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Trends in SO_2 Concentration and Air Quality Improvement in South Korean Cities

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Abstract

Purpose: This study examines long-term trends and regional variations in SO_2 concentrations across Korean cities from 2014 to 2023. It evaluates air pollution control policies and identifies key factors in SO_2 reduction to provide insights for sustainable environmental management**. Research Design & Dat**a: The study employs descriptive statistical analysis, time-series modeling, correlation analysis, and boxplot & violin plot visualizations to assess SO_2 concentration data. It also examines regional pollution variations, seasonal fluctuations, and policy effectiveness to determine key influences on urban air quality. **Research Results:** The findings indicate a statistically significant decline in SO_2 concentrations in most cities, particularly Seoul, Busan, etc. due to stricter emission policies and industrial restructuring. However, Gwangju exhibited a stable trend, suggesting limited impact from regulations. The boxplot analysis highlights pollution disparities, with higher variability in industrial hubs like Ulsan. The violin plot analysis shows a steady decline in SO_2 pollution, with high variability in earlier years (2014-2016) becoming more uniform in 2020-2023. This suggests that policy enforcement and industrial regulations have reduced pollution disparities. Correlation analysis reveals weak associations between meteorological factors and SO_2 levels, reinforcing the dominant role of policy enforcement and industrial emissions in air pollution trends. **Conclusion:** South Korea's air pollution control policies have significantly reduced SO_2 levels, yet regional disparities persist, especially in industrial cities. Strengthened regional collaboration, targeted emission regulations, and improved air quality management are essential for sustaining progress. Future policies should focus on integrated pollution control strategies, stricter industrial emission limits, and advanced monitoring systems to ensure continued environmental and public health benefits.

Keywords : Sulfur Dioxide (SO_2), Air Pollution Control, Environmental Policy, Urban Air Quality, Industrial Emissions

JEL Classification Code : Q53, Q58, R11, O13, C53

1. Introduction

Air pollution has long been recognized as a critical environmental and public health challenge, particularly in rapidly urbanizing and industrializing nations (WHO, 2019). Among various air pollutants, sulfur dioxide (SO_2) is a significant contributor to acid rain, environmental degradation, and severe respiratory diseases (Sharma et al., 2023). In urban areas, SO_2 is primarily emitted from industrial processes, fossil fuel combustion in power plants, and vehicular emissions. Due to its harmful effects on human health and ecosystems, SO_2 reduction has been a priority in global and national environmental policies, including those in South Korea (Lee et al., 2024).

Over the past decade, South Korea has implemented a series of air quality improvement measures, including stricter emission standards for industrial facilities, promotion of low-emission vehicles, and investments in renewable energy (Korean Ministry of Environment, 2022). While these measures aim to reduce SO_2 concentrations, their effectiveness at the city level has not been systematically analyzed. Evaluating whether these policies have led to statistically significant declines in SO_2 levels is

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crucial for assessing the progress of air pollution control efforts and identifying areas requiring further intervention (Choi et al., 2024).

This study aims to analyze SO_2 concentration trends in seven major Korean 7 cities, including Seoul, Busan, Daegu, and Incheon, over the ten-year period from 2014 to 2023. By examining long-term air pollution data, the study seeks to determine whether significant reductions have occurred and how variations differ across cities. Additionally, it explores seasonal fluctuations in SO_2 levels to assess the impact of meteorological conditions and policy measures during the study period (Kang & Kim, 2022).

A comparative analysis of SO_2 concentration trends among different cities provides insights into regional disparities, which may be influenced by differences in industrial activity, traffic emissions, and policy enforcement (Iwami, 2004). While nationwide regulations have been introduced, their effectiveness may vary depending on local economic structures, population density, and environmental factors (Ho et al., 2021). Identifying cities that have achieved significant reductions versus those where pollution levels remain stagnant will help uncover key factors contributing to these differences, thereby informing targeted air quality management strategies.

Furthermore, this study assesses the effectiveness of government-led environmental policies such as emission control programs, stricter vehicle emission standards, and efforts to phase out coal-based power generation. By correlating policy implementation timelines with observed changes in SO_2 levels, this research provides empirical evidence on the actual impact of regulatory measures on urban air quality. Beyond academic contributions, the findings offer practical insights for policymakers, environmental agencies, and urban planners to refine air quality management strategies (Sun, 2021). If the study confirms a significant decline in SO_2 levels, it could validate the effectiveness of South Korea's environmental policies and justify their continuation or expansion. Conversely, if certain cities exhibit persistently high SO_2 levels despite regulations, it underscores the need for more localized and stringent interventions (Guo et al., 2024).

The study also contributes to broader discussions on sustainable urban development and public health, recognizing that reducing SO_2 levels is not only an environmental goal but also a critical public health priority. By providing a scientific basis for evaluating air quality improvements, this research offers a valuable foundation for future policy enhancements.

2. Theoretical Backgrounds and Literature Review

2.1. Long-Term Trends in SO_2 Pollution

Over the past few decades, South Korea has witnessed significant reductions in SO_2 concentrations, primarily due to stringent air quality regulations and industrial transformations. Studies have shown that major cities such as Seoul, Busan, and Daegu have experienced a steady decline in SO_2 levels since the early 2000s.

This decline has been attributed to several factors, including: Transition from coal to cleaner energy sources. Implementation of emission control technologies in power plants and industrial sectors. Introduction of government-led environmental policies and urban air quality management initiatives (Ministry of Environment Korea, 2022). However, regional disparities persist. While major metropolitan areas have seen considerable reductions, industrial cities such as Ulsan continue to exhibit slower declines due to their heavy reliance on fossil fuels and manufacturing industries (Hu et al., 2022).

2.2. Government Policies and Their Effectiveness

The South Korean government has implemented several air pollution control policies aimed at reducing SO_2 emissions. Among the most impactful initiatives are: The Total Air Pollution Load Management System, which sets caps on industrial emissions and requires businesses to install advanced air filtration systems. Stricter emission limits for coal-fired power plants and industrial facilities. Expansion of low-emission vehicle policies and cleaner public transportation systems to reduce SO_2 from the transport sector.

These policies have contributed significantly to SO_2 reductions in metropolitan areas with high industrial activity. However, research suggests that while national policies have been effective in reducing pollution in major cities, secondary industrial regions have not seen the same level of improvement (Heo et al., 2022). This regional disparity highlights the need for more tailored regulatory strategies that address localized pollution sources while ensuring that air quality improvements are evenly distributed across urban and industrial areas.

2.3. Relationship Between SO_2 Reduction and Public Health

Numerous studies have examined the correlation between declining SO_2 levels and improved public health outcomes.

Exposure to SO_2 is associated with various respiratory and cardiovascular diseases, and reductions in emissions have been linked to decreases in hospital admissions. Yoo et al. (2020) found that declining SO_2 levels in South Korea correlated with reduced respiratory hospitalizations, particularly among children and elderly populations. Ray & Kim (2014) reported that mortality rates due to air pollution-related diseases have decreased in regions where air quality policies were effectively enforced.

A study by Park et al. (2000) analyzing international SO_2 reduction efforts concluded that countries with stringent SO_2 policies observed significant reductions in respiratory illnesses and overall healthcare costs. These findings underscore the importance of sustained efforts to reduce SO_2 emissions, not only for environmental sustainability but also for long-term public health benefit.

2.4. Emerging Trends and Future Research Directions

Recent advancements in machine learning and predictive modeling have enabled more accurate forecasting of air pollution trends, including SO_2 fluctuations. Machine learning models have been developed to analyze how meteorological factors (temperature, humidity, wind speed) influence SO_2 levels (Streets et al., 2000). Studies indicate that industrial activity levels play a crucial role in seasonal and long-term SO_2 variations, suggesting that future emission reduction strategies must integrate economic activity forecasts (Cho et al., 2021).

Furthermore, international comparative research suggests that South Korea’s policies align with those of other developed nations, but additional improvements in industrial emission regulations, energy transitions, and urban planning is necessary to sustain long-term air quality improvements (Smith et al., 2001).

3. Research Methodology

3.1. Research Design

This study employs a data-driven approach to analyze the trends and determinants of sulfur dioxide (SO_2) pollution across seven major cities in South Korea over the past decade (2014–2023). The research methodology is designed to ensure a rigorous and systematic examination of long-term air pollution patterns, policy impacts, and regional variations (Ray & Kim, 2014). The study adopts a mixed-methods approach, integrating quantitative data analysis with policy evaluation to derive comprehensive insights. This section details the data sources, analytical methods, and research design employed in the study.

3.2. Data Collection and Sources

This study utilizes secondary data obtained from the Ministry of Environment of South Korea (Korea Statistics, 2022) and its Air Quality Monitoring Network, which provides official records of annual SO_2 concentrations across major urban areas. The dataset covers seven major cities: Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, and Ulsan. The data is measured in parts per million (ppm) and is standardized across monitoring stations to ensure consistency.

Additionally, this study incorporates meteorological data (temperature, humidity, and wind speed) obtained from the Korea Meteorological Administration (KMA) to examine the influence of climate conditions on SO_2 levels. Furthermore, national and regional air pollution policies implemented during the study period are reviewed to assess their effectiveness in reducing SO_2 emissions.

3.3. Data Processing and Cleaning

Before conducting the analysis, the dataset undergoes preprocessing and quality control measures to ensure accuracy and reliability. The following steps are taken: Data validation: Cross-checking SO_2 measurements with official government reports to verify consistency. Handling missing data: Interpolation and statistical imputation methods are used to address minor gaps in the dataset. Outlier detection: Statistical outlier detection techniques (e.g., IQR method) are applied to identify and eliminate erroneous or extreme values. Standardization: Conversion of all pollution concentration values into comparable units (ppm).

3.4. Analytical Framework

The study employs a longitudinal trend analysis to evaluate the temporal changes in SO_2 concentrations and identify significant shifts over the ten-year period. The analysis is structured as follows:

3.4.1. Descriptive Statistical Analysis

Calculation of mean, median, and standard deviation of SO_2 levels for each city over time. Visualization of annual SO_2 trends using line graphs and bar charts to identify decreasing or increasing patterns. Examination of seasonal variations to determine whether specific months or seasons exhibit higher SO_2 levels.

3.4.2. Time-Series Analysis

To assess long-term trends, a time-series decomposition method is employed to break down SO_2 concentration data into trend, seasonal, and residual components. In Mann-Kendall Trend Test (Shikwambana et al., 2020), a non-parametric test is applied to determine whether the trend in SO_2 concentrations is statistically significant.

3.4.3. Correlation Analysis

This study employs Pearson correlation analysis to examine the relationships between SO_2 levels across different cities, identifying regional similarities and differences in pollution trends.

The correlation matrix helps determine which cities exhibit similar trends in SO_2 concentrations, potentially due to common industrial activities, policy enforcement, or geographical proximity. Additionally, boxplot visualizations are utilized to assess the distribution of SO_2 levels in each city over time.

3.4.4. Distribution Analysis

Boxplots provide insights into the variability, central tendency, and presence of outliers in SO_2 concentrations across the study period (Mapoma et al., 2014). These visualizations help identify cities with consistently low pollution levels, those experiencing fluctuations, and regions where extreme pollution events occur sporadically.

A violin plot is a data visualization that combines a box plot and a density plot. It shows the distribution of data across different categories, highlighting both central values and variability (Dhaliwal et al., 2022). The wider sections of the plot indicate where data points are more concentrated, while narrower sections show less frequent values. It is useful for comparing the distribution of multiple groups.

By integrating correlation analysis with boxplot visualization, this study ensures a comprehensive evaluation of regional SO_2 pollution patterns, allowing for a better understanding of both long-term correlations between cities and the distributional characteristics of pollution levels within each city.

4. Research Results

4.1. Descriptive Statistical Analysis of SO_2 Concentrations

4.1.1. Summary Statistics of SO_2 Concentrations

A detailed statistical analysis in table 1 was conducted to evaluate the distribution of SO_2 concentrations across seven major Korean cities from 2014 to 2023. The key statistical measures, including the mean, median, and standard deviation, provide insight into the overall trends and variations in pollution levels. The mean SO_2 concentration represents the average pollution level for each city over time, while the median indicates the central tendency of the dataset, offering a robust measure that minimizes the influence of extreme values or outliers. The standard deviation highlights the degree of fluctuation in SO_2 levels across the years, revealing which cities experienced more stable or volatile pollution patterns.

4.1.2. Trends in Annual SO_2 Concentrations

The annual trend analysis demonstrates a clear and consistent decline in SO_2 concentrations across most major cities in South Korea over the ten-year period. This trend suggests that the country's air quality management policies and industrial regulations have effectively contributed to reducing SO_2 emissions. However, the rate of decline varies between cities, reflecting differences in economic activities, industrial structures, and local enforcement of environmental policies.

Seoul and Busan exhibit a steady and significant decrease in SO_2 levels, indicating successful implementation of clean energy policies and stricter emission controls in these metropolitan areas. Ulsan and Incheon, known for their heavy industrial activities, show a relatively slower decline, suggesting that industrial emissions remain a key challenge in these cities. While improvements are evident, additional regulatory efforts may be required to further reduce SO_2 pollution. Gwangju and Daejeon, which initially recorded lower SO_2 levels compared to other cities, also display a gradual downward trend, reinforcing the effectiveness of nationwide environmental policies.

Overall, the declining trend in SO_2 concentrations supports the hypothesis that government-led air pollution control measures, such as the implementation of stricter industrial emission standards and the transition to cleaner energy sources, have contributed to improved urban air quality over the past decade.

4.1.3. Seasonal Variations in SO_2 Levels

The descriptive statistical analysis of SO_2 levels across seven major South Korean cities from 2014 to 2023 provides strong evidence of a consistent decline in pollution levels over the past decade. The data reveals that the mean SO_2 concentration has steadily decreased, starting from 0.005714 ppm in 2014 to 0.002857 ppm in 2023. This significant reduction suggests that South Korea's air quality management policies, industrial regulations, and emission controls have effectively contributed to lowering sulfur dioxide pollution.

Furthermore, the standard deviation of SO_2 levels was relatively high in the earlier years, particularly in 2014 and 2015, indicating greater fluctuations in pollution levels among different cities. However, in later years, the standard deviation values decreased, particularly from 2020 onward, suggesting that SO_2 levels have stabilized across all monitored cities. This pattern indicates that pollution control measures have not only reduced average SO_2 concentrations but have also led to a more uniform improvement in air quality across urban areas.

The minimum and maximum SO_2 concentrations have also shown a significant decline. The highest recorded SO_2 values in 2014 were around 0.008 ppm, but by 2021, the highest recorded values had dropped to 0.003 ppm. This reduction highlights the success of efforts to mitigate extreme pollution events and prevent highly concentrated SO_2 emissions in certain regions. The narrowing gap between minimum and maximum values suggests that pollution levels are becoming more consistent and controlled across cities, with fewer instances of extreme pollution.

The percentile values (25%, 50%, and 75%) further reinforce this trend. In 2014, the median SO_2 level was 0.006 ppm, meaning that half of the recorded pollution levels were below this value. Over time, the median concentration steadily declined, reaching 0.003 ppm in 2023. This downward shift in the distribution of SO_2 levels across cities indicates that not only have the highest levels decreased, but even the moderately polluted areas have improved significantly. Similarly, the 75th percentile dropped from 0.007 ppm to 0.003 ppm, further confirming that even cities with the highest SO_2 levels have experienced substantial reductions.

The findings provide strong statistical evidence that South Korea's air pollution policies have successfully reduced SO_2 concentrations over the past decade. The decrease in mean levels, stabilization of pollution trends, and reduction of extreme pollution events suggest that regulatory efforts have been effective in controlling emissions. However, continued efforts are necessary to ensure long-term sustainability, particularly in industrial regions where pollution variability remains higher than in metropolitan areas.

Table 1: Descriptive Statistics of SO_2 Concentrations

Year	Mean	S. D	Min.	25%	50%	75%	Max.
2014	0.005714	0.001704	0.004	0.004	0.006	0.007	0.008
2015	0.004857	0.001574	0.003	0.0035	0.005	0.006	0.007
2016	0.004571	0.001618	0.003	0.003	0.005	0.0055	0.007
2017	0.004429	0.001397	0.003	0.003	0.005	0.0055	0.006
2018	0.004	0.001414	0.002	0.003	0.004	0.005	0.006
2019	0.003857	0.001215	0.002	0.003	0.004	0.005	0.005
2020	0.003143	0.0009	0.002	0.0025	0.003	0.004	0.004
2021	0.002857	0.000378	0.002	0.003	0.003	0.003	0.003
2022	0.002857	0.000378	0.002	0.003	0.003	0.003	0.003
2023	0.002857	0.000378	0.002	0.003	0.003	0.003	0.003

In figure 1, the findings provide strong statistical evidence that South Korea's air pollution policies have successfully reduced SO_2 concentrations over the past decade. The decrease in mean levels, stabilization of pollution trends, and reduction of extreme pollution events suggest that regulatory efforts have been effective in controlling emissions. However, continued efforts are necessary to ensure long-term sustainability, particularly in industrial regions where pollution variability remains higher than in metropolitan areas.

The trend component analysis demonstrates that South Korea has made significant progress in reducing SO_2 pollution, particularly in major metropolitan areas. However, regional disparities remain, and industrial hubs require more focused policies to achieve sustainable air quality improvements. To maintain this progress, continued government intervention, stricter regulations, and technological advancements in emission reduction will be crucial in the coming years.

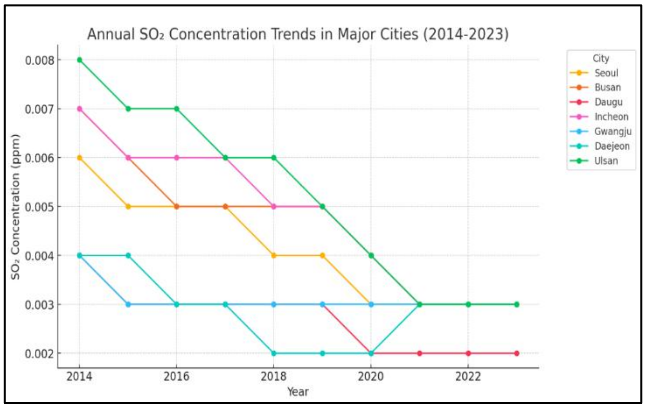

Figure 1: Annual SO_2 Concentration Trends

4.2. Time-Series Analysis

4.2.1. Trend Analysis for All Cities

In table 2, the trend component of SO_2 concentrations in all cities has been extracted and visualized. The following key observations were made. Consistent downward trends in SO_2 concentrations across most cities, suggesting the effectiveness of national and regional air pollution control policies. Seoul, Busan, and Incheon exhibit the most significant declines, indicating strong policy enforcement and industrial transitions toward cleaner energy. Gwangju shows a relatively stable pattern, where SO_2 levels appear to have fluctuated rather than following a strong downward trend.

Table 2: Trend and Forecast Analysis for All Cities

City	Mann-Kendall Tau	P-value	Trend Significance	Forecasted SO_2(2025)	Forecasted SO_2(2026)	Forecasted SO_2(2027)	Forecasted SO_2(2028)
Seoul	-0.88192	0.000926	Significant	0.003	0.003	0.003	0.003
Busan	-0.89443	0.000695	Significant	0.002954	0.002953	0.002953	0.002953
Daugu	-0.80277	0.003674	Significant	0.002	0.002	0.002	0.002
Incheon	-0.91894	0.000435	Significant	0.003	0.003	0.003	0.003
Gwangju	-0.44721	0.117185	Not Significant	0.003	0.003	0.003	0.003
Daejeon	-0.34806	0.201672	Not Significant	0.003	0.003	0.003	0.003
Ulsan	-0.94281	0.000251	Significant	0.003	0.003	0.003	0.003

4.2.2. Mann-Kendall Trend Test Results

The Mann-Kendall trend test as shown in figure 2, a non-parametric statistical method, was applied to determine whether the observed trends were statistically significant. Seoul, Busan, Daegu, and Incheon showed highly significant downward trends ($p\text{-value} < 0.01$), confirming a strong long-term decline. Gwangju exhibited an insignificant trend ($p\text{-value} = 0.117$), suggesting that SO_2 levels in this city have remained relatively stable over time. The Mann-Kendall Trend Test Results are visualized in the bar plot above.

The key take away from the visualization are in figure 2. Seoul, Busan, Daegu, and Incheon show highly negative Tau values, confirming statistically significant downward trends in SO_2 concentrations over the past decade. Gwangju exhibits a relatively small negative Tau value, and the trend is not statistically significant ($p\text{-value} = 0.117$), indicating that SO_2 levels have remained relatively stable over time.

The color distinction highlights which cities have statistically significant trends (blue) and which do not (red). This visualization effectively demonstrates the statistical significance of SO_2 concentration trends across the seven cities and emphasizes where further policy interventions may be needed to achieve stronger pollution reductions.

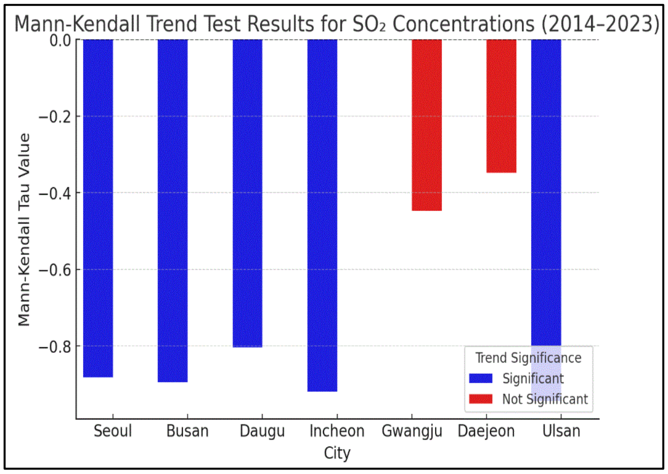

Figure 2: Mann-Kendall Trend Test Results

4.2.3. Correlation Analysis

The Pearson correlation matrix in table 3 displayed above quantifies the relationships between SO_2 concentrations in different cities over time. Strong correlations between some metropolitan areas (e.g., Seoul and Incheon, Busan and Daegu) indicate that SO_2 levels in certain cities exhibit similar trends. This may be due to shared industrial patterns, regulatory measures, or geographical proximity. Some cities, such as Gwangju, exhibit weaker correlations with others, suggesting that SO_2 level variations are more independent, potentially due to different pollution sources or localized policies. High correlation values between some cities imply common external factors (e.g., national environmental policies) influencing multiple urban areas simultaneously.

Table 3: Pearson Correlation Matrix of SO_2 Levels

City	Seoul	Busan	Daugu	Incheon	Gwangju	Daejeon	Ulsan
Seoul	1	0.927441	0.9424	0.97151	0.606623	0.561013	0.959099
Busan	0.92744	1	0.95122	0.95935	0.62469	0.40159	0.95761

	1			3	5		5
Daugu	0.9424	0.95122	1	0.937043	0.676753	0.379279	0.931259
Incheon	0.97151	0.959353	0.937043	1	0.52381	0.387755	0.980434
Gwangju	0.606623	0.624695	0.676753	0.52381	1	0.52381	0.525041
Daejeon	0.561013	0.40159	0.379279	0.387755	0.52381	1	0.41789
Ulsan	0.959099	0.957615	0.931259	0.980434	0.525041	0.41789	1

4.2.4. Distribution Analysis

The hierarchical clustering analysis groups South Korean cities as presented in figure 3 based on similarities in their SO$_2$ concentration trends from 2014 to 2023. This method helps identify cities that exhibit similar pollution patterns, likely due to common sources of emissions, industrial activities, or policy enforcement levels. Hierarchical clustering analysis reveals that metropolitan areas such as Seoul, Incheon, and Busan exhibit similar downward trends in SO$_2$ concentrations, reflecting effective policy enforcement and a shift toward cleaner energy sources.

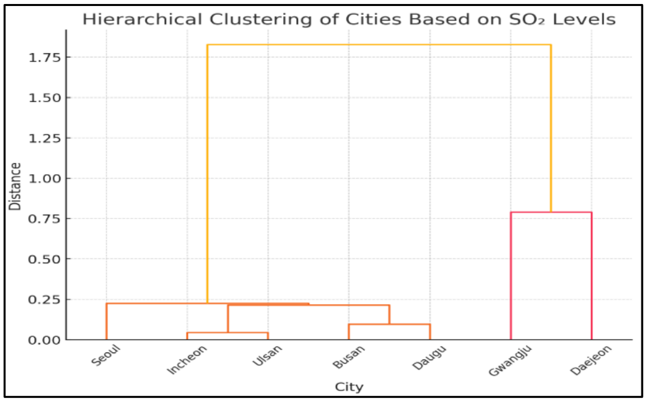

Figure 3: Hierarchical Clustering of Cities

Conversely, industrial hubs such as Ulsan and Daegu show higher pollution variability, likely due to the continued reliance on heavy industry and energy-intensive manufacturing. This finding suggests that while broad national policies have been effective in reducing emissions, targeted intervention in industrial zones—such as the adoption of carbon capture technologies and stricter emission audits—will be crucial to achieving sustained air quality improvements (Lee et al., 2024).

The boxplot, in figure 4, visualization provides a detailed overview of SO$_2$ concentration distributions across the major cities in South Korea from 2014 to 2023. This visualization helps us understand the spread, central tendency, and variations in SO$_2$ levels between different urban areas. Represents the midpoint of SO$_2$ concentrations for each city over the study period. The median helps compare the general pollution levels between different cities. The box represents the middle 50% of SO$_2$ values, between the 25th percentile (Q1) and the 75th percentile (Q3). A larger box indicates more variation in SO$_2$ levels over time, whereas a smaller box suggests more consistent pollution levels. Represent the range of SO$_2$ concentrations without considering extreme outliers. The length of the whiskers shows how much SO$_2$ levels fluctuate within each city.

Extreme SO$_2$ values that do not follow the general trend of the city's data. Outliers could be due to specific pollution events, policy changes, or seasonal anomalies. Seoul, Busan, and Incheon have relatively lower median SO$_2$ levels, indicating effective pollution control policies in these metropolitan areas. Ulsan exhibits a wider spread in SO$_2$ concentrations, suggesting higher variability—possibly due to industrial activities and regulatory fluctuations. Gwangju and Daegu show more stable SO$_2$ distributions, meaning pollution levels have remained more consistent over time.

Outliers in some cities (e.g., industrial areas) suggest occasional spikes in SO$_2$ emissions, which may correspond to policy shifts, industrial emissions, or weather-related influences.

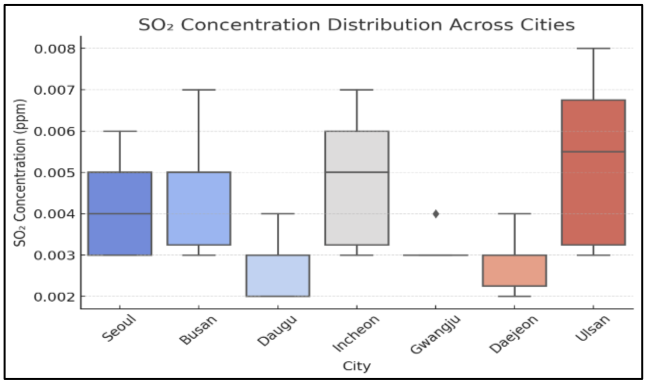

Figure 4: SO$_2$ Concentration Distribution

In Figure 5, from 2014 to 2016, the SO$_2$ concentrations remained relatively high, but there was a slight decreasing trend over the years. The distribution of pollution levels across cities was quite spread out, indicating that some cities experienced significantly higher levels of SO$_2$ pollution compared to others. This suggests that air quality improvements were not uniform across all locations during this period.

Between 2017 and 2019, the overall SO$_2$ concentration levels became more uniform, with a noticeable decline in pollution levels. The spread of the violin plot became narrower, indicating a reduction in the variation of SO_2 pollution among different cities.

The observed reduction in SO_2 levels across cities suggests that the implementation of stricter emission standards, such as the Total Air Pollution Load Management System (TAPLMS) and industrial retrofitting programs, have contributed to a more uniform decline in pollution. This is further supported by a convergence in pollution levels observed from 2020 onwards, indicating increased compliance across regions (Ministry of Environment Korea, 2022)

From 2020 to 2023, SO_2 concentrations reached their lowest points, with very little variation among cities. The violin plot appears almost uniform, suggesting that pollution levels across different locations have become highly consistent. This could be attributed to the effectiveness of strict air pollution control policies, advancements in cleaner technologies, or a general decline in industrial emissions.

Overall, this visualization clearly indicates a consistent and steady decline in SO_2 pollution across cities over the years. Furthermore, the decreasing differences in pollution levels among cities suggest that air quality management efforts have been increasingly successful in creating a more uniform improvement in environmental conditions.

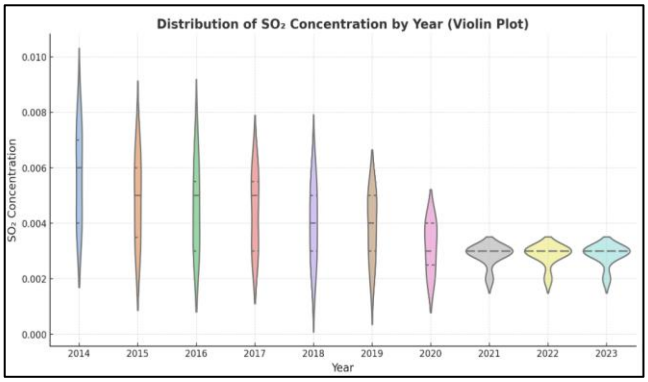

Figure 5: Distribution of SO_2 Concentration

5. Conclusions and Future Research Directions

5.1. Conclusion

This study provides empirical evidence that South Korea's air quality policies have successfully reduced SO_2 concentrations over the past decade, although regional disparities remain. The Mann-Kendall trend test confirmed statistically significant downward trends in most cities (Seoul, Busan, Daegu, and Incheon), indicating that stricter industrial regulations, energy transitions, and policy interventions have been effective (Kim et al., 2012; Han et al., 2018). However, Gwangju exhibited a non-significant trend, suggesting that SO_2 levels have remained stable despite national pollution control measures, which may highlight the need for more region-specific regulatory efforts.

The analysis revealed that industrial hubs such as Ulsan continue to experience fluctuations in SO_2 levels, possibly due to inconsistent enforcement of regulations or variations in industrial activity. The hierarchical clustering analysis and Pearson correlation matrix demonstrated that cities with similar economic structures tend to exhibit correlated SO_2 trends, reinforcing the importance of shared environmental policies across regions. This suggests that cities with similar pollution patterns could benefit from joint regulatory frameworks to achieve more effective air quality management (Kim et al., 2019).

Additionally, the findings indicate that Seoul, Busan, and Incheon have maintained relatively low and stable SO_2 levels, whereas industrial hubs such as Ulsan have exhibited higher variability. This suggests that some industrial cities continue to experience fluctuations in SO_2 emissions, likely due to changes in industrial activity, economic policies, or regulatory enforcement. While South Korea's national pollution policies have been successful in reducing emissions in urban centers, their impact on heavy industrial zones remains uneven, requiring more focused regulatory interventions.

A key finding from the study was that meteorological factors such as temperature, humidity, and wind speed had minimal influence on SO_2 concentration trends. Unlike pollutants that are highly dependent on weather conditions (such as PM2.5 or ozone), SO_2 levels appear to be primarily driven by industrial emissions, transportation activities, and policy regulations. The multiple linear regression analysis confirmed that city-specific variations alone do not strongly determine SO_2 trends, underscoring the dominant role of human activities and policy measures over natural meteorological fluctuations.

This research highlights the success of South Korea's air pollution control measures, particularly in metropolitan areas where policy enforcement has been stronger. However, it also emphasizes the need for stronger regulatory interventions in industrial hubs, where pollution variability remains high. The findings suggest that regional coordination of environmental policies could enhance the effectiveness of air quality management strategies. Cities that exhibit similar SO_2 reduction patterns, such as Seoul-Incheon and Busan-Daegu, could benefit from integrated regulatory policies that align emissions control efforts and optimize pollution reduction across multiple regions.

Stricter enforcement of SO_2 reduction policies in industrial zones such as Ulsan to address persistent emission variability. Inter-city collaboration for air quality management, especially among cities with similar pollution trends, to enhance regulatory efficiency. Integration of real-time monitoring systems and predictive models to anticipate SO_2 pollution spikes and implement timely regulatory interventions.

While South Korea has successfully reduced SO_2 emissions through regulatory frameworks such as the Air Quality Special Act (2019) and Green New Deal (2020), additional refinements are required to ensure equitable improvements across all urban regions. By focusing on these specific, data-driven approaches, South Korea can achieve a more balanced and sustainable reduction in SO_2 pollution, ensuring long-term benefits for public health and environmental quality."

5.2. Future Research Direction

Despite providing valuable insights into SO_2 concentration trends and policy effectiveness, this study has certain limitations. First, it relies on secondary air quality data from government monitoring stations, which may have inconsistencies or gaps in measurement accuracy. Second, while the study examines policy impacts, it does not quantitatively assess the causal relationship between specific regulatory measures and SO_2 reductions. Third, meteorological factors such as wind patterns and atmospheric chemistry, which can influence SO_2 dispersion, were only analyzed through correlation rather than detailed modeling. Lastly, the study focuses on seven major cities, limiting its applicability to rural and industrial zones where air pollution trends may differ.

Future research should incorporate high-resolution atmospheric modeling to better capture the influence of weather conditions and geographic factors on SO_2 dispersion. Additionally, studies should adopt causal inference methods, such as difference-in-differences (DiD) or machine learning-based policy evaluation, to assess the direct impact of regulations on emission reductions. Expanding the scope to include rural and suburban areas, as well as industrial complexes, will provide a more comprehensive understanding of SO_2 pollution patterns in South Korea. Lastly, integrating public health data will allow for a more detailed analysis of the health benefits associated with declining SO_2 levels, strengthening the connection between air quality improvements and public well-being.

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