hurts, my nose hurts . . . . I can't avoid ventilating the house, but doing so makes it feel like dust is piling up, and even indoors, my throat hurts again . . . . It's driving me crazy." In Topic 1, the majority of posts expressed physical discomfort caused by PM, such as eye and throat irritation. Therefore, we labeled Topic 1 "Physical Risk."

The main words in Topic 2 included "PM (0.079)," "China (0.035)," "concentration (0.022)," "cause (0.021)," "domestic (0.02)," and "research (0.016)." Example posts include, "Everyone knows that China is a much bigger factor than domestic sources, but China refuses to admit it"; "During COVID, when Chinese factories stopped, PM in Korea dropped to its lowest level, so it's clear that China is the main cause"; and "Government PM research excluded the impact of Chinese pollutants." This topic focused on discussions about the causes of PM, with most people asserting that PM originates from China. Thus, we labeled Topic 2 "Chinese-Origin PM."

The main words in Topic 3 included "China (0.068)," "PM (0.06)," "South Korea (0.04)," "citizen (0.026)," "government (0.021)," "problem (0.016)," "country (0.014)," "Moon Jae-in (0.014)," and "health (0.012)." Example posts for this topic include, "In a situation where it's hard to even breathe due to PM, South Korean citizens are left wondering whether the government even exists. What is the Moon Jae-in administration doing with taxpayer money? They claim to focus on people's livelihoods, but do they even care about what the citizen wants?" "Why isn't the government taking fundamental and practical measures to alleviate the suffering of the people?" "Are they telling us all to die? The government should be strongly protesting to China regarding PM-related sanctions—this is the most urgent issue this winter. Please, the government needs to address this with China at a national level. Shouldn't the Minister of Health and Welfare step in? Honestly, I'm going crazy. If we keep breathing this PM for a few more months, I think people will start dying." Based on the content of the posts, we labeled Topic 3 "Calls for Active Government Intervention."

The main words in Topic 4 included "PM (0.08)," "Seoul (0.027)," "concentration (0.025)," "region (0.024)," "fine particle (0.016)," "yellow dust (0.016)," "nationwide (0.014)," "rain (0.014)," and "the worst (0.014)." Posts related to this topic were identified as news articles shared within the community regarding PM forecasts. Examples include, "Tomorrow, high concentrations of PM will blanket the entire country, along with yellow dust." "The worst air quality of this winter . . . . PM will be very thick throughout the weekend, with concentrations several times the usual level . . . . The stagnant air isn't clearing, and Emergency Reduction Measures have been implemented in most regions as PM and yellow dust have flowed in, worsening air quality to the worst levels this winter on the 7th." "As a result, today, fine particle levels will rise to 'unhealthy' across most regions, and in the western coastal areas, some places may see levels rise to 'very unhealthy.'" Thus, we labeled Topic 4 "High Interest in PM Forecasts."

The main words in Topic 5 included "China (0.071)," "PM (0.052)," "factory (0.036)," "resolve (0.025)," "coal (0.023)," "South Korea (0.018)," "sky (0.014)," "operation (0.012)," and "thermal power plant (0.011)." Examples of posts using these keywords include, "Aside from PM emitted by outdated factories, coal-fired power plants, and old vehicles, many households in China still use coal for cooking and heating, especially in winter, unlike here, where most homes are individual houses"; "It seems China is back to burning coal at full throttle"; "I hear all the factories on China's western coast are coal-powered . . . "; "When

Table 4
Centrality distribution results.

	Word	Degree Centrality	Word	Betweenness Centrality	Word	Closeness Centrality	Word	Eigenvector Centrality
1	PM	0.9839	PM	0.1949	PM	0.9841	PM	0.3240
2	China	0.8548	China	0.1182	China	0.8732	China	0.2977
3	South Korea	0.6613	South Korea	0.0697	South Korea	0.7470	South Korea	0.2325
4	Cause	0.4355	Government	0.0184	cause	0.6392	cause	0.1775
5	Government	0.4355	Cause	0.0183	government	0.6392	government	0.1721
6	Seoul	0.4194	Seoul	0.0177	Seoul	0.6327	Seoul	0.1657
7	Vehicle	0.4032	Vehicle	0.0169	vehicle	0.6263	originating from China	0.1627
8	Atmosphere	0.3871	Problem	0.0159	atmosphere	0.6200	atmosphere	0.1620
9	Problem	0.3871	Person	0.0147	problem	0.6200	vehicle	0.1603
10	Domestic	0.3710	Concentration	0.0134	domestic	0.6139	problem	0.1548
11	originating from China	0.3710	yellow dust	0.0133	originating from China	0.6139	domestic	0.1539
12	Person	0.3548	Outdoor	0.0128	person	0.6078	citizen	0.1430
13	yellow dust	0.3548	Atmosphere	0.0128	yellow dust	0.6078	yellow dust	0.1429
14	Air	0.3387	Air	0.0119	air	0.6019	fine particle	0.1419
15	Citizen	0.3387	Domestic	0.0118	citizen	0.6019	person	0.1410
16	Concentration	0.3387	fine particle	0.0115	concentration	0.6019	emission	0.1381
17	fine particle	0.3387	Citizen	0.0106	fine particle	0.6019	air	0.1357
18	Emission	0.3226	Country	0.0106	emission	0.5962	concentration	0.1331
19	Outdoor	0.3226	originating from China	0.0100	outdoor	0.5962	region	0.1290
20	Country	0.3065	Pollution	0.0091	country	0.5905	pollution	0.1280
21	Pollution	0.3065	Chinese	0.0082	pollution	0.5905	environment	0.1269
22	Region	0.2903	Solution	0.0075	region	0.5849	outdoor	0.1261
23	Dust	0.2742	Emission	0.0075	dust	0.5794	country	0.1252
24	Solution	0.2742	Wind	0.0073	solution	0.5794	mackerel	0.1202
25	Environment	0.2742	Region	0.0068	environment	0.5794	dust	0.1186
26	Mackerel	0.2581	Dust	0.0058	mackerel	0.5741	solution	0.1178
27	News	0.2581	News	0.0057	news	0.5741	news	0.1130
28	Factory	0.2419	State	0.0053	factory	0.5688	factory	0.1115
29	State	0.2419	Eye	0.0050	state	0.5688	coal	0.1099
30	Wind	0.2419	COVID-19	0.0049	wind	0.5688	pollutant	0.1088
31	Chinese	0.2419	Environment	0.0046	Chinese	0.5688	state	0.1084
32	COVID-19	0.2419	House	0.0045	COVID-19	0.5688	policy	0.1076
33	Coal	0.2258	Mackerel	0.0041	coal	0.5636	COVID-19	0.1035
34	Pollutant	0.2258	factory	0.0040	pollutant	0.5636	wind	0.1016
35	Policy	0.2258	Moon Jae-in	0.0038	policy	0.5636	research	0.1003
36	face mask	0.2097	fine	0.0036	Moon Jae-in	0.5586	Chinese	0.0999
37	Moon Jae-in	0.2097	face mask	0.0035	fine	0.5586	economy	0.0981
38	Fine	0.2097	child	0.0035	nuclear power plant	0.5586	nuclear power plant	0.0976
39	nuclear power plant	0.2097	Japan	0.0033	Japan	0.5586	the press	0.0969
40	Japan	0.2097	sky	0.0030	house	0.5586	USA	0.0959
41	House	0.2097	policy	0.0029	economy	0.5536	Japan	0.0945
42	Economy	0.1935	nationwide	0.0028	face mask	0.5536	Ministry of the Environment	0.0925
43	USA	0.1935	pollutant	0.0028	USA	0.5536	Moon Jae-in	0.0920
44	Child	0.1935	coal	0.0025	child	0.5536	capital	0.0909
45	the press	0.1935	ventilation	0.0025	the press	0.5536	the worst	0.0904
46	Research	0.1935	nuclear power plant	0.0025	research	0.5536	fine	0.0898
47	the worst	0.1935	health	0.0023	the worst	0.5536	face mask	0.0878
48	Health	0.1774	the worst	0.0019	health	0.5487	child	0.0855
49	Eye	0.1774	rain	0.0017	capital	0.5487	house	0.0844
50	Capital	0.1774	USA	0.0017	nationwide	0.5487	sky	0.0823
51	Nationwide	0.1774	the press	0.0016	sky	0.5487	health	0.0773
52	Sky	0.1774	economy	0.0016	Ministry of the Environment	0.5487	nationwide	0.0747
53	Ministry of the Environment	0.1774	air purifier	0.0015	eye	0.5439	resolve	0.0738
54	air purifier	0.1452	capital	0.0014	air purifier	0.5391	reduction	0.0719
55	Reduction	0.1452	Ministry of the Environment	0.0012	reduction	0.5391	weather	0.0644
56	Ventilation	0.1452	research	0.0012	weather	0.5345	air purifier	0.0617
57	Weather	0.1290	window	0.0011	rain	0.5345	eye	0.0589
58	Rain	0.1290	throat	0.0011	resolve	0.5345	the Korean Peninsula	0.0578
59	Resolve	0.1290	weather	0.0009	ventilation	0.5345	rain	0.0561
60	Window	0.1129	reduction	0.0009	window	0.5299	ventilation	0.0511
61	the Korean Peninsula	0.1129	the Korean Peninsula	0.0005	the Korean Peninsula	0.5299	window	0.0434
62	Throat	0.0968	resolve	0.0003	throat	0.5254	throat	0.0419
63	Spy	0.0806	spy	0.0001	spy	0.5082	spy	0.0399

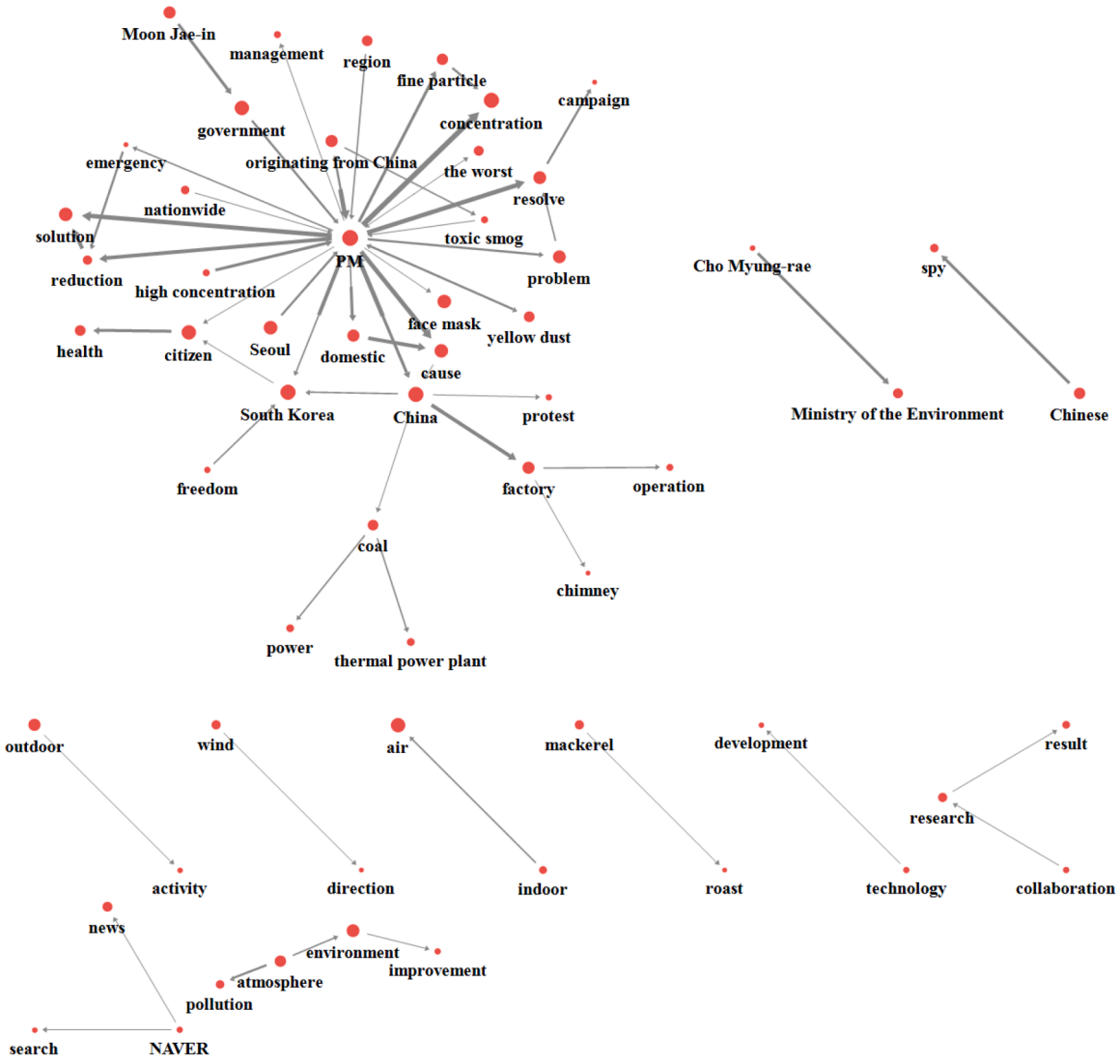


Fig. 4. Network visualization.

China implemented zero-COVID, the skies were clear for a while, but now that their factories are running again, we have to suffer from PM 365 days a year"; and "It's not like all our factories are only in the west, yet there's so much PM in the west while the east is clean—it's like the west is sucking in all the PM like an air purifier, making the east pristine." The majority of opinions in this topic claimed that PM is caused by coal use in Chinese factories. Therefore, we labeled Topic 5 "Chinese Factories as a Major Source of PM."

The main words in Topic 6 included "PM (0.059)," "government (0.023)," "solution (0.022)," "environment (0.015)," "policy (0.012)," "citizen (0.012)," "reduction (0.011)," "management (0.009)," and "National Assembly (0.008)." Examples of posts using these words include, "Seoul implemented free public transportation, including buses and subways during rush hours, as part of its Emergency Reduction Measures"; "They call it an Emergency Reduction Measure, but all it really does is stop the power plants for a few days"; "Isn't there a way to handle PM with domestic policies?" "To protect the citizen from PM, we need to actively implement domestic policies to reduce it"; "The government isn't properly addressing the PM problem"; and "Emergency Reduction Measures were implemented in the Seoul metropolitan area, and while the levels dropped slightly from yesterday, the concentrations remain high." The posts primarily discussed Emergency Reduction Measures and whether these policies were effective. Therefore, we labeled Topic 6 "Debates on the Effectiveness of Particulate Matter Reduction Policies."

The main words in Topic 7 included "Chinese (0.035)," "South Korea (0.029)," "Moon Jae-in (0.023)," "China (0.023)," "spy (0.022)," "toxic smog (0.014)," "smog (0.012)," "North Korea (0.01)," and "person (0.009)." Example posts using these words include, "The Chinese can't eliminate PM overnight, nor do they intend to"; "Journalists, who are all Chinese-paid spies, are colluding to hide China's toxic smog, replacing the term 'toxic smog' with 'PM' in their reports, don't you realize that yet?" "Considering this is the worst smog crisis on Earth, worse than London's, it should be called 'Seoul smog' or 'Korean smog,' but they just call it PM"; "President Moon Jae-in and his cronies should at least pretend to fight against China over PM, but can they really?" and "The worst of the worst China-originated PM (China's toxic smog) is going to kill us all. At this point, shouldn't we be organizing massive nationwide anti-China protests, just like the anti-communist protests against North Korean spies in the past, willing to go to war if necessary?" These posts primarily criticized the government for appearing pro-China, arguing that calling the deadly smog PM made the public perceive it as less severe and that the government failed to take concrete action. Thus, we labeled Topic 7 "Criticism of the Korean Government's Passive Response to China."

The main words in Topic 8 included "vehicle (0.046)," "PM (0.045),"

Table 5
Topic modeling results.

Category	Topic Name	Relevant Words
Topic-1 21.92 %	Physical risk	PM(0.091), face mask(0.038), person(0.02), eye(0.018), air (0.016), outdoor(0.015), concentration(0.014), throat (0.013), COVID-19(0.013)
Topic-2 8.29 %	Chinese-Origin PM	PM(0.079), China(0.035), concentration(0.022), cause(0.021), domestic(0.02), research(0.016), atmosphere(0.015), originating from China(0.015), South Korea (0.014)
Topic-3 14.08 %	Calls for Active Government Intervention	China(0.068), PM(0.06), South Korea(0.04), citizen(0.026), government(0.021), problem (0.016), country(0.014), Moon Jae-in(0.014), health(0.012)
Topic-4 12.68 %	High Interest in PM Forecasts	PM(0.08), Seoul(0.027), concentration(0.025), region (0.024), fine particle(0.016), yellow dust(0.016), nationwide(0.014), rain(0.014), the worst(0.014)
Topic-5 8.99 %	Chinese Factories as a Major Source of PM	China(0.071), PM(0.052), factory (0.036), resolve(0.025), coal(0.023), South Korea(0.018), sky(0.014), operation(0.012), thermal power plant(0.011)
Topic-6 4.86 %	Debates on the Effectiveness of Particulate Matter Reduction Policies	PM(0.059), government(0.023), solution(0.022), environment (0.015), policy(0.012), citizen (0.012), reduction(0.011), management(0.009), National Assembly(0.008)
Topic-7 4.02 %	Criticism of the Korean Government's Passive Response to China	Chinese(0.035), South Korea (0.029), Moon Jae-in(0.023), China (0.023), spy(0.022), toxic smog (0.014), smog(0.012), North Korea (0.01), person(0.009)
Topic-8 5.75 %	Debates on Old Diesel Vehicles and the Odd-Even Traffic Policy	vehicle(0.046), PM(0.045), Seoul (0.026), solution(0.017), citizen (0.01), diesel vehicle(0.009), news (0.009), person(0.009), reduction (0.007)
Topic-9 19.42 %	Personal Responses to PM	PM(0.071), ventilation(0.043), window(0.034), air purifier(0.029), concentration(0.025), house(0.025), dust(0.017), air(0.016), solution (0.016)

"Seoul (0.026)," "solution (0.017)," "citizen (0.01)," and "diesel vehicle (0.009)." Examples of posts using these words include, "To fundamentally solve the problem, we need to address both the PM coming from China and vehicle emissions in Seoul"; "Does the odd-even traffic rule really solve PM?" "The so-called PM solutions are things like the odd–-even traffic rule and subsidies for scrapping old diesel cars, but why isn't the government saying anything to China?" "There's no evidence that PM in South Korea is caused by vehicles in Seoul"; and "Even if China is a major cause, the government should at least implement measures like controlling old vehicles or encouraging public transportation use with subsidies." These posts discussed how old diesel vehicles were considered a major domestic cause of PM, with some supporting or opposing policies like the odd–even traffic rule to address PM. Therefore, we labeled Topic 8 "Debates on Old Diesel Vehicles and the Odd-Even Traffic Policy."

Finally, the main words in Topic 9 included "PM (0.071)," "ventilation (0.043)," "window (0.034)," "air purifier (0.029)," "concentration (0.025)," and "house (0.025)." Examples of posts using these words include, "Finally, I'm going to ventilate . . . . Friday and Saturday were the worst"; "I'm scared to ventilate"; "Should I ventilate or not? I know I should, but I'm too scared to open the windows"; "I'm running two air purifiers"; "If I leave the windows open, the air purifiers go into overdrive"; "It's frustrating that I can't even open the windows and have to rely solely on air purifiers"; and "During the peak PM season in February and March, everyone's wearing masks and there's a huge rush to buy air purifiers." These posts show that because of high PM levels, people are restricted from ventilating freely and must rely on air purifiers and masks, paying personal costs to deal with the PM. Thus, we labeled Topic 9 "Personal Responses to PM."

Among the nine extracted topics, Topic 1 accounted for 21.92 %, Topic 9 for 19.42 %, and Topic 3 for 14.08 %, making up the largest portions. This finding indicates that the public expressed the most concern about the physical risks of PM, followed by personal responses to PM. Particularly, because the ongoing environmental issue of PM remains unresolved, individuals are bearing the costs personally by purchasing and using masks outdoors and air purifiers indoors to cope with the problem. The public is purchasing and using masks and air purifiers as temporary measures to protect their health, but they recognize that these are not fundamental solutions and are ultimately urging the government to take active steps to resolve the PM issue.

5. Discussion

In this study, we aimed to explore public perception of PM in Korea, noting that despite the implementation of policies and the reduction in PM concentrations, public anxiety about PM remains high. First, we compared monthly trends of news articles, PM concentrations, and online community posts, and performed cross-correlation analysis between PM concentrations and posts to determine how public responses vary with changes in PM concentrations. We also conducted topic modeling on online community posts related to PM to derive major topics.

First, looking at the relationship between news articles and posts through monthly data, it appears that the public became aware of PM through the news coverage. The public was unaware of PM when PM concentrations were already high in early 2013. However, when the media started reporting in the fourth quarter of 2013, they became aware of the problem and started writing posts around the same time. In addition, the pattern of increase and decrease in news and posts tended to be similar. However, in some periods, the number of posts rose despite the decrease in news reports, indicating the possible influence of the self-generated community discussions.

It is also worth noting that, there was a sharp increase in the number of posts in March 2023, despite fewer news articles in March 2023 compared to March 2019. This may be due to increased awareness of PM since 2019 and improved accessibility of information through the PM information app. The number of downloads of weather apps that provide information on PM concentration in South Korea was 1.8 million in the first quarter of 2017 and 2.8 million in the first quarter of 2019, a 55 % increase over the two years (Lee, 2019). This increase in the use of applications dedicated to PM and the increase in real-time alerts such as PM warnings may have made the public more sensitive to the issue.

The results suggest that the public began to become aware of PM when the media began to raise the issue in 2013, and that the public responded to media coverage of PM concentrations and PM-related policies. A similar pattern of news articles and community posts suggests that news articles may have influenced the public; however, this does not establish a causal relationship and is not generalizable, so further research is needed to verify this.

Next, when comparing PMs and posts in the graph, we see a similar pattern between the increase and decrease in PMs and posts. In particular, a seasonal pattern was observed, with an increase PMs and posts during the spring and winter months, and a decrease during the summer months. To statistically confirm this relationship, we performed a cross-correlation analysis. Given that the increase in posts was observed in April 2016, we split the period into January 2013 to November 2023 and April 2016 to November 2023. The results showed that the correlation coefficient was largest at lag 0 for all PM concentrations in both periods and was statistically significant at lag 0 ($p < 0.001$). These results show

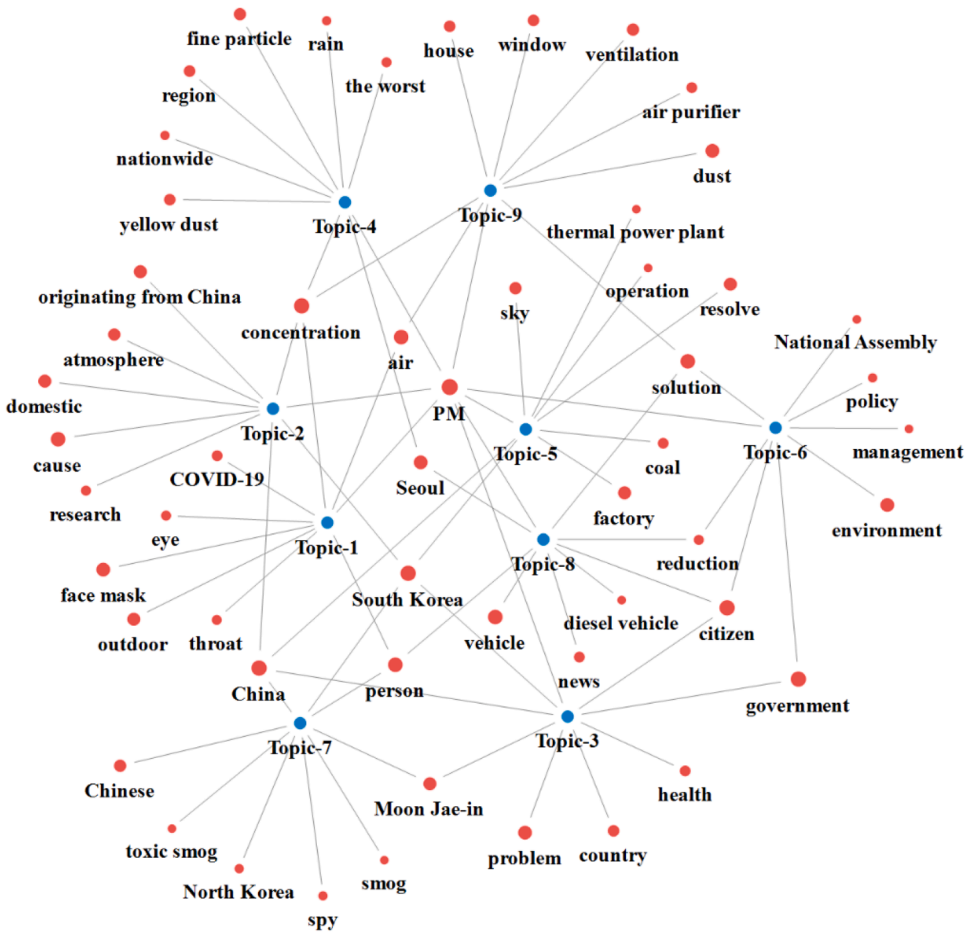


Fig. 5. Topic modeling visualization.

that an increase in PM concentrations was concurrent with an increase in posts during the same periods. It suggests that the public reacted immediately to the increase in PM concentrations.

Certain periods coincided with spikes in concentrations and posts, such as March 2019 and March 2023; however, the response was stronger, with the number of posts increasing more than the average increase in PM concentrations. This is likely owing to the media coverage of Emergency Reduction Measures and PM advisories, which amplified the public's reaction to PM concentrations. Therefore, there may have been a combination of media coverage and government policies besides PM levels.

Taken together, the results suggest that the public generally reacts to PM concentrations immediately, but these reactions are not solely driven by PM concentrations themselves; rather, they are amplified by a combination of factors, including policy implementation and news coverage. For example, checking the PM concentration through the PM information app triggered the response. An additional set of factors, including policy measures, real-time alerts and Emergency Reduction Measures, media reports, and learning from past experiences, appeared to have amplified the response.

Specifically, to understand the public's perception of PM, we conducted a topic modeling analysis by collecting a total of 2714 posts from January 2013 to December 15, 2023 from 10 online communities. Nine topics emerged. The main types of topics included physical risks and personal responses to PM (Topic 1, Topic 9), calls for the government to actively solve the problem (Topic 3, Topic 7), major policies addressing domestic causes of PM in South Korea (Topic 6, Topic 8), interest in PM forecasts (Topic 4), and negative attitudes toward China as a primary cause of PM (Topic 2, Topic 5). These topics can be summarized as covering the risks of PM, personal responses, China's role as the perceived cause, and calls for policies to address domestic factors and government-level solutions. Based on these findings, the following points can be discussed.

First, the public was concerned about their health because of PM, showing interest in PM forecasts and purchasing masks and air purifiers as personal responses. When perceiving the invisible risks of PM, people referred to forecasts or judged the severity through physical reactions, such as eye and throat discomfort. Additionally, it is important to consider why the public chose to respond on an individual level rather than trusting the government to handle this serious environmental issue. Based on Chen and You (2021), who found that the higher the levels of measured and perceived environmental pollution, the lower the trust in the government, it can be inferred that the public's perception of the severity of the PM problem may have led to a decline in trust in the government, prompting individual actions. In other words, the public perceived the issue as severe through concentration and physical reactions, which influenced its attitudes toward the government, leading people to respond in more limited ways, such as purchasing personal protection products.

Considering the media's coverage of PM-related product promotions and mentions of the air purifier market (Chung, 2021; Kim et al., 2015a; Yoon and Kim, 2020), it can be assumed that the public purchased products because of marketing influence from companies selling products related to PM. This is because the sales and revenue of PM-related products have been increasing. For example, a news article promoted a cleaning product event by emphasizing not only outdoor PM concentrations but also the dangers of indoor PM (Dong, 2019). This effect was particularly pronounced during periods of high PM concentrations.

Between February and March 2019, when $PM_{2.5}$ levels were "unhealthy" for 2 weeks, South Korean hypermarket E-Mart reported a 345 % increase in sales of masks and a 249 % increase in sales of air purifiers compared to the same period a year ago (Kyungbuk Maeil, 2019). This suggests that companies are promoting face masks and air purifiers as products to overcome PM, and the public may have been influenced by such marketing.

Second, the findings indicated that the public perceives PM primarily through the lens of "China." The key word "China" ranked second after "PM" in word frequency, TF-IDF, and centrality analysis, confirming its central role in the perception structure related to PM. These findings suggest that the public strongly associates PM with China and tends to view China as the main cause of PM. This finding aligns with previous research that found the public attributes PM to China, influenced by media reports (Chung, 2021; Kim et al., 2016).

Third, however, it is important to note the discrepancy between the causes of PM and the responses or solutions being discussed. The public primarily identified China as the cause of PM, whereas government policies were perceived as addressing mainly internal factors. However, this public perception did not fully align with the policies that the government was actually implementing. The government has been engaging in joint air quality monitoring, forecast exchanges, and collaborative research with China (Comprehensive Portal for Particulate Matter, 2025), but the public was largely unaware of these efforts. Specifically, policies targeting the public, such as fines for operating old diesel vehicles, are seen as more forceful, whereas government actions toward China, such as data exchange and research collaboration, are perceived as less stringent, contributing to the sense that policies concerning China are lacking. In this context, the public perceived that government policies focused only on internal factors and not on China, which is considered the main source of PM, and that policies need to be improved.

This perceived disconnect leads to public dissatisfaction and frustration with the government. This mirrors the argument by the Three Major Academies (2017) that although more than 70 % of PM in South Korea is attributed to emissions facilities and everyday pollution, over 70 % of government measures focus on vehicles, which contribute only about 30 % to PM in South Korea, highlighting a mismatch between the causes of PM and reduction policies. This mismatch between the perceived cause and the target of policies leads the public to adopt an increasingly negative attitude toward the government.

Fourth, in contrast to public attitudes that largely attribute the problem of PM to China, different studies report different opinions on China's contribution. Because South Korea is located in the downwind area of Asian continent, air pollutants emitted from Mongolia, China, and North Korea can be transported to South Korea. Degree of the outside transport to South Korean PM concentration differed among the studies (Bae et al., 2020; Han et al., 2021). For example, according to Han et al. (2021), the annual average contribution to the $PM_{2.5}$ mass burden in South Korea from China dropped significantly from 28.0 % in 2010 to 15.7 % in 2017, whereas Bae et al. (2020) estimated Chinese contribution to South Korea being 40 %–65 % between 2010 and 2017.

As shown, there is a wide range of results reported on China's contribution, and it is difficult to make a definitive statement on China's contribution, especially because PM is highly variable depending on the season and weather conditions. However, despite these uncertainties, the public is primarily focused on China as the main cause, while feeling that the government is only addressing internal sources, unaware of the government's efforts in international cooperation through information exchanges and research. Additionally, the public has expressed hostility toward China and expects the South Korean government to take stronger political action against China in response to the PM issue. In other words, with the uncertainty of contribution to PM, the public focused on expressing negative feelings toward China. This also aligns with Chung (2021), who found that in PM-related news comments, individuals express their subjective perceptions rather than engaging in rational debate, leading to emotional discussions.

Despite the controversy over the actual attribution rate, we can speculate on the following reasons the public over-attributes China over domestic factors. First, there is the influence of the media. The public is influenced by the framing of media reports, and South Korean media reports attributing the PM problem to China seem to lead the public to understand that the main source of PM is coming from China (Chung, 2021; Kim et al., 2016). The second reason relates to the fact that in this study we collected and analyzed information from online communities. Online communities play the role of a public forum where individuals produce and share their opinions (Cho et al., 2015). However, it is important to note that when the public exchanges opinions in these communities, it is not a space for productive, scientifically based discussions on specific issues. Instead, individuals freely share their opinions, even if the information is not fact-based. Specifically, people tend to share their emotions on social media when they perceive a threat (Steinert, 2021), and negative emotions expressed in online communities or social media regarding particular issues can spread to other users (Ferrara and Yang, 2015; Kramer et al., 2014). This emotional contagion can affect the emotional climate of society and, in turn, influence shifts in societal value structures (Steinert, 2021), potentially distorting the public's understanding of specific issues. Based on this, it can be understood that, unlike experts, the public has a fragmented understanding of PM (Kim et al., 2016). As online communities exchange opinions on the issue, negative sentiments about China are disseminated and reinforced, resulting in hardening of negative perceptions and feelings. In other words, the public responds to actual PM concentrations, but negative emotions are amplified by the media, which seems to have reinforced negative emotions and risk perceptions about PM. They also share these feelings in online communities and seem to be constantly anxious because their emotions are contagious.

This study has the following theoretical implications. First, we focused on online communities, which previous studies had not closely examined, to understand public perceptions of PM. We collected posts written by the public and analyzed them using semantic network analysis and topic modeling. Previous research investigated how media coverage specifically reports PM or the relationship between PM concentrations and public behavior. Specifically, previous researchers explored how PM was socially discussed through media reports (Kim et al., 2015a; Yoon and Kim, 2020) or media reports and news comments (Chung, 2021). By analyzing freely written content from online communities, which are used as spaces for social opinion exchange, we aimed to overcome the social desirability bias often present in surveys and gain insight into public perceptions. These online communities allow users to express opinions related to their interests or political views freely. Therefore, it can be assumed that users honestly expressed their thoughts on PM. By understanding the perception structure through community posts, in this study we provide foundational data for understanding the societal value structure surrounding the environmental issue of PM.

Second, we showed that the public is likely to respond to a combination of factors, including PM concentrations and news articles. In some cases, the increase in posts was larger than the increase in PM concentrations. This suggests that, rather than an increase in PM concentrations alone, the increase in the number of posts was due to a combination of factors, such as increased news coverage and policy implementation. In other words, the public responds to PM concentrations immediately, but this reaction is amplified by factors such as news and policy implementation.

Third, by specifically identifying the causes and solutions that the public focuses on, we confirm that the public perceives a mismatch between the causes of PM and the responses to it. Previous research has found a gap between causes and solutions, with the media blaming China for PM while emphasizing individual responses (Kim et al., 2015a; 2015b). In this study we expand on those discussions by revealing, not through media but directly through public perceptions, the specific

mismatch between the causes of PM and the responses being proposed. These findings could serve as practical data for future policy improvements aimed at enhancing public perception.

As a result of the public perceptions of PM identified in this study, the following policy and communication strategies can be suggested. First, it is necessary to quantify the contributions of domestic and foreign factors to air pollution in South Korea and disclose them to the public on a regular basis. In the same way that the concentration of PM is currently measured and provided on a daily, monthly, and yearly basis, information on domestic and foreign contributions to PM in Korea should be provided. Estimating the emission rate is a complex and time-consuming process, which may result in a time lag. However, disclosing estimates of domestic and foreign contributions with a certain level of reliability will prevent public perception from being distorted. In addition, the publication of these results will naturally influence media reports, which will balance the media reports that have been attributed to China, and the public will be able to understand PM in a more scientific manner.

In addition, it is necessary to create opportunities for various stakeholders involved in the PM problem to dialogue and share their perceptions and reflect them in policies. This is because PM problems are difficult to identify clearly because of the complex factors at work, and relevant stakeholders tend to perceive them differently depending on their positions (Kim et al., 2022). For example, government officials, local residents, and power plant operators in some areas with high concentrations of PM in South Korea have different views on the causes and solutions depending on their positions, so interactive communication is needed to identify the needs of various publics. By identifying the needs of stakeholders and providing opportunities to reflect them, it is possible to raise awareness among stakeholders to participate in solving the problem together. This can also reduce distrust and negative perceptions of policies.

Finally, we can work with media organizations to ensure balanced coverage of internal and external factors. Existing media coverage tends to attribute the source of PM to China (Kim et al., 2015a), and media coverage is unbalanced, with government officials being utilized as the primary source of information (Lee et al., 2021). As such, the media's framing or unbalanced reporting rather than factual reporting can lead to distorted public perceptions. Therefore, improving the frequency of balanced reporting based on scientific facts by using experts as sources of information and fact-checking the existing misconceptions of the public will help improve public perception. In particular, since the public responses were primarily based on PM concentrations, but tended to be amplified by the media, it seems that the media can help the public understand and perceive the problem of PM in a more scientific way.

The limitations of this study are as follows: This study collected posts from January 2013 to December 15, 2023 and analyzed them collectively. Future research could compare public perceptions before and after specific government policies over the past decade to track changes in perception. Additionally, in this study we did not quantitatively control for factors such as domestic and international PM emissions and weather conditions, and we did not examine how perceptions of PM differed by region and demographic factors such as education, income level, and political affiliation. Future research should look at how perceptions vary by different demographics. In this study, we conducted a cross-correlation analysis to explore the relationship between PM concentrations and posts, but a Granger causality test could be conducted in the future to determine the impact of PMs on posts. In addition, this study suggests that media may amplify the public responses to PM concentrations, but further research is needed to demonstrate this.

Despite these limitations, this study is significant in that it highlights the growing public anxiety, independent of government policies, and examines how the public perceives issues related to PM.

6. Conclusion

This study conducted monthly trend comparisons and cross-correlation analysis to understand the relationship between PM concentrations and public responses, and applied semantic network analysis and topic modeling to understand public perceptions of PM. The results showed that the public reacted to PM concentrations simultaneously, with the number of posts increasing when PM concentrations rose, and that this effect could be amplified by news or policies. According to the topics identified through topic modeling, the public pointed to China as the main source of PM and emphasized the government's active efforts on this issue. The public was also concerned about the health effects of PM and responded by purchasing masks and air purifiers. The significance of this study lies in its ability to capture the public's immediate response and complex perceptions of the PM issue in Korea through online communities. Based on the results, this study is expected to provide policy implications for developing communication strategies to address PM in Korea. In the future, a balanced diagnosis of domestic and foreign factors contributing to air pollution in Korea is needed, and it is necessary to examine the relationship between media coverage and public responses to PM concentrations.

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CRediT authorship contribution statement

Hansol Choi: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Yong Pyo Kim:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Yungwook Kim:** Validation, Investigation, Formal analysis. **Ji Yi Lee:** Validation, Resources. **Hyemi Lee:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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