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Analysis of Health Impacts from Future Air Quality Changes Considering the Aging Population in Korea

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Abstract: When predicting the health impacts of $PM_{2.5}$ from future air quality changes, it is crucial to consider both air quality improvements and population aging. This study divided future emission scenarios into a base and control scenario to project air quality from 2015 to 2030 and assess health outcomes. The GUIDE model, an Integrated Assessment Model (IAM), was used to estimate future emissions, while the CMAQ (Chemical Transport Model) and BenMAP (Health Impact Model) evaluated health impacts resulting from changes in air quality in Korea. The study focused on the impact of population aging on future health outcomes. Both scenarios showed improved $PM_{2.5}$ concentrations, with the control scenario showing more substantial improvements due to stronger policy measures. When applying current age patterns, health impacts decreased as $PM_{2.5}$ concentrations decreased. However, when considering future population aging, health impacts increased despite improved air quality. The results excluding aging show that the number of premature deaths due to cardiovascular disease and all other causes caused by $PM_{2.5}$ is 18,413 in the base year, while in the future control scenario, the number decreases to 11,729. In contrast, when aging is taken into account, the number of premature deaths increases to 23,037. This finding suggests that, although $PM_{2.5}$ concentrations are expected to decline, the increasing proportion of elderly individuals will exacerbate health risks. Therefore, accounting for aging population trends is essential when studying the health impacts of future air quality changes.

Keywords: emission scenarios; health impacts; $PM_{2.5}$ concentration; cardiovascular; aging society; future air quality changes

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1. Introduction

Air pollutants are emitted into the environment through natural phenomena or anthropogenic activities and can negatively impact human health and the environment. In particular, anthropogenic activities are a major cause of air pollutant emissions. Among the air pollutants emitted through anthropogenic activities, $PM_{2.5}$ is a major environmental health impact pollutant. $PM_{2.5}$ is known to cause adverse health effects, including acute and chronic respiratory diseases such as pneumonia and chronic bronchitis, and cardiovascular diseases such as coronary heart disease, congestive heart failure, and premature death [1–4]. For this reason, many studies have been conducted to analyze how airborne $PM_{2.5}$ concentrations affect human health.

A variety of applications have been developed to assess the health-related and economic impacts associated with air pollutants. BenMAP is one such tool published by the US Environmental Protection Agency (U.S. EPA) in 2003 to estimate the economic benefit of attaining current and potentially future National Ambient Air Quality Standards (NAAQS) [5,6]. In order to utilize BenMAP, representative data on air pollutant concentrations, population, and base year damage are required. Previous studies have collected and utilized the relevant data in various ways.

In many past studies, human health impacts have been estimated by considering $PM_{2.5}$ concentrations alongside population density and distribution. Many studies have used $PM_{2.5}$ concentrations measured at air pollution monitoring stations [7–9]. While these measurements have the advantage of capturing the temporal variability of concentrations, they are limited by their inability to account for spatial variability. This means that assumptions must be made to estimate human health impacts in areas distant from the monitoring stations, which could result in incorrect estimations. As an alternative to solve the disadvantages of such spatial variability, a method of estimating concentrations using a chemical transport model (CTM) is widely used [10–12]. This method has the advantage of being able to examine the entire modeled area, rather than considering only the concentrations representing the area around the monitoring stations in assessing human health risks. In addition, observation data can only utilize the current $PM_{2.5}$ concentration. In order to predict the change in $PM_{2.5}$ concentration that will occur by applying future air quality policies, the use of a CTM is necessary.

In this study, we used a CTM to analyze the human health impacts of future air quality changes in Korea. To predict future air quality changes, we applied two types of future emission scenarios based on energy and air quality policy plans established in Korea. The changes in emissions for each scenario were estimated using the GHGs (GreenHouseGases) and air pollutants Unified Information Design system for Environment (GUIDE) [13], one of the Integrated Assessment Models (IAMs). In a previously published study [14], the effects of policies were analyzed by examining projected emission changes up to 2030, with 2015 as the baseline year. The estimated emissions for each scenario were used as input values for the CTM in this study. In this study, future changes in $PM_{2.5}$ concentrations for each scenario were estimated to analyze the corresponding human health impacts. This study quantified the changes in health impacts due to the aging society in Korea. It predicted future $PM_{2.5}$ concentrations by applying two policy sets: one that is actually planned and another that includes stronger policies. The study quantified the differences in health impacts caused by these changes, both when considering the aging society and when not considering it.

Other important variables in this study are the population density and age distribution. Population density determines the affected area and the number of people at risk, while age distribution reflects how pollutants affect different age groups. As previously reported in other studies investigating the link between air pollution and health effects, the elderly have been identified as a particularly sensitive group to air pollutants [15–19]. This is a crucial factor that should be considered when estimating human health impacts under future scenarios. Many developed countries are entering an aging society, and incorporating this aspect into analyses is necessary to quantify the human health impact. This is also the case for Korea, the subject of this study.

According to the future population projections by Statistics Korea (KOrean Statistical Information Service (KOSIS)) [20], the proportion of people aged 65 and over in Korea is expected to increase from 17.4% in 2022 to 20.3% in 2025, 30.9% in 2036, and exceed 40% in

2050, as a result of increased life expectancy and declining birth rates. According to UN standards, a population where 7% or more are aged 65 or over is classified as an aging society, 14% or more as an aged society, and 20% or more as a super-aged society [21]. Korea is projected to become a super-aged society by 2025. Therefore, as Korea becomes a super-aged society, when establishing future health and environmental policies, the impact of environmental pollution on the elderly must be accurately assessed.

Therefore, this study evaluated the change in $PM_{2.5}$ concentration and the resulting health impacts according to future emission scenarios. When evaluating future health impacts in Korea, we aimed to identify the change in the impact of environmental pollution due to aging. In addition, we used an IAM and CTM to estimate $PM_{2.5}$ concentrations based on air policies from neighboring countries and Korea, and quantified the health impacts resulting from them. Section 2.1.2, Future Population in Korea, summarizes the results of a survey on future population changes in Korea, and Sections 2.2 and 3.1 describes the method and results for predicting future $PM_{2.5}$ concentrations. Section 3.2 summarizes the methodology and results for estimating future health impacts, and finally, Section 4 discusses the findings from this study.

2. Data and Methods

2.1. Future Health Impact Assessment

2.1.1. BenMAP Equation

The $PM_{2.5}$ concentration data calculated for each scenario were used to quantify regional health impacts using the Environmental Benefits Mapping and Analysis Program (BenMAP) formula [22]. BenMAP formula is as follows:

$$\Delta Y = Y_0\left(1 - \frac{1}{\exp(\beta \times \Delta X)}\right) = Incidence \times Population \times \left(1 - \frac{1}{\exp(\beta \times \Delta X)}\right) \quad (1)$$

ΔY: Health benefits of reducing an air pollutant.
Y_0: Baseline incidence (=$Incidence \times Population$).
Incidence: Baseline incidence rates.
Population: Exposed population.
β: C-R Function coefficient value (health effect estimate).
ΔX: $PM_{2.5}$ concentration change.

Here, *Incidence* refers to the mortality or morbidity rate of specific health effects in the base year, *Population* refers to the number of people exposed, and β represents the concentration-response (C-R) function coefficient. ΔX represents the change in air pollution concentration ($PM_{2.5}$ in this study), and ΔY represents the change in health impacts due to this pollution (change in premature deaths and disease cases) [23]. Since health benefit estimation is based on the target population, the data used for estimating health benefits in this study are presented in Table 1.

Table 1. Input data and sources for applying BenMAP.

Category	Data	Source
Concentration	$PM_{2.5}$	CMAQ results
Population	Population by region and age	Statistics Korea
C-R Function	Korea C-R Function Standards	Ha et al., 2016 [24]
Disease incidence/ prevalence population data	Prevalence—Number of hospitalizations	Health Insurance Review & Assessment Service—"Health Insurance Coverage Hospitalization Statistics 2010–2016"
	Mortality rate	Statistics Korea

Among the important factors in the health impact function are incidence and population, which are significantly influenced by changes due to population aging and are proportionally related to the health impact function. Therefore, when analyzing the impact of concentration changes resulting from future emission projections, these factors are crucial and were investigated and applied using Korean official data. ΔX was estimated and applied based on the CMAQ results for each scenario.

1. Baseline Mortality Data

The BenMAP formular estimates the change in health impacts resulting from changes in pollutant concentration. To estimate the absolute change in the number of cases using this function, data on incidence or prevalence rates for the given health impact endpoint are needed. The incidence rate and prevalence rate mentioned here are data applied to the "Incidence" shown in Formula (1).

In this study, the Korea Health Insurance Corporation's big data were used for prevalence and incidence rates. Mortality data were obtained from the Statistics Korea's 2015 mortality statistics, categorized by cause of death and age group (Table A1) [25]. Mortality statistics consist of population and death data in 5-year increments from 0 to 90 years of age and older. Causes of death include circulatory diseases and respiratory diseases (cardiovascular diseases). Examining the death rate by age, it can be confirmed that the death rate approximately doubles for every 5-year increase in age. This indicates that the older the population, the higher the probability of death due to cardiovascular disease.

When quantifying health impacts, changes in the future age distribution of Korea were considered to analyze the effects of aging on future health outcomes. In South Korea, where aging is currently progressing, failing to account for this could lead to inaccurate predictions of health impacts due to future changes in concentration. Additionally, the population is densely concentrated in large cities, and it has been observed that $PM_{2.5}$ concentration is higher in more urbanized areas. Therefore, establishing a future population database at the municipal level to estimate domestic health impacts is crucial. Consequently, this study considered both municipal-level population distribution and the effects of aging in its analysis.

2. Concentration-Response Coefficient Value

Mortality statistics consist of population and death data in 5-year increments from 0 to 90 years of age and older. Causes of death include circulatory diseases and respiratory diseases (cardiovascular diseases). Examining the death rate by age, it can be confirmed that the death rate approximately doubles for every 5-year increase in age. This indicates that the older the population, the higher the probability of death due to cardiovascular disease. Unless the health impact function is directly derived for a specific research purpose, it typically uses results from existing epidemiological studies on air pollution [13]. Related research includes the 2020 GUIDE development study for Korea, which used the C-R values summarized in KEITI, 2020 [13]. These values are detailed in Table 2.

Table 2. C-R function coefficient value of health impact caused by $PM_{2.5}$.

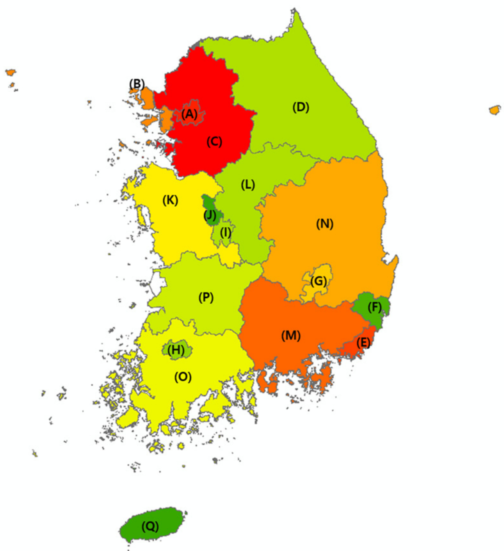
Pollutant	Exposure	Impact	Population Group	C-R Function Coefficient Value	Report	Reference
$PM_{2.5}$	Long-term	Other	Adult	0.006015	WHO HRAPIE	Hoek et al., 2013 [26]
		Cardiovascular	Adult	0.01133	EC APHEKOM	Pope et al., 2002 [2]

2.1.2. Future Population in South Korea

Population data are used to identify the size and distribution characteristics of the target population exposed to air pollutants, categorized by region, age, and gender. When estimating the health benefits that can be obtained through air pollution reduction policies, it is reasonable to estimate the benefits while reflecting the characteristics of the target population at the point in time targeted by the policy. However, when conducting research reaching several decades into the future, it is advisable to consider population changes in estimating health benefits, as there may be significant changes in the population distribution of the region.

In this study, the base year was set as 2015, and the target analysis years were 2020, 2025, and 2030. Population data for these target years were obtained from the population statistics provided by Statistics Korea [27]. These data provide population statistics by region and age. The populations for 2020, 2025, and 2030 are projections based on the total population census of the base year, reflecting recent trends in population change factors (birth, death, and population migration) by province, and assuming future changes. Population data from 226 basic local governments were collected, and the population by region from 2015 to 2030 was summarized at the level of 17 metropolitan local governments in Table A2. Although Korea's total population is projected to increase until 2030, recent research results [28] indicate that it will start to decline after 2035.

First, the regional population distribution in the base year of 2015 is as follows. Figure 1 illustrates the population distribution across the 17 municipalities. As shown in the figure, approximately 49% of Korea's population resides in metropolitan areas, which include regions A, B, and C. In addition, the southern region, E (Busan), Korea's second-largest city, has the highest population outside the metropolitan area (about 8%). These densely populated areas are likely to have higher emissions of air pollutants, leading to increased health risks. This overall regional population distribution is not expected to change significantly by 2030, although there are variations in the growth rates by region.



Region		Population	Area	Density
		Persons	km²	Persons/km²
A	Seoul	10,022,181	605	16,566
B	Incheon	2,925,815	1067	2742
C	Gyeonggi-do	12,522,606	10,200	1228
D	Gangwon-do	1,549,507	16,830	92
E	Busan	3,513,777	771	4557
F	Ulsan	1,173,534	1063	1104
G	Daegu	2,487,829	885	2811
H	Gwangju	1,472,199	501	2939
I	Daejeon	1,518,775	540	2813
J	Sejong	210,884	465	454
K	Chungcheongnam-do	2,077,649	8247	252
L	Chungcheongbuk-do	1,583,952	7407	214
M	Gyeongsangnam-do	3,364,702	10,542	319
N	Gyeongsangbuk-do	2,702,826	19,036	142
O	Jeollanam-do	1,908,996	12,361	154
P	Jeollabuk-do	1,869,711	8073	232
Q	Jeju	624,395	1850	338
South Korea		51,529,338	100,444	513

Figure 1. Population in 2015 by region.

While Korea's total population is projected to increase by 2.7% in 2030 compared to 2015, a closer look at each region reveals that Seoul, Busan, Daegu, Gyeongsangbuk-do, Jeollanam-do, and Jeollabuk-do are expected to decrease by 5.9%, 6.6%, 4.9%, 0.3%, 6.4%, and 3.2%, respectively. In contrast, regions like Incheon, Gyeonggi-do, Gangwon-do, Ulsan, Gwangju, Daejeon, Chungcheongnam-do, Chungcheongbuk-do, and Gyeongsangnam-do are expected to increase by 7.7%, 11%, 1.3%, 1.2%, 0.5%, 2.5%, 13.7%, 7.9%, and 1.8%, respectively. Notably, Sejong, which had a relatively small population in the base year, is projected to experience a population increase of about 124.3%. (Refer to Table A2, Figure A1).

Next, the changes in the age groups of the Korean population were analyzed. Figure 2 is a graph that shows the population of Korea divided into different age groups. It can be observed that Korea's population distribution shifts to the right as time progresses, meaning the age group with the highest proportion of the total population is shifting to older ages. While the age group with the largest population in 2015 was 45–49 years old, the age group with the largest population in 2030 is expected to be 55–59 years old. This indicates that, in the future, as the proportion of the elderly population increases, the population in age groups that are more sensitive to the effects of air pollutants will also increase.

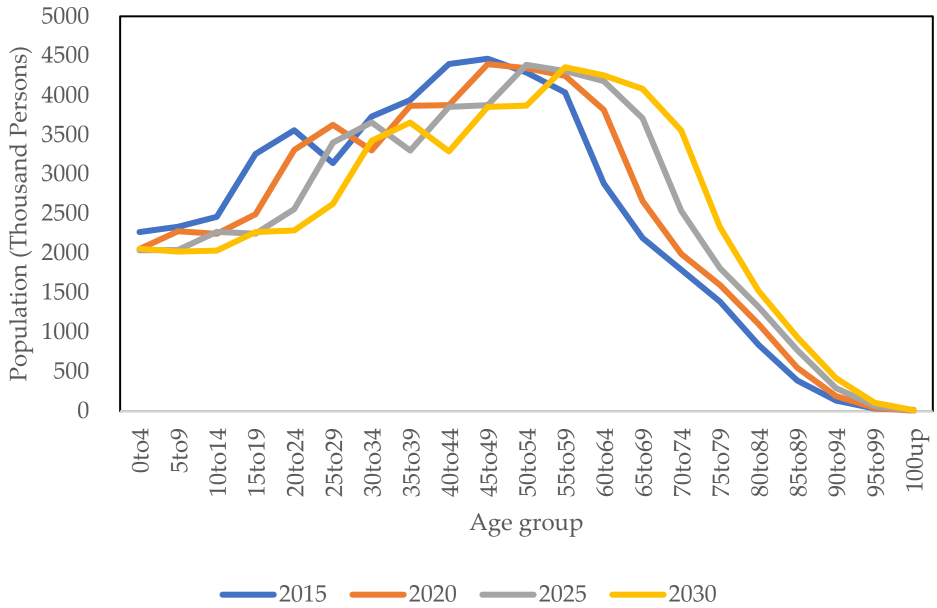


Figure 2. Population by age group from 2015 to 2030.

2.2. Future $PM_{2.5}$ Concentrations

2.2.1. Future $PM_{2.5}$ Concentrations Prediction Procedure in South Korea

Figure 3 provides a brief outline of the procedure used in this study to predict future $PM_{2.5}$ concentration in Korea. First, future emission scenarios were developed by investigating Korea's energy and air quality mitigation policy plans. Second, the emissions of air pollutants in each future scenario were estimated using GUIDE. Next, the $PM_{2.5}$ concentration for each future scenario was predicted, and finally, the health impacts resulting from exposure to $PM_{2.5}$ among air pollutants were analyzed.

The construction of scenarios and the estimated future emissions were based on the research results of Jang et al., 2024 [14]. In this study, the estimated emissions of air pollutants for each scenario were used as input data for the Community Multiscale Air Quality (CMAQ; U.S. EPA), a CTM, to estimate the ambient $PM_{2.5}$ concentrations. The study was conducted by dividing the scenarios into a base scenario and a control scenario. A detailed description of the scenarios is provided in Section 2.2.2. The $PM_{2.5}$ concentrations predicted for each scenario were averaged at the level of 17 regions. These regionally averaged $PM_{2.5}$ concentrations, along with the regional population data, were used to estimate the changes in health impacts for each scenario.

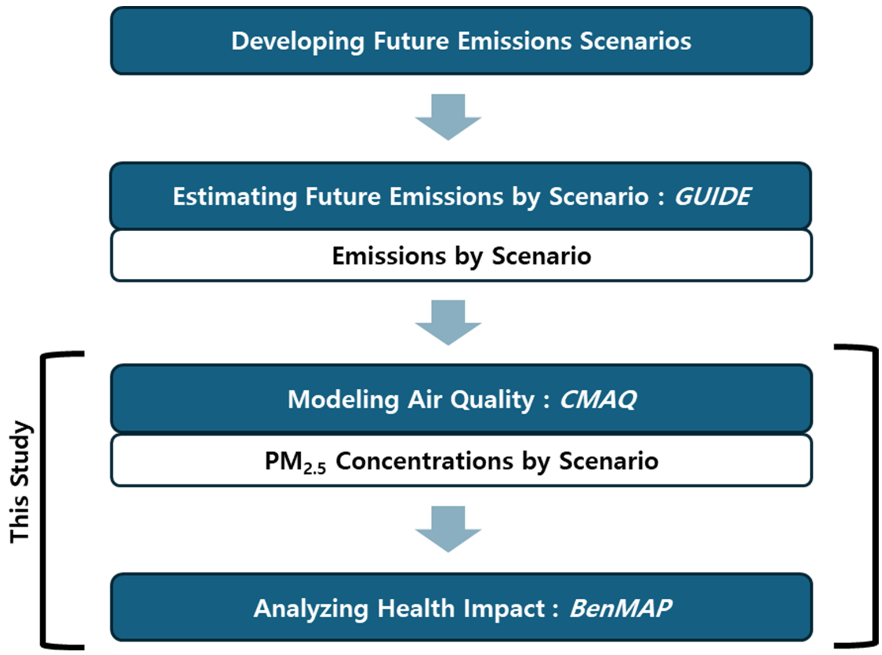


Figure 3. Process of estimating health impacts through estimation of future $PM_{2.5}$ concentration.

2.2.2. Prediction of Future Emissions

- Future emission scenarios description

To develop the scenarios, as shown in Figure 4, air quality policies and energy pathways were classified, and scenarios were constructed by combining these two pathways. Air quality policies were divided into two pathways: No Further Control (NFC) and Current Legislation (CLE). The NFC scenario maintains only the air pollution reduction policies implemented in the base year into the future, while the CLE scenario foresees the implementation of additional air pollution reduction policies planned for the future.

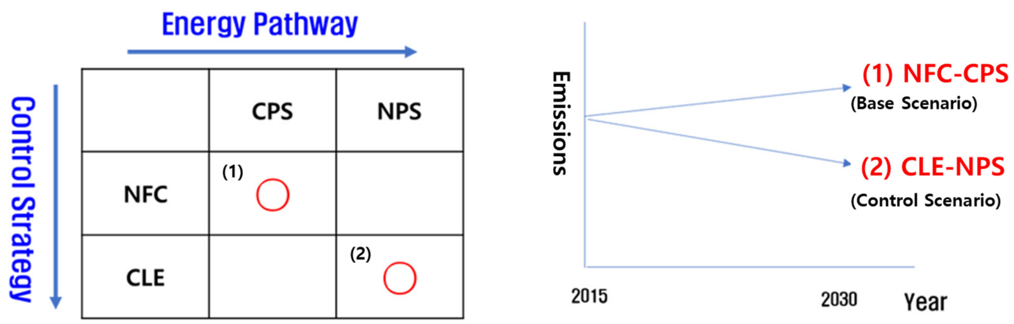


Figure 4. Future scenario setting.

The energy pathways were set as the Current Policies Scenario (CPS) and the New Policies Scenario (NPS). The CPS scenario is based on current energy demand and policies, while the NPS scenario considers not only ongoing energy policies and actions but also official targets (such as the Nationally Determined Contributions, NDC, proposed for the implementation of the Paris Climate Agreement) and energy technologies (including those close to application).

In this study, two future emission scenarios, the base scenario and the control scenario, were developed for analysis. The base scenario is the NFC-CPS scenario, which uses 2015 as the base year and applies socioeconomic projections for intermediate levels of development. It assumes that only the policies implemented in the base year will be applied in the future, without additional energy or air pollution reduction policies. The control scenario is the

CLE-NPS scenario, in which additional energy and air quality policies are applied to the base scenario. The energy policy applied is the Nationally Determined Contributions (NDC) announced in 2018 [29], and the air quality policy is Korea's "The Master Plan for Air Quality Management by Region" [30]. The control scenario was designed to achieve greater reductions in air pollutants in the future compared to the base scenario.

- Future emissions prediction results by scenario

Regional, pollutant, and sectoral emission estimates for the NFC-CPS and CLE-NPS scenarios estimated using GUIDE utilizing the methodology of Jang et al., 2024 [14] were used as input data for CMAQ. Here, the trends in emissions of air pollutants by sector for each scenario were examined. As shown in Figure 5A, the NFC-CPS scenario shows a decrease in CO_2, CO, SO_2, NOx, and $PM_{2.5}$ emissions until 2025, followed by an increasing trend. In the case of VOC and NH_3, there is a steady increase in emissions. As shown in Figure 5B, the CLE-NPS scenario indicates a decreasing trend in CO_2, CO, SO_2, NOx, $PM_{2.5}$, and VOC emissions, while NH_3 emissions show a continuous increasing trend.

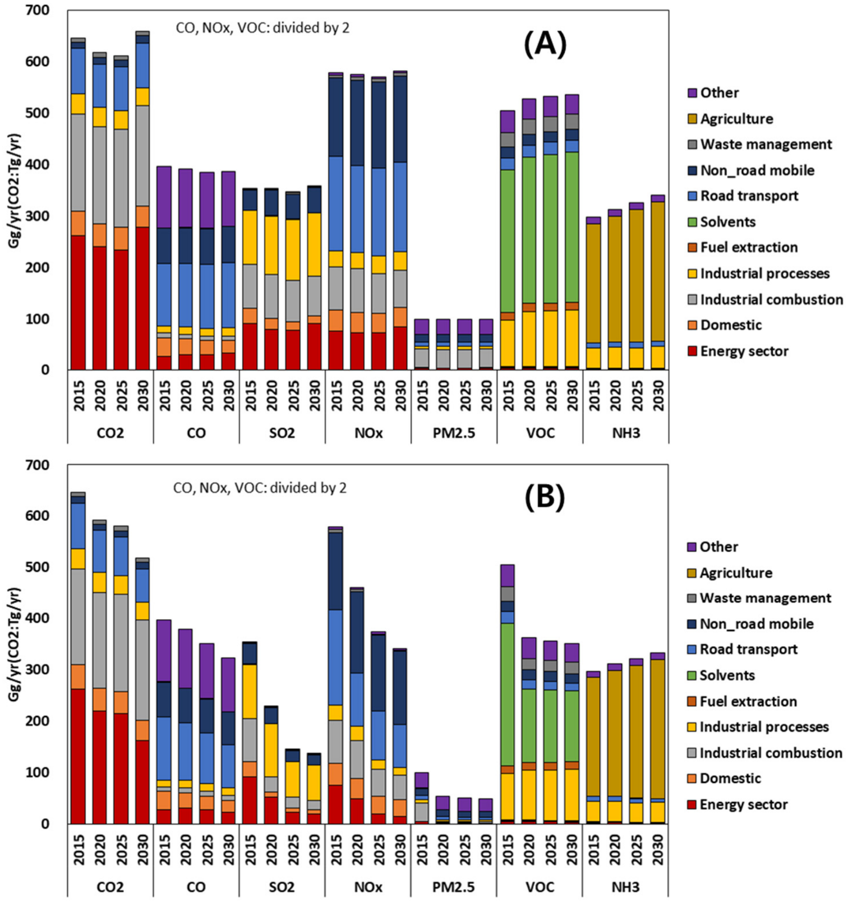


Figure 5. (**A**) Future emissions by NFC-CPS scenario from 2015 to 2030. (**B**) Future emissions by CLE-NPS scenario from 2015 to 2030 [14].

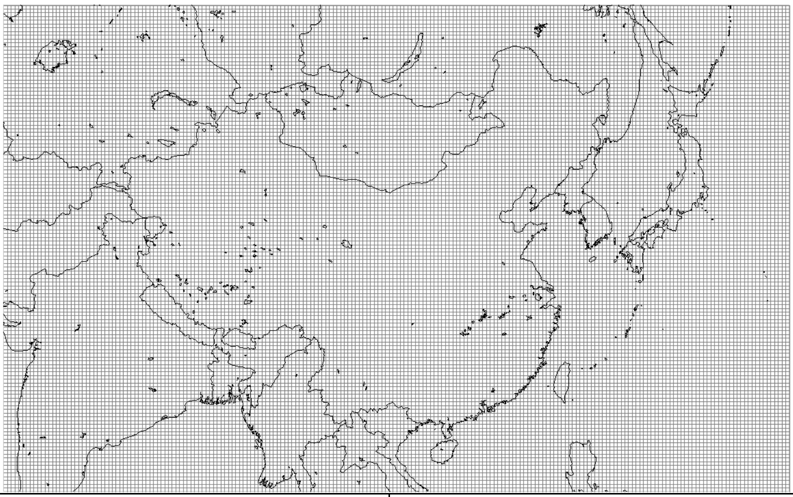
When comparing Figure 5A,B, it can be observed that the future emissions of air pollutants in the CLE-NPS scenario are lower than those in the NFC-CPS scenario. This reduction is because of the emission reduction policies in the CLE-NPS scenario, such as strengthening emission standards in the industrial combustion sector, converting anthracite coal to cleaner fuels, and strengthening solid fuel standards for industrial sites. As a result, the emissions of NOx, SO_2 (precursors of $PM_{2.5}$), and primary $PM_{2.5}$ are analyzed and are seen to decrease. Consequently, the simulation of future air quality in Korea is expected to show that the $PM_{2.5}$ concentration in the CLE-NPS scenario will be lower than that in the NFC-CPS scenario.

2.2.3. Chemical Transport Modeling Method of Future $PM_{2.5}$ Concentrations

The modeling was conducted using a 3D-CTM and a meteorological model over the domain shown in Figure 6A. The domain covers the East Asian region (15–54N, 69–150E) and is set with a horizontal grid resolution of 36 × 36 km^2, including a total of 210 × 130 grids within the entire domain. To estimate $PM_{2.5}$ concentrations in Korea due to changes in emissions, the emissions from neighboring countries were considered. In particular, the influence of China, located on the upwind side of Korea, must be taken into account. To this end, China's future energy and air quality policies were applied to its emissions by setting scenarios based on the level at which the planned policies are currently implemented.

The modeling framework for this domain is illustrated in Figure 6B. Emission processing was conducted using SMOKE-Asia, an adaptation of the Sparse Matrix Operator Kernel Emissions (SMOKE; U.S EPA) model developed for Asia [31]. To estimate air quality concentrations, CMAQ was utilized. To utilize CMAQ, the previously written emissions (Section 2.2.2) were converted into modeling emissions using the latest study's spatiotemporal allocation data and chemical speciation data [32]. The simulation periods were selected to represent winter, spring, summer, and autumn, with January, April, July, and October chosen as the representative months. Korea, located in the mid-latitudes of the Northern Hemisphere, has four distinct seasons. Generally, March, April, and May are spring, June, July, and August are summer, September, October, and November are fall, and December, January, and February are winter. Accordingly, the months in the middle, January (winter), April (spring), July (summer), and October (fall), were selected as representative months. The concentrations were simulated at hourly intervals.

(A)



(B)

Chemical Transport Model	CCTM in CMAQ v4.7 (U.S. EPA)
· Chemical Mechanism	SAPRC-99, AERO5
Emissions	
· Anthropogenic emission model	SMOKE-Asia (Woo et al., 2012)
· Base Emissions inventory	CREATE v3.0 (NIER, 2020)
Meteorological Model	WRF v3.7.1 (U.S. NCAR)
Period	January, April, July, October. 2015.
Domain	Extent: 15-54N, 69-150E
	Grid resolution: 36 km × 36 km (210 × 130)
	Number of vertical Layer: 30

Figure 6. (**A**) Modeling domain (36 × 36 km^2 grid). (**B**) Chemical transport model framework [31,33].

3. Results

3.1. $PM_{2.5}$ Concentration Estimation Results for South Korea by Scenario

Figure 7 shows the $PM_{2.5}$ concentration simulation results for the base year (2015) and for the years 2020, 2025, and 2030 under different scenarios. As policies are implemented, differences between the two scenarios can be observed; however, in both the NFC-CPS and CLE-NPS scenarios, $PM_{2.5}$ concentrations in Korea are expected to decrease by 2030. The CLE-NPS scenario, with relatively stronger policies, shows more significant improvements in $PM_{2.5}$ concentrations. The average $PM_{2.5}$ concentration in Korea for the base year is 22.6 μg/m^3. In the NFC-CPS scenario, concentrations are projected to decrease to 21.9 μg/m^3 in 2020, 18.0 μg/m^3 in 2025, and 17.0 μg/m^3 in 2030. In contrast, the CLE-NPS scenario shows concentrations decreasing more rapidly, with projections of 21.3 μg/m^3 in 2020, 16.4 μg/m^3 in 2025, and 11.6 μg/m^3 in 2030. This indicates a more pronounced reduction in $PM_{2.5}$ concentrations under the CLE-NPS scenario compared to the NFC-CPS scenario. The more rapid decrease in the CLE-NPS scenario is consistent with the reductions in NOx, SO_2, and primary $PM_{2.5}$ emissions explained in the emission changes discussed in Section 2.2.2.

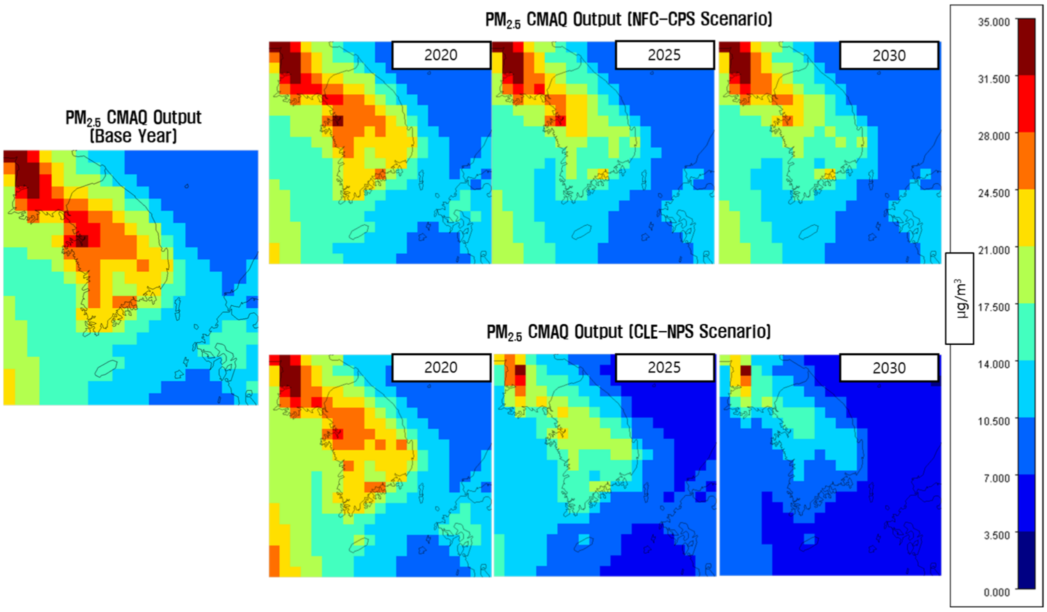


Figure 7. Distribution of $PM_{2.5}$ concentrations in South Korea by year and scenario (μg/m^3).

Using the grid-based future concentration estimation results by scenario, the average values for Korea as a whole and for the 17 regions were calculated (Table 3). Changes in $PM_{2.5}$ concentrations compared to the base year were calculated for the 17 regions (Table 3). The average concentration for Korea in the base year is 22.6 μg/m^3. The NFC-CPS scenario predicted a −25% decrease from the base year value to 17.0 μg/m^3 by 2030. In contrast, the CLE-NPS scenario predicted a −49% decrease from the base year value to 11.6 μg/m^3.

Under the NFC-CPS scenario, the concentrations in all regions decreased by −33% to −12% by 2030 compared to the base year, showing a relatively mild decrease. However, under the CLE-NPS scenario, the $PM_{2.5}$ concentrations in all regions are expected to decrease by −62% to −39% compared to the base year, showing a much larger decrease.

The $PM_{2.5}$ concentrations generated through CMAQ were compared with the observed data to assess the validity of the modeling results. The annual average observed data is released until 2023, and since the $PM_{2.5}$ concentrations in 2023 were not simulated in this study, the observed concentrations in 2023 and the modeled concentrations in 2025 were compared. Detailed data for this are shown in Tables A3 and A4. The observed concentrations decreased by 29% from 26 μg/m^3 in 2015 to 18 μg/m^3 in 2023, and the modeled concentrations improved from 22.6 μg/m^3 in 2015 to 18 μg/m^3 (20% reduction, NFC-CPS) and 16.4 μg/m^3 (27% reduction, CLE-NPS) in 2025. Through the observed concentrations, it was confirmed that the actual improvement and the improvement predicted by the model were similar.

Table 3. Average $PM_{2.5}$ concentrations by region, year and scenario (unit: μg/m^3) and concentration change rate compared to base year (unit: %).

Year	**2015**	**2020**		**2025**		**2030**	
Scenario	**Base**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**
South Korea	22.6	21.9 (−2%)	21.3 (−6%)	18.0 (−20%)	16.4 (−27%)	17.0 (−25%)	11.6 (−49%)
Seoul	27.7	27.3 (−2%)	26.8 (−3%)	25.4 (−9%)	23.7 (−15%)	24.1 (−13%)	15.4 (−44%)
Incheon	22.0	21.6 (−2%)	21.0 (−5%)	19.9 (−10%)	18.3 (−17%)	19.3 (−12%)	12.1 (−45%)
Gyeonggi-do	27.0	26.6 (−2%)	25.6 (−5%)	23.5 (−13%)	19.4 (−28%)	22.2 (−18%)	15.0 (−45%)
Gangwon-do	19.8	17.7 (−11%)	17.3 (−13%)	14.3 (−28%)	14.3 (−28%)	13.5 (−32%)	10.5 (−47%)
Busan	22.2	21.3 (−4%)	21.2 (−5%)	17.2 (−22%)	15.6 (−30%)	16.1 (−27%)	7.9 (−64%)
Ulsan	23.5	22.7 (−4%)	22.2 (−6%)	17.5 (−26%)	17.6 (−25%)	16.1 (−31%)	8.9 (−62%)
Daegu	24.3	23.1 (−5%)	22.8 (−6%)	17.3 (−29%)	16.7 (−31%)	16.2 (−33%)	11.6 (−52%)
Gwangju	25.5	24.8 (−3%)	24.6 (−4%)	19.8 (−22%)	18.2 (−29%)	18.3 (−28%)	9.7 (−62%)
Daejeon	26.0	25.3 (−3%)	24.6 (−5%)	20.5 (−21%)	18.3 (−30%)	18.8 (−27%)	11.6 (−55%)
Sejong	20.5	20.1 (−2%)	18.4 (−10%)	16.6 (−19%)	14.3 (−30%)	15.8 (−23%)	12.6 (−39%)
Chungcheongnam-do	23.6	22.9 (−3%)	21.6 (−8%)	18.9 (−20%)	16.8 (−29%)	17.9 (−24%)	11.6 (−51%)
Chungcheongbuk-do	25.7	25.1 (−2%)	24.0 (−7%)	20.1 (−22%)	18.8 (−27%)	18.5 (−28%)	13.3 (−48%)
Gyeongsangnam-do	20.5	19.6 (−4%)	18.8 (−8%)	15.6 (−24%)	14.3 (−30%)	14.8 (−28%)	9.1 (−56%)
Gyeongsangbuk-do	21.4	20.8 (−3%)	20.2 (−5%)	16.2 (−24%)	15.2 (−29%)	15.1 (−29%)	10.9 (−49%)
Jeollanam-do	18.4	17.7 (−4%)	17.4 (−5%)	14.4 (−22%)	13.1 (−29%)	14.0 (−24%)	8.6 (−53%)
Jeollabuk-do	22.0	21.2 (−4%)	20.8 (−6%)	16.4 (−25%)	15.3 (−31%)	15.6 (−29%)	9.9 (−55%)
Jeju	14.4	14.4 (0%)	14.3 (0%)	12.2 (−15%)	9.5 (−34%)	12.1 (−16%)	6.3 (−56%)

3.2. Analysis of Health Impact Due to $PM_{2.5}$ in South Korea by Scenario

Using the method described Sections 2.1 and 2.2, the number of premature deaths by region and year for each scenario was estimated. The results without considering aging are shown in Figure 8, and the results considering aging are shown in Figure 9.

First, as shown in Figure 8 and Table A5, for the results without considering aging, the total number of premature deaths due to cardiovascular diseases and all other causes from $PM_{2.5}$ in the base year is 18,413. Among these, 14,442 deaths are due to cardiovascular diseases, accounting for approximately 80% of all premature deaths. The future scenarios show a gradual decrease in the projected number of premature deaths.

In contrast, Figure 9 and Table A6 show the results when the impact of aging is considered. For the NFC-CPS scenario in 2030, the number of premature deaths due to cardiovascular diseases is 11,853 without considering aging, but with aging considered, the number increases to 22,962, nearly double. Similarly, for the CLE-NPS scenario, the number of premature deaths due to cardiovascular diseases in 2030 is 9250 without considering aging and 17,894 when aging is considered. This demonstrates that while the health impacts are estimated based on the same concentration changes, the results can differ significantly depending on whether aging rates are reflected.

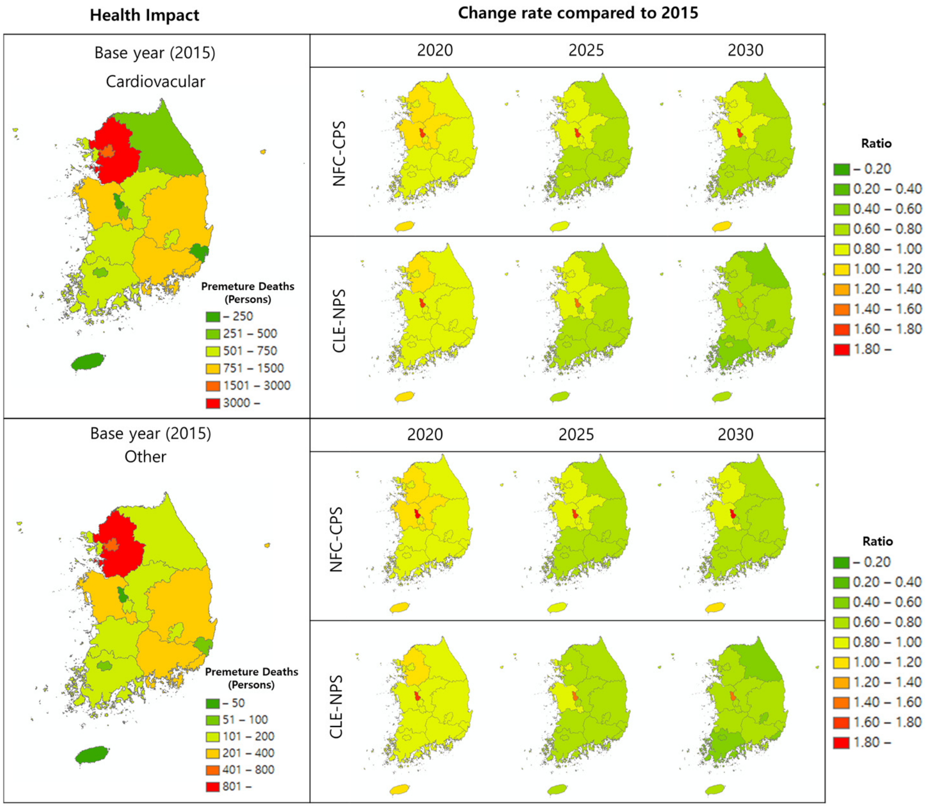


Figure 8. Number of cardiovascular disease and other premature deaths caused by $PM_{2.5}$ by region in the base year and change rate by scenario (Not Considering Aging).

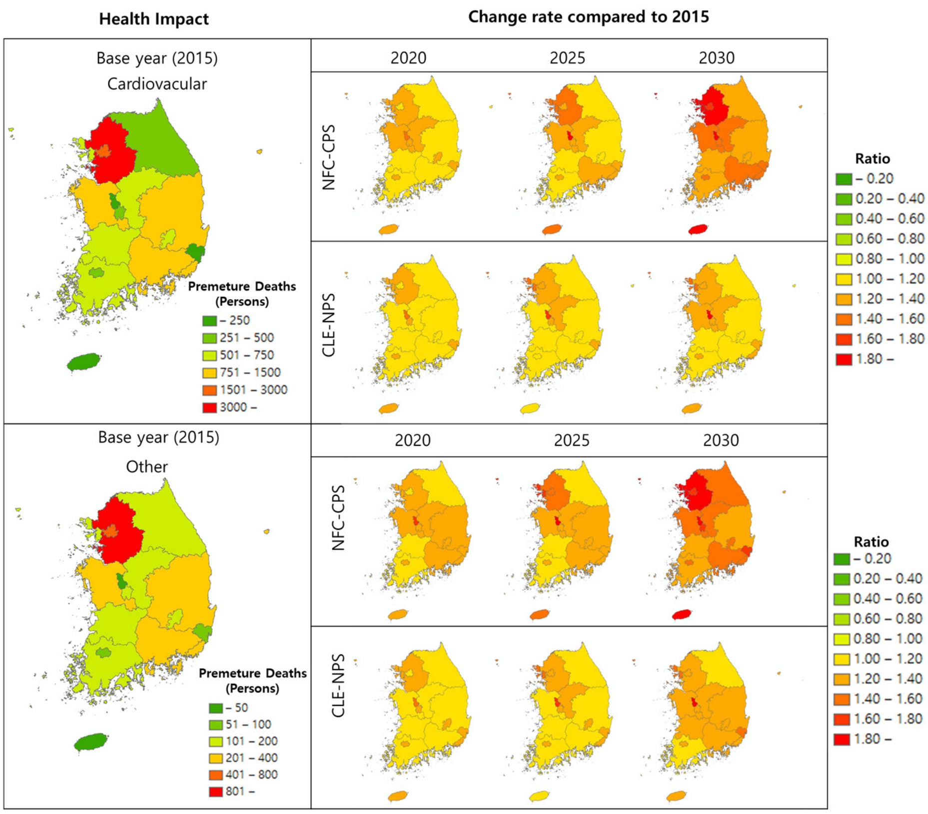


Figure 9. Number of cardiovascular disease and other premature deaths caused by $PM_{2.5}$ by region in the base year and change rate by scenario (Considering Aging).

Figure 10 shows the predicted number of premature deaths based on changes in the average $PM_{2.5}$ concentration in Korea by scenario and year, with and without considering the impact of aging. The graph displays results on the left without considering the aging pattern and on the right with the aging pattern considered. On the left side, it can be observed that in both NFC-CPS and CLE-NPS scenarios, the numbers of premature deaths decrease as $PM_{2.5}$ concentrations decrease. Moreover, in the CLE-NPS scenario, where more stringent reduction policies are applied, the number of premature deaths decreases more significantly due to the more rapid improvement in concentration. This suggests that air quality policies have been effective in reducing health impacts.

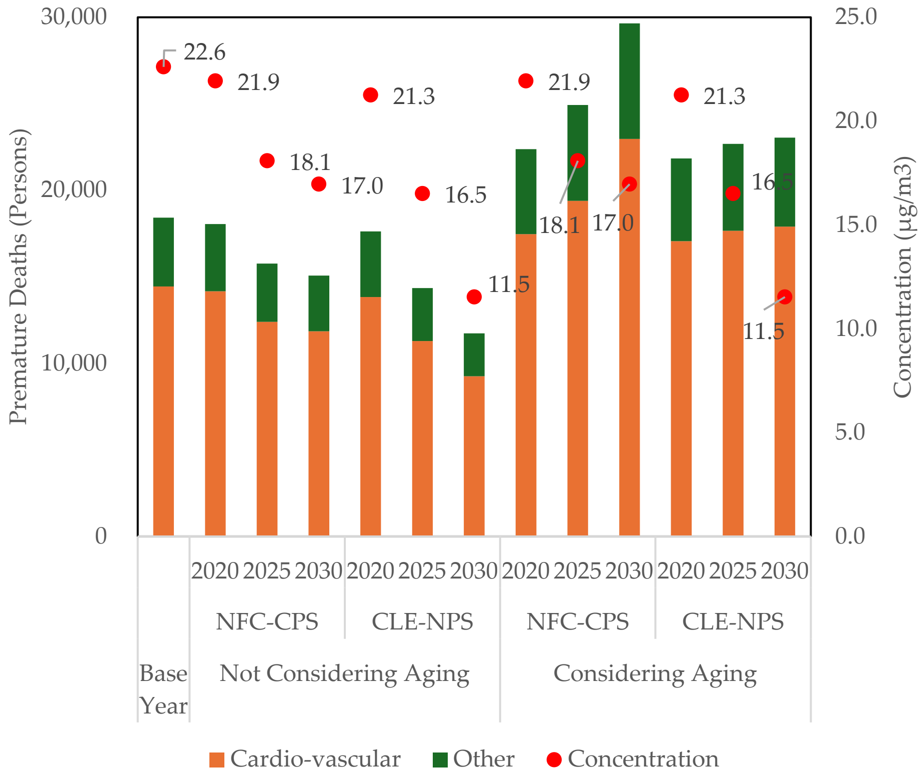


Figure 10. Number of premature deaths due to $PM_{2.5}$ by scenario and year (not considering and considering the impact of aging).

However, the right side of the graph, which considers the effects of aging, shows that despite the same decrease in concentration, the number of premature deaths increases. It is observed that in the CLE-NPS scenario, where stronger air quality policies are applied, the increase in premature deaths is less when aging is considered. This indicates that in the future, with an increasing elderly population that is more sensitive to air quality impacts, air quality policies need to be more stringent to achieve the expected reduction in health impacts.

4. Conclusions

This study quantified the health impact caused by future $PM_{2.5}$ concentration in Korea. For this purpose, the CMAQ model was run using the future emission values estimated for each scenario in the study by Jang et al. (2024) [14]. As a result, future $PM_{2.5}$ concentrations were simulated. Jang et al.'s study set up future air pollutant emission scenarios reflecting South Korea's future energy and air quality policies, and the emissions for each scenario were estimated using GUIDE.

Two future emission scenarios were established: the base scenario (NFC-CPS), which maintains existing policies, and the control scenario (CLE-NPS), which includes additional reduction policies. Even in the base scenario, where policies are maintained until 2030, a reduction in emissions and $PM_{2.5}$ concentrations was predicted. In the control scenario, where additional reduction policies for primary $PM_{2.5}$ and its precursors are implemented, a greater reduction in emissions and $PM_{2.5}$ concentrations was predicted.

In the baseline year, Korea's $PM_{2.5}$ concentration was 22.6 $\mu g/m^3$. Under the NFC-CPS scenario, which maintains current emission reduction efforts, future air quality is expected to improve to a $PM_{2.5}$ concentration of 17.0 $\mu g/m^3$ by 2030. However, with the additional implementation of planned policies as in the CLE-NPS scenario, the $PM_{2.5}$ concentration is projected to be 11.5 $\mu g/m^3$ by 2030, representing an improvement of approximately 5.5 $\mu g/m^3$. This air quality improvement was analyzed for its health impact on the Korean population.

To assess the importance of accounting for future population aging, two scenarios were analyzed: one without considering aging and one with aging considered. The analysis revealed significant differences in health impact results between the two scenarios. When using the current population's age pattern, the reduction in $PM_{2.5}$ concentrations due to changes in air quality from the NFC-CPS and CLE-NPS scenarios resulted in a decrease in premature deaths. However, when considering future age patterns (aging), the number of premature deaths appears to increase even if air quality improves. Although $PM_{2.5}$ concentrations decreased, the aging population, which is more susceptible to health effects, led to a higher number of premature deaths.

These results suggest that developed countries such as Korea, where future aging is expected, must consider changing age patterns when studying future health impacts. Additionally, as the aging population, which is more sensitive to air quality impacts, increases in the future, air quality policies will need to be more robust to achieve the expected reductions in health impacts. This means that when planning policies, we should not only focus on reducing emissions, but also consider whether the changes brought about by the planned policies can sufficiently improve the impact on receptors.

The limitation of this study is that, when running the CTM, both anthropogenic and natural emissions were used from the base year of 2015 to model future air quality. This approach poses the risk that, as air quality policies are implemented, only anthropogenic emissions may decrease in future years, potentially increasing the proportion of natural emissions. This could lead to changes in $PM_{2.5}$ concentration, and future research will address this by considering variations in natural emissions over time. Additionally, sensitivity tests on the predicted $PM_{2.5}$ concentrations based on reasonable adjustments to input data and model parameters are planned for future studies.

The estimates derived using the BenMAP formula can vary in reliability depending on the accuracy and relevance of the data used. The input data include air pollutant concentrations, baseline incidence rates, and estimated population. Although this study aimed to use the most reliable input data available, uncertainties in each data set can affect the final estimate of mortality changes. Additionally, uncertainties may arise from the construction, formulation, and inputs of the air quality model, which can affect the modeled concentrations of air pollutants. Despite these uncertainties, the significance of this study lies in its clear demonstration that analyzing the impact of future air quality on public health requires considering both $PM_{2.5}$ concentrations and population aging. The results of this study provide meaningful information for air quality management and public health protection.

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investigation, J.K., H.H. and B.K.; methodology, J.K., Y.J., S.J.Y. and J.-H.W.; project administration, J.-H.W.; resources, J.-H.W.; supervision, J.-H.W.; validation, J.K., Y.J. and Y.K.; visualization, J.K., Y.J. and B.K.; writing—original draft, J.K. and Y.J.; writing—review and editing, J.K., H.H. and J.-H.W. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Number of deaths cause by age in 2015.

Class	Disease	Age Group	Deaths	Population by Age	Death Rate
Mortality	Circulatory Diseases	0TO4	35	2,192,603	0.0016%
		5TO9	15	2,287,123	0.0007%
		10TO14	14	2,288,612	0.0006%
		15TO19	31	3,056,728	0.0010%
		20TO24	53	3,400,634	0.0016%
		25TO29	94	3,068,970	0.0031%
		30TO34	187	3,415,599	0.0055%
		35TO39	376	3,852,007	0.0098%
		40TO44	729	4,031,799	0.0181%
		45TO49	1207	4,369,603	0.0276%
		50TO54	1746	4,030,564	0.0433%
		55TO59	2585	4,076,050	0.0634%
		60TO64	2924	3,010,386	0.0971%
		65TO69	3597	2,179,524	0.1650%
		70TO74	5840	1,736,294	0.3363%
		75TO79	9711	1,418,480	0.6846%
		80TO84	12,256	880,699	1.3916%
		85TO89	10,715	398,827	2.6866%
		90UP	8262	157,808	5.2355%
	Respiratory Diseases	0TO4	33	2,192,603	0.0015%
		5TO9	11	2,287,123	0.0005%
		10TO14	9	2,288,612	0.0004%
		15TO19	10	3,056,728	0.0003%
		20TO24	12	3,400,634	0.0004%
		25TO29	26	3,068,970	0.0008%
		30TO34	33	3,415,599	0.0010%
		35TO39	53	3,852,007	0.0014%
		40TO44	84	4,031,799	0.0021%
		45TO49	168	4,369,603	0.0038%
		50TO54	336	4,030,564	0.0083%
		55TO59	552	4,076,050	0.0135%
		60TO64	935	3,010,386	0.0311%
		65TO69	1400	2,179,524	0.0642%
		70TO74	2618	1,736,294	0.1508%
		75TO79	4931	1,418,480	0.3476%
		80TO84	6742	880,699	0.7655%
		85TO89	6267	398,827	1.5714%
		90UP	5178	157,808	3.2812%

Table A2. Population in 2015 and projected population in 2020, 2025 and 2030 (KOSIS, 2017) (Unit: Persons).

Region		2015	2020	2025	2030
South Korea		51,529,338	51,973,817	52,609,988	52,941,342
A	Seoul	10,022,181	9,635,114	9,545,279	9,428,800
B	Incheon	2,925,815	2,978,706	3,079,506	3,151,654
C	Gyeonggi-do	12,522,606	13,220,552	13,644,535	13,900,568
D	Gangwon-do	1,549,507	1,531,889	1,549,909	1,569,101
E	Busan	3,513,777	3,396,020	3,341,609	3,281,203
F	Ulsan	1,173,534	1,172,306	1,185,090	1,188,098
G	Daegu	2,487,829	2,446,239	2,408,834	2,366,938
H	Gwangju	1,472,199	1,496,093	1,491,177	1,478,923
I	Daejeon	1,518,775	1,521,598	1,541,362	1,556,008
J	Sejong	210,884	377,391	428,161	472,914
K	Chungcheongnam-do	2,077,649	2,203,891	2,291,157	2,363,022
L	Chungcheongbuk-do	1,583,952	1,629,704	1,672,870	1,709,661
M	Gyeongsangnam-do	3,364,702	3,385,992	3,414,375	3,424,536
N	Gyeongsangbuk-do	2,702,826	2,684,814	2,690,815	2,693,747
O	Jeollanam-do	1,908,996	1,793,547	1,787,283	1,787,400
P	Jeollabuk-do	1,869,711	1,823,507	1,815,361	1,809,662
Q	Jeju	624,395	676,454	722,665	759,107

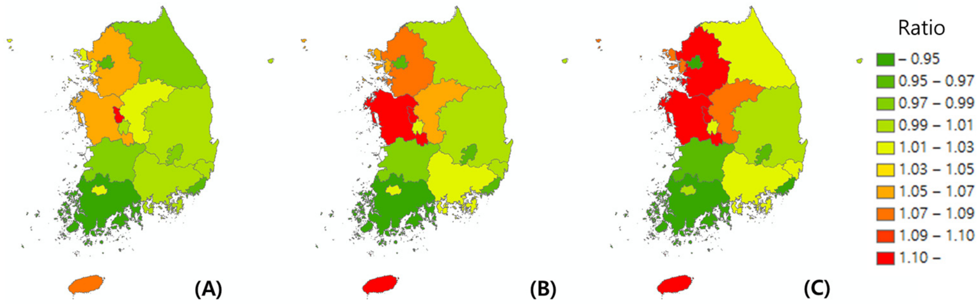

Figure A1. Population change rate by region compared to 2015 ((**A**): 2020, (**B**): 2025, (**C**): 2030).

Table A3. Comparison of observed concentration and model concentration (NFC-CPS) (unit: μg/m^3).

Year	2015			2020			2025		
NFC-CPS Scenario	Mod.	Obs.	Mod./ Obs.	Mod.	Obs.	Mod./ Obs.	Mod.	Obs. (2023)	Mod./ Obs.
South Korea	22.60	26.00	0.87	21.90	19.00	1.15	18.00	18.42	0.98
Seoul	27.70	23.00	1.20	27.30	21.00	1.30	25.40	19.75	1.29
Incheon	22.00	29.00	0.76	21.60	19.00	1.14	19.90	21.50	0.93
Gyeonggi-do	27.00	26.00	1.04	26.60	21.00	1.27	23.50	20.75	1.13
Gangwon-do	19.80	26.00	0.76	17.70	17.00	1.04	14.30	15.33	0.93
Busan	22.20	26.00	0.85	21.30	17.00	1.25	17.20	16.25	1.06
Ulsan	23.50	25.00	0.94	22.70	17.00	1.34	17.50	17.83	0.98
Daegu	24.30	26.00	0.93	23.10	20.00	1.16	17.30	17.67	0.98
Gwangju	25.50	26.00	0.98	24.80	18.00	1.38	19.80	16.83	1.18

Table A3. *Cont.*

Year	2015			2020			2025		
NFC-CPS Scenario	**Mod.**	**Obs.**	**Mod./ Obs.**	**Mod.**	**Obs.**	**Mod./ Obs.**	**Mod.**	**Obs. (2023)**	**Mod./ Obs.**
Daejeon	26.00	28.00	0.93	25.30	18.00	1.41	20.50	18.42	1.11
Sejong	20.50	-	-	20.10	20.00	1.01	16.60	18.67	0.89
Chungcheongnam-do	23.60	29.00	0.81	22.90	21.00	1.09	18.90	20.75	0.91
Chungcheongbuk-do	25.70	30.00	0.86	25.10	21.00	1.20	20.10	20.25	0.99
Gyeongsangnam-do	20.50	25.00	0.82	19.60	16.00	1.23	15.60	15.83	0.99
Gyeongsangbuk-do	21.40	28.00	0.76	20.80	17.00	1.22	16.20	18.00	0.90
Jeollanam-do	18.40	25.00	0.74	17.70	15.00	1.18	14.40	14.50	0.99
Jeollabuk-do	22.00	35.00	0.63	21.20	20.00	1.06	16.40	20.25	0.81
Jeju	14.40	23.00	0.63	14.40	15.00	0.96	12.20	13.75	0.89

Table A4. Comparison of observed concentration and model concentration (CLE-NPS) (unit: μg/m^3).

Year	2015			2020			2025		
CLE-NPS Scenario	**Mod.**	**Obs.**	**Mod./ Obs.**	**Mod.**	**Obs.**	**Mod./ Obs.**	**Mod.**	**Obs. (2023)**	**Mod./ Obs.**
South Korea	22.60	26.00	0.87	21.30	19.00	1.12	16.40	18.42	0.89
Seoul	27.70	23.00	1.20	26.80	21.00	1.28	23.70	19.75	1.20
Incheon	22.00	29.00	0.76	21.00	19.00	1.11	18.30	21.50	0.85
Gyeonggi-do	27.00	26.00	1.04	25.60	21.00	1.22	19.40	20.75	0.93
Gangwon-do	19.80	26.00	0.76	17.30	17.00	1.02	14.30	15.33	0.93
Busan	22.20	26.00	0.85	21.20	17.00	1.25	15.60	16.25	0.96
Ulsan	23.50	25.00	0.94	22.20	17.00	1.31	17.60	17.83	0.99
Daegu	24.30	26.00	0.93	22.80	20.00	1.14	16.70	17.67	0.95
Gwangju	25.50	26.00	0.98	24.60	18.00	1.37	18.20	16.83	1.08
Daejeon	26.00	28.00	0.93	24.60	18.00	1.37	18.30	18.42	0.99
Sejong	20.50	-	-	18.40	20.00	0.92	14.30	18.67	0.77
Chungcheongnam-do	23.60	29.00	0.81	21.60	21.00	1.03	16.80	20.75	0.81
Chungcheongbuk-do	25.70	30.00	0.86	24.00	21.00	1.14	18.80	20.25	0.93
Gyeongsangnam-do	20.50	25.00	0.82	18.80	16.00	1.18	14.30	15.83	0.90
Gyeongsangbuk-do	21.40	28.00	0.76	20.20	17.00	1.19	15.20	18.00	0.84
Jeollanam-do	18.40	25.00	0.74	17.40	15.00	1.16	13.10	14.50	0.90
Jeollabuk-do	22.00	35.00	0.63	20.80	20.00	1.04	15.30	20.25	0.76
Jeju	14.40	23.00	0.63	14.30	15.00	0.95	9.50	13.75	0.69

Table A5. Number of premature deaths due to cardi-vascular disease and other by PM2.5 by region, year and scenario (Not Considering Aging; Unit: Persons).

Year		**2015**	**2020**		**2025**		**2030**	
Scenario		**Base**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**
Cardio-vascular	South Korea	14,442	14,162	13,829	12,393	11,289	11,853	9250
	Seoul	2917	2763	2725	2573	2426	2428	1802
	Incheon	637	637	621	613	568	611	444
	Gyeonggi-do	3204	3333	3228	3095	2611	2997	2145
	Gangwon-do	487	435	426	363	362	347	292
	Busan	934	871	866	710	648	656	546
	Ulsan	216	209	205	168	168	156	140
	Daegu	647	609	603	464	449	430	371
	Gwangju	367	364	361	298	276	275	224
	Daejeon	380	373	364	313	284	294	240
	Sejong	45	79	73	76	66	80	63
	Chungcheongnam-do	755	780	742	683	615	672	540
	Chungcheongbuk-do	550	554	532	469	441	445	372
	Gyeongsangnam-do	877	849	818	696	644	665	561
	Gyeongsangbuk-do	950	920	898	737	696	693	611
	Jeollanam-do	677	615	607	507	465	494	388
	Jeollabuk-do	674	635	625	503	472	480	422
	Jeju	125	136	135	125	98	130	89
Other	South Korea	3972	3887	3788	3372	3055	3216	2479
	Seoul	798	755	744	700	657	659	480
	Incheon	171	171	166	163	151	162	116
	Gyeonggi-do	871	905	874	834	696	805	566
	Gangwon-do	137	121	119	100	100	96	80
	Busan	251	234	232	189	171	174	143
	Ulsan	55	53	52	42	42	39	35
	Daegu	174	163	161	123	118	113	97
	Gwangju	100	99	98	80	74	74	59
	Daejeon	103	101	98	84	75	78	63
	Sejong	12	22	20	21	18	22	17
	Chungcheongnam-do	216	222	211	193	173	189	151
	Chungcheongbuk-do	155	156	149	130	122	123	102
	Gyeongsangnam-do	241	233	224	189	174	180	151
	Gyeongsangbuk-do	268	259	253	206	194	193	169
	Jeollanam-do	193	175	173	143	131	139	109
	Jeollabuk-do	192	180	177	141	132	134	117
	Jeju	35	38	37	34	27	36	24

Table A6. Number of premature deaths due to cardi-vascular disease and other by PM2.5 by region, year and scenario (Considering Aging; Unit: Persons).

Year		**2015**	**2020**		**2025**		**2030**	
Scenario		**Base**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**	**NFC-CPS**	**CLE-NPS**
Cardio-vascular	South Korea	14,442	17,466	17,060	19,384	17,658	22,962	17,894
	Seoul	2917	3366	3319	4049	3817	4819	3575
	Incheon	637	801	781	986	915	1239	900
	Gyeonggi-do	3204	4155	4024	4912	4143	5953	4260
	Gangwon-do	487	534	523	560	558	657	553
	Busan	934	1105	1100	1176	1074	1378	1146
	Ulsan	216	268	262	279	280	333	298
	Daegu	647	783	775	772	747	895	772
	Gwangju	367	454	450	473	438	543	442
	Daejeon	380	471	460	506	458	592	485
	Sejong	45	72	67	88	76	117	91
	Chungcheongnam-do	755	917	872	979	881	1140	916
	Chungcheongbuk-do	550	671	646	703	661	802	670
	Gyeongsangnam-do	877	1040	1003	1061	982	1240	1046
	Gyeongsangbuk-do	950	1129	1102	1125	1062	1273	1123
	Jeollanam-do	677	751	740	754	692	863	678
	Jeollabuk-do	674	790	778	780	731	891	783
	Jeju	125	159	158	181	143	227	156

Table A6. *Cont.*

Year		2015	2020		2025		2030	
Scenario		Base	NFC-CPS	CLE-NPS	NFC-CPS	CLE-NPS	NFC-CPS	CLE-NPS
Other	South Korea	3972	4903	4779	5539	5021	6679	5143
	Seoul	798	937	923	1161	1090	1413	1030
	Incheon	171	220	214	277	256	356	255
	Gyeonggi-do	871	1155	1115	1393	1163	1721	1211
	Gangwon-do	137	152	149	162	161	193	161
	Busan	251	305	304	332	302	398	328
	Ulsan	55	70	69	75	75	92	82
	Daegu	174	217	214	217	210	257	220
	Gwangju	100	126	125	133	123	156	125
	Daejeon	103	131	128	143	129	170	138
	Sejong	12	20	18	24	21	33	25
	Chungcheongnam-do	216	267	253	288	258	338	269
	Chungcheongbuk-do	155	193	185	204	191	235	195
	Gyeongsangnam-do	241	291	280	300	277	356	299
	Gyeongsangbuk-do	268	326	318	328	309	375	330
	Jeollanam-do	193	218	214	221	202	256	199
	Jeollabuk-do	192	230	226	229	214	264	231
	Jeju	35	45	44	52	40	66	45

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