Environmental Pollution 336 (2023) 122405

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

# Quantifying the potential effects of air pollution reduction on population health and health expenditure in Taiwan☆

Yi-Hsuan Roger Chen[a,b], Wan-Chen Lee[c], Bo-Chen Liu[b], Po-Chieh Yang[d], Chi-Chang Ho[e], Jing-Shiang Hwang[e], Tzu-Hsuan Huang[b,f], Hsien-Ho Lin[b,g], Wei-Cheng Lo[h,i,*]

[a] Department of Environmental Health and Engineering, Johns Hopkins University, Baltimore, MD, USA
[b] Institute of Epidemiology and Preventive Medicine, College of Public Health, National Taiwan University, Taipei, Taiwan
[c] Institute of Environmental and Occupational Health Sciences, College of Public Health, National Taiwan University, Taipei, Taiwan
[d] Department of Industrial Economics, Tamkang University, Taipei, Taiwan
[e] Institute of Statistical Science, Academia Sinica, Taipei, Taiwan
[f] AbbVie Inc. North Chicago, Illinois, USA
[g] Global Health Program, College of Public Health, National Taiwan University, Taipei, Taiwan
[h] Master Program in Applied Epidemiology, College of Public Health, Taipei Medical University, Taipei, Taiwan
[i] Taipei Medical University Research Center of Urology and Kidney, Taipei Medical University, Taipei, Taiwan

ARTICLE INFO

*Keywords:*
$PM_{2.5}$
Comparative risk assessment
Disease burden
Healthcare expenditure
ARIMA model
Emission target

ABSTRACT

Air pollution, particularly ambient fine particulate matter ($PM_{2.5}$) pollution, poses a significant risk to public health, underscoring the importance of comprehending the long-term impact on health burden and expenditure at national and subnational levels. Therefore, this study aims to quantify the disease burden and healthcare expenditure associated with $PM_{2.5}$ exposure in Taiwan and assess the potential benefits of reducing pollution levels. Using a comparative risk assessment framework that integrates an auto-aggressive integrated moving average model, we evaluated the avoidable burden of cardiopulmonary diseases (including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and diabetes mellitus) and related healthcare expenditure under different air quality target scenarios, including status quo and target scenarios of 15, 10, and 5 μg/m$^3$ reduction in $PM_{2.5}$ concentration. Our findings indicate that reducing $PM_{2.5}$ exposure has the potential to significantly alleviate the burden of multiple diseases. Comparing the estimated attributable disease burden and healthcare expenditure between reference and target scenarios from 2022 to 2050, the avoidable disability-adjusted life years were 0.61, 1.83, and 3.19 million for the 15, 10, and 5 μg/m$^3$ target scenarios, respectively. Correspondingly, avoidable healthcare expenditure ranged from US$ 0.63 to 3.67 billion. We also highlighted the unequal allocation of resources and the need for policy interventions to address health disparities due to air pollution. Notably, in the 5 μg/m$^3$ target scenario, Kaohsiung City stands to benefit the most, with 527,368 disability-adjusted life years avoided and US$ 0.53 billion saved from 2022 to 2050. Our findings suggest that adopting stricter emission targets can effectively reduce the health burden and associated healthcare expenditure in Taiwan. Overall, this study provides policymakers in Taiwan with valuable insights for mitigating the negative effects of air pollution by establishing a comprehensive framework for evaluating the co-benefits of air pollution reduction on healthcare expenditure and disease burden.

## 1. Introduction

Long-term exposure to fine particulate matter ($PM_{2.5}$) is a major public health problem that may increase the risk of cardiometabolic disease, chronic obstructive pulmonary disease (COPD), and lung cancer (Karimi et al., 2019; Lo et al., 2022; Yazdi et al., 2019; Yuan et al., 2019). Over two-thirds of the global environmental burden is attributable to air pollution, including $PM_{2.5}$, which poses serious public health concerns

☆ This paper has been recommended for acceptance by Admir Créso Targino.

* Corresponding author. Master Program in Applied Epidemiology, College of Public Health, Taipei Medical University, No. 301, Yuantong Rd., Zhonghe Dist., New Taipei City, Taiwan.

*E-mail address:* nicholaslo@tmu.edu.tw (W.-C. Lo).

https://doi.org/10.1016/j.envpol.2023.122405
Received 29 May 2023; Received in revised form 12 August 2023; Accepted 16 August 2023
Available online 17 August 2023
0269-7491/© 2023 Elsevier Ltd. All rights reserved.

in aging societies (Atella et al., 2019; Landrigan et al., 2018; Lo et al., 2022; van Oostrom et al., 2016).

The cumulative effects of $PM_{2.5}$ exposure contribute to substantial economic and health burdens. He et al. (2023) conducted a study in Southwest China to estimate the economic burden associated with air pollutant exposure. Their findings revealed that $PM_{2.5}$ and other specific air pollutants were associated with an increased risk of pneumonia and bronchitis in children, with a specific lag time, resulting in significant financial burdens due to hospitalizations. Moreover, the COVID-19 pandemic has had a profound impact on various aspects of our lives, including increased demand for goods and transportation. Brusselaers et al. (2023) demonstrated that freight-related air pollution disproportionately affects vulnerable population groups, leading to higher health costs. Additionally, Zhang et al. (2022) highlighted the significant influence of health service factors on catastrophic healthcare expenditure, particularly when interacting with air pollution. Their study emphasized the spatial effects of air pollution on the economic burden of disease.

In recent years, driven by increasing awareness of environmental protection, many developed and developing countries have taken proactive measures to control air pollutant emissions from transportation and energy consumption, thereby resulting in a decrease in ambient air pollution levels (Ke et al., 2017). However, despite these efforts, air pollution inequality has been increasing in certain areas (Rosofsky et al., 2018). To address this problem, researchers have focused on the benefits of certain actions in specific locations. For example, Lai et al. (2020) evaluated the health benefits of 14 pollution control measures aimed at reducing point, mobile, and area sources of air pollution in Taiwan and discovered that implementing these measures outweighed the technology costs. Currently, the Environmental Protection Administration (EPA) of Taiwan has set the standard $PM_{2.5}$ annual mean concentration at 15 $\mu g/m^3$. However, Wang et al. (2021) estimated the toxicity of $PM_{2.5}$ at this level and suggested that the current standard may not be stringent enough to safeguard public health, emphasizing the need for regional considerations in adjusting the standard. The air quality standard in Taiwan has yet to meet the World Health Organization (WHO) Guidelines of 5 $\mu g/m^3$ (WHO, 2021) for annual mean exposure of $PM_{2.5}$. Therefore, evaluating the expected health benefits of achieving air quality targets in Taiwan may serve as a valuable incentive for authorities to work toward meeting these targets.

According to the 2019 Global Burden of Disease (GBD) study, exposure to $PM_{2.5}$ is a major contributor to disease burden in Taiwan, accounting for 4.47% of all related disease disability-adjusted life years (DALYs), 18.8% of cardiometabolic disease DALYs, 16.5% of COPD DALYs, and 16.8% of lung cancer DALYs (Ghosh et al., 2021). The GBD research, exemplified by Wilson et al. (2023), has proven to be highly valuable in identifying cardiovascular disease (CVD) risk factors in New Zealand. Through the utilization of the GBD results tool, this study successfully prioritized risk factor domains based on DALYs and simulated the potential benefits of interventions. The findings demonstrated that implementing these interventions could lead to substantial reduction in DALYs and financial burden of the healthcare system. However, despite the significant contributions of GBD research, there remains a need for more precise estimations at finer scales and future trend forecasts for various risks. Such information would greatly assist policymakers and stakeholders in formulating effective policies across different sectors of the country. Therefore, to estimate the mortality and morbidity burden of $PM_{2.5}$ exposure, researchers have used the comparative risk assessment (CRA) framework developed in the GBD study at the global, national, and subnational levels (Li et al., 2019; Lo et al., 2017; Xiao et al., 2021; Yang et al., 2021). For example, Chio et al. (2019) used a CRA model to estimate the annual mean $PM_{2.5}$ concentration increase in 19 cities and counties in Taiwan caused by a single coal-fired power plant, predicting an associated rise in $PM_{2.5}$-related mortality in nearby areas. Previous studies have focused on estimating the expenses and avoidable healthcare expenditure associated with changes in air pollution levels to better understand the costs and benefits of various energy transition and air pollution control strategies. Baldwin et al. (2021) projected that electrifying transportation in the United States could prevent 150,000 premature deaths and approximately $1.3 trillion in health and environmental expenditures by 2050.

Addressing air pollution requires collective efforts and cannot be achieved solely through individual actions; it necessitates the intervention of public authorities. By implementing emission targets as part of a comprehensive policy approach, improvements in health outcomes can be realized, along with a reduction in associated costs. These potential benefits serve as a compelling incentive for governments to prioritize and promote air pollution control. However, evidence regarding long-term estimates and projections of the disease burden and healthcare expenditures attributable to $PM_{2.5}$ exposure is still limited. Therefore, in this study, we used a CRA framework that integrates a time-based prediction model and well-established age-specific population projections to forecast the avoidable disease burden and healthcare expenditure associated with $PM_{2.5}$ exposure under various air quality target scenarios. Through this approach, we expect to provide a comprehensive understanding of regional heterogeneity in environmental health and the health co-benefits of air pollution control in Taiwan.

## 2. Materials and methods

In this study, we incorporated the CRA framework developed in the GBD study to estimate the disease burden attributable to $PM_{2.5}$ exposure and forecast the $PM_{2.5}$-related health and economic burdens of disease for various air quality goals. The analytical procedure of this study is illustrated in Fig. S1. The prediction analysis process was divided into assessments involving, first, $PM_{2.5}$ and, second, health indicators. We first used the current $PM_{2.5}$ concentration to estimate the population attributable fraction (PAF) of each city or country, and determined the nonattributable DALY rate by age group, year, and city. Subsequently, an ARIMA model was used to predict the trend of the nonattributable DALY rate until 2050, assuming a constant trend. $PM_{2.5}$ concentration under the current trend (status quo) is projected to 2050 with a log-linear model. The unattributable rate is divided by (1 - PAF) for each projected year to obtain the projected total DALY rate, which served as the baseline estimates of disease burden for scenario forecasting. As a next step, we multiplied the result by the projected PAF calculated under each air quality target scenario to obtain the attributable DALY rate, and to estimate the DALY count by multiplying the population projection by the National Development Institute. Finally, we obtained the avoidable DALY, and healthcare expenditures were calculated by subtracting the value of each scenario from the status quo scenario, serving as an indicator of health impact assessment.

### 2.1. $PM_{2.5}$ concentration data

Estimates of ambient $PM_{2.5}$ levels were obtained from a published prediction model (Ho et al., 2020). The model employed a two-step spatiotemporal approach, integrating data from air quality monitoring stations, land-use terms, meteorological data, and a network of 1882 microsensors in 2017. Daily mean $PM_{2.5}$ levels of all $3 \times 3$ $km^2$ were predicted at $3 \times 3$ km grids based on the microsensor data. We calculated population-weighted mean $PM_{2.5}$ concentrations and assigned them to each county. Estimated $PM_{2.5}$ levels in the grids were then used as predictors in the models to predict the monthly mean concentration of $PM_{2.5}$ at all grids in the previous year or subsequent year. The prediction procedures were implemented from 2017 back to 2001 and even earlier, and forward to 2021, generating monthly mean $PM_{2.5}$ concentrations for all the grids. The concentrations were calculated by averaging the grid levels that overlapped with each township for the study years. To forecast levels beyond 2021, a log-linear model was fitted. Population-weighted mean $PM_{2.5}$ concentrations were then calculated for each county, serving as inputs for PAF calculations. For the estimation of attributable disease burden, the 10-yr mean $PM_{2.5}$ concentrations were used as a cumulative exposure measure. For example, the mean $PM_{2.5}$ concentration during 2011–2020 was used to represent the exposure level of 2020. We also assumed that future $PM_{2.5}$ concentrations would continue their past trend and that no major climate events would occur.

### 2.2. PAF calculation

We used the county level as our study unit and selected five disease outcomes in the present study, including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and diabetes mellitus. To quantify the effect of $PM_{2.5}$ exposure on disease burden, we calculated the PAF of each county. PAF represents the proportion of disease burden that can be prevented by reducing $PM_{2.5}$ exposure to a lower risk level. We used the following formula to calculate the PAF of a specific disease attributed to air pollution exposure at the county level (Evans et al., 2013; Lo et al., 2017):

$$PAF_{c(i),j,k} = \frac{RR_{c(i),j,k} - 1}{RR_{c(i),j,k}} \tag{1}$$

where $c(i)$ is the annual mean concentration of air pollution exposure in city $i$ and $RR_{c(i),j,k}$ is the relative risk (RR) function of disease $j$ in age group $k$ according to the annual mean concentration of air pollution exposure in city $i$. The relative risk functions between ambient $PM_{2.5}$ and specific disease causes were obtained from the estimates of the 2019 GBD study (Vos et al., 2020). We adopted an integrated exposure response model which captured the nonlinear patterns in the association between pollutant concentration and corresponding disease causes, in accordance with high-quality cohort studies (Stanaway et al., 2018). Therefore, $PAF_{c(i),j,k}$ indicates that county $i$ is exposed to an attributable fraction for disease $j$ in age group $k$ at concentration $c(i)$.

### 2.3. Health metrics

In this study, two health metrics were estimated. DALYs were used to quantify the health impact caused by exposure to $PM_{2.5}$, while healthcare expenditure associated with specific disease outcomes was used to assess the economic burden attributable to $PM_{2.5}$ exposure. DALYs, a composite metric, encompass both years of life lost to premature death (YLL) and years of life lost to disability (YLD) (Murray et al., 2020). To estimate nonfatal and fatal disease burdens, we utilized data from the National Health Insurance Research Database (NHIRD) and the National Death Registry, respectively. years of life lost to premature death (YLL) and years of life lost to disability (YLD). We used the National Health Insurance Research Database (NHIRD) and National Death Registry data to estimate the nonfatal and fatal burdens of disease, respectively. Additionally, national insurance claim data were used to calculate healthcare expenditure, and a regression-based approach was applied to account for the effect of comorbidities. For the estimation of mortality and YLL, data from the national death registry were used and garbage codes were redistributed by using previous algorithms (Ng et al., 2020). Causes of death were coded according to the International Classification of Diseases, Ninth Revision (ICD-9th) before 2008, and the ICD-10th version thereafter. The diseases were defined using specific ICD codes, which are listed in Tables S1–S5 in Supplementary. Cause-specific ($a$) YLL was then calculated by multiplying the number of fatal cases ($N$) by the residual expected life expectancy ($e$) at the age ($k$) and sex ($s$) of death, utilizing the GBD life table:

$$\mathrm{YLL}_{a,s,k} = \sum N_{a,s,k} \times e_{a,s,k} \tag{2}$$

The NHIRD was utilized for estimating prevalence and YLD, as it contains individual-level information including date of birth, sex, date of diagnosis, date of death, relevant drug prescriptions, and surgical information. Prevalent cases of selected cardiopulmonary diseases generally were identified based on the presence of specific ICD codes, requiring either one inpatient diagnosis or two outpatient diagnoses (further details provided in Section 1 of the Supplementary. YLD was calculated by multiplying the prevalence of a sequela ($P_{j,k,s,a}$) multiplied by the disability weight ($DW_{i,s,a}$) associated with that sequela:

$$\mathrm{YLD}_{j,k,s,a} = \sum P_{j,k,s,a} \times DW_{j,k,s,a} \tag{3}$$

where $P_{j,k,s,a}$ and $DW_{j,k,s,a}$ are the health outcome $\mathrm{YLD}_{j,k,s,a}$ of sequela $j$ for age group $k$ and sex $s$ for disease $a$. The disability weight reflects the severity of the disability, ranging from 0 (complete health) to 1 (death) (Vos et al., 2020). In addition, the residence of prevalent cases was determined using a modified algorithm based on the most frequently visited medical facilities and registered residence, which was updated annually (additional details in Section 1 of the Supplementary) (Ku et al., 2018).

The claims recorded in the NHIRD were utilized to estimate direct medical costs, which encompassed all expenditures related to the treatment of selected cardiopulmonary diseases, which included the costs of outpatient visits, hospitalizations, laboratory tests, prescription drugs, surgery, and procedures. Healthcare expenditures were aggregated by primary diagnosis, age group, sex, place of residence, and year. Generally, the presence of comorbidities substantially affects healthcare expenses, which vary depending on the primary diagnosis. To account for this, a regression-based method was employed to adjust the expenditure data, providing an estimate of the costs attributable to each specific disease (Dieleman et al., 2016). For more details on the adjustment of healthcare expenditures, please refer to Section 2 in Supplementary.

### 2.4. Forecasting models and data analysis procedure

To forecast the impact of $PM_{2.5}$ on health and economic burden from 2022 to 2050, we assumed that the morbidity and mortality rates within each age group would be influenced solely by their respective time series, disregarding external events like COVID-19 during this period. Following the PAF calculation procedure mentioned earlier, we calculated the nonattributable DALY rate by age group, year, and location based on $PM_{2.5}$ concentration data spanning from 2000 to 2015. To predict the trend of the nonattributable DALY rate until 2050, we employed an ARIMA model (Kumar et al., 2020) in R software (version 4.1.0) (R Core Team, R., 2022). Specifically, we used the “auto.arima” function in the “forecast” package in our analysis (Dhamo & Puka, 2010; Hyndman et al., 2020). For more details on the model setting, please refer to Section 3.2 in Supplementary. Next, we divided the unattributable rate by $(1 - PAF_{c(i),j,k})$ for each year after the forecast, obtaining the total rate as the baseline for scenario forecasting. Finally, by multiplying the predicted $PAF_{c(i),j,k}$ of each scenario with the total rate during the base period to obtain the attributable rate. This value was further multiplied by future population data, sourced from a report by the National Development Council of Taiwan (National Development Council, 2022), to determine the absolute volume of attributable burden. For more details on ARIMA model setting and Taiwanese population forecasting, please refer to Sections 3.3 in Supplementary.

Four scenarios were employed to assess the potential impact of $PM_{2.5}$ control on health and economic burdens until 2050. The first scenario, known as the Status quo, maintained the same annual mean $PM_{2.5}$ concentration from 2022 to 2050 as in 2021. The second scenario, labeled Target 15, extended the forecast to 2050 with a maximum limit of 15 $\mu g/m^3$, aligning with Taiwan’s EPA standard. The third scenario, named Target 10, projected the forecast to 2050 with a maximum limit of 10 $\mu g/m^3$, in accordance with the WHO Guidelines of 2005. Lastly, the fourth scenario, referred to as Target 5, extended the forecast to 2050 with a maximum limit of 5 $\mu g/m^3$, following the latest WHO Guidelines of 2021 (WHO, 2021).

To address the impact of sampling variability and incorporate parameter uncertainty into the prediction models, statistical simulation procedures were employed. A total of 10,000 sets of $PM_{2.5}$ estimates, and corresponding RR were randomly selected from the prior normal distribution of RR and $PM_{2.5}$ concentrations. Subsequently, the sampled RR values were utilized to estimate the PAF and attributable burden for each county, stratified by age group. The mean values of the estimated PAFs served as the point estimates, and a ranking was performed on the resulting 10,000 PAFs and burdens attributable to $PM_{2.5}$ to determine the 95% confidence interval (CI) by considering the 2.5th and 97.5th percentiles of the ranked values, thus capturing the uncertainty associated with the estimates.

## 3. Results

### 3.1. $PM_{2.5}$ exposure levels

Fig. 1a illustrates the annual exposure levels by county in 2021, ranging from 7.70 μg/m$^3$ to 21.19 μg/m$^3$. Eastern Taiwan displayed low $PM_{2.5}$ concentrations, while central and southern Taiwan, particularly Tainan city, Kaohsiung city, and Pingtung county, exhibited high $PM_{2.5}$ concentrations. Although the national $PM_{2.5}$ concentrations decreased from 33.02 μg/m$^3$ in 2000 to 14.74 μg/m$^3$ in 2021 (Fig. 1b), the spatial pattern of $PM_{2.5}$ exposure remained consistent, with higher levels in central and southern Taiwan and lower levels in eastern Taiwan from 2000 to 2021. The $PM_{2.5}$ concentration data from 2000 to 2021 were used as input to forecast the annual exposure concentrations of each county with a log-linear model. Fig. 1b presents the forecasted national annual mean $PM_{2.5}$ concentrations across all scenarios. Based on the historical trend, it is expected that all counties and cities will meet Target 15 by 2025 and Target 10 by 2033.

### 3.2. Impacts on DALYs and healthcare expenditures

Table 1 shows the cumulative DALYs and healthcare expenditure attributable to $PM_{2.5}$ exposure for each projected decade in each scenario. By 2030, the health and economic burden attributable to $PM_{2.5}$ exposure in the four scenarios are comparable. The cumulative DALYs are estimated at 4.36 million, 4.29 million, 4.22 million, and 4.20 million DALYs, while the cumulative health expenditures amount to 5.32 billion US dollars (US$), 5.24 billion, 5.16 billion, and 5.13 billion for the Status quo, Target 15, Target 10, and Target 5 scenarios, respectively. However, as the projection period extends, different target scenarios gradually demonstrate significant differences in cumulative disease burden and healthcare expenditure. By 2050, the reference scenario (Status quo) is projected to accumulate 11.06 million DALYs (95% CI: 6.99–15.14) and approximately US$ 13.18 billion (95% CI: 8.28–18.08) in healthcare expenditures due to $PM_{2.5}$ exposure. The scenario with a target of 15 μg/m$^3$ set by the EPA is expected to accumulate 10.46 million DALYs (95% CI: 6.44–14.48) and approximately US$ 12.57 billion (95% CI: 7.73–17.38) in healthcare expenditures due to $PM_{2.5}$ exposure. The scenario with a counterfactual target of 10 μg/m$^3$ is projected to accumulate 9.23 million DALYs (95% CI: 5.46–13.01) and approximately US$ 11.16 billion (95% CI: 6.67–15.67) in healthcare expenditures due to $PM_{2.5}$ exposure. The optimal scenario with a target of 5 μg/m$^3$ suggested by the WHO Guidelines is expected to accumulate 7.88 million DALYs (95% CI: 4.51–11.25) and approximately US$ 9.51 billion (95% CI: 5.54–13.49) in healthcare expenditures due to $PM_{2.5}$

**Table 1**
Cumulative disability-adjusted life years and healthcare expenditures attributable to $PM_{2.5}$ exposure by scenarios.

| Disability-adjusted life years (million, 95% CI) | | | | |
|---|---|---|---|---|
| Year | Status quo | Target 15 | Target 10 | Target 5 |
| 2020 | 1.56 (1.07–2.05) | 1.56 (1.07–2.05) | 1.56 (1.06–2.05) | 1.56 (1.06–2.05) |
| 2030 | 4.36 (2.84–5.89) | 4.29 (2.77–5.81) | 4.22 (2.71–5.73) | 4.20 (2.69–5.70) |
| 2040 | 7.55 (4.82–10.29) | 7.23 (4.52–9.94) | 6.66 (4.07–9.26) | 6.28 (3.78–8.78) |
| 2050 | 11.06 (6.99–15.14) | 10.46 (6.44–14.48) | 9.23 (5.46–13.01) | 7.88 (4.51–11.25) |
| Healthcare expenditures (US$ billion, 95% CI) | | | | |
| Year | Status quo | Target 15 | Target 10 | Target 5 |
| 2020 | 1.93 (1.30–2.56) | 1.93 (1.30–2.56) | 1.93 (1.30–2.56) | 1.93 (1.30–2.56) |
| 2030 | 5.32 (3.43–7.20) | 5.24 (3.36–7.14) | 5.16 (3.29–7.04) | 5.13 (3.26–7.00) |
| 2040 | 9.05 (5.72–12.38) | 8.71 (5.42–12.01) | 8.08 (4.94–11.20) | 7.60 (4.59–10.61) |
| 2050 | 13.18 (8.28–18.08) | 12.57 (7.73–17.38) | 11.16 (6.67–15.67) | 9.51 (5.54–13.49) |

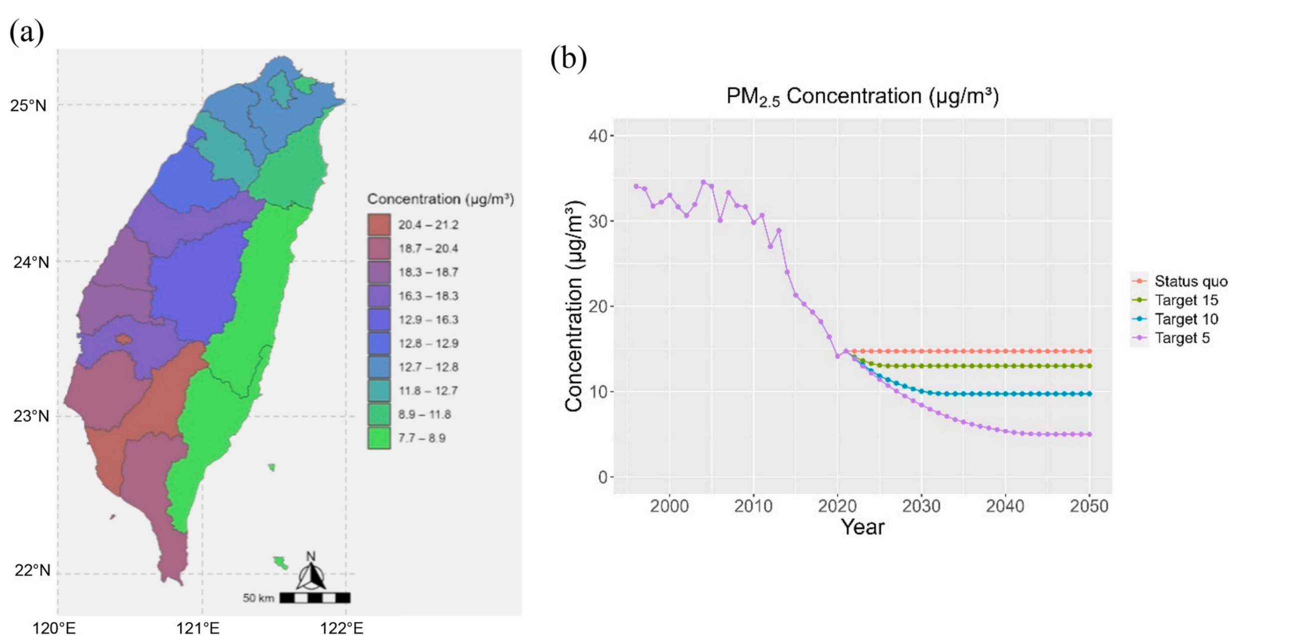


**Fig. 1.** The overall $PM_{2.5}$ concentration: (a) Geographic distribution of $PM_{2.5}$ concentrations in 2021; (b) Trends of national $PM_{2.5}$ concentrations by scenario.

exposure.

Avoidable disease burden refers to the difference in the estimated attributable disease burden between each $PM_{2.5}$ target scenario and the current scenario. In this study, we evaluated the estimates of Taiwan's avoidable disease burden and healthcare expenditures in 2050 in the Target 15, Target 10, and Target 5 scenarios. Fig. 2 presents the cumulative avoidable disease burden and healthcare expenditures, which refers to the difference in the estimated attributable disease burden between each $PM_{2.5}$ target scenario and the Status quo scenario. The results indicated that the avoidable disease burden was 0.61 million DALYs (95% CI: 0.55–0.66) in the Target 15 scenario, 1.83 million DALYs (95% CI: 1.53–2.12) in the Target 10 scenario, and 3.19 million DALYs (95% CI: 2.48–3.89) in the Target 5 scenario. In addition, the avoidable healthcare expenditure was US$ 0.63 billion (95% CI: 0.55–0.70) in the Target 15 scenario, US$ 2.02 billion (95% CI: 1.61–2.42) in the Target 10 scenario, and US$ 3.67 billion (95% CI: 2.74–4.59) in the Target 5 scenario. These results suggest that Taiwan still has ample opportunity to improve population health and reduce related health expenditures through air quality control policies.

### 3.3. Spatial difference

Our prediction model also estimated the spatial variations in attributable disease burden and healthcare expenditures among counties and cities under different air quality target scenarios. Among the four scenarios considered, Kaohsiung City was projected to have the highest cumulative DALYs by 2050, with an estimated 1.11 million DALYs (95% CI: 0.75–1.4) in the Status quo scenario, whereas New Taipei City was projected to have the highest cumulative healthcare expenditures, with US$ 2.09 billion (95% CI: 1.24–2.93). Although the number of DALYs and healthcare expenditures appeared to be concentrated in northern and southern Taiwan, the results varied when analyzed in terms of DALY rate and healthcare expenditure per capita. Yunlin County had the highest DALY rate, at 2475.18 DALYs per 100,000 population (95% CI: 1560.83–3390.87) in the Target 15 scenario, whereas Hsinchu City had the lowest DALY rate, at 941.52 DALYs per 100,000 population (95% CI: 507.75–1375.14). In terms of attributable healthcare expenditures, Chiayi City had the highest healthcare expenditure per capita, at US$ 22.86 (95% CI: 15.01–30.69) in the Target 15 scenario, whereas Hsinchu City had the lowest healthcare expenditure per capita, at US$ 10.03 (95% CI: 5.34–14.73) in the Target 5 scenario. These findings indicated that both central and southwestern Taiwan were the regions most affected by ambient air pollution. For a detailed geographic distribution of the effect of each scenario on disease burden and healthcare expenditures, please refer to the map in Supplementary (Section 4.5, Fig. S7).

Fig. 3 presents the spatial differentiation of the potential benefits in terms of avoided DALYs and healthcare expenditures if the target levels of $PM_{2.5}$ exposure are achieved. The results highlighted three metropolitan areas in Taiwan, Kaohsiung City, Tainan City, and New Taipei City, as having the greatest potential for reducing the disease burden associated with air pollution. In the Target 5 scenario, Kaohsiung City would derive the most significant health benefits, with an estimated avoidance of 527,368 DALYs (95% CI: 431,783–621,548) and healthcare expenditures savings of US$ 0.53 billion (95% CI: 0.41–0.66).

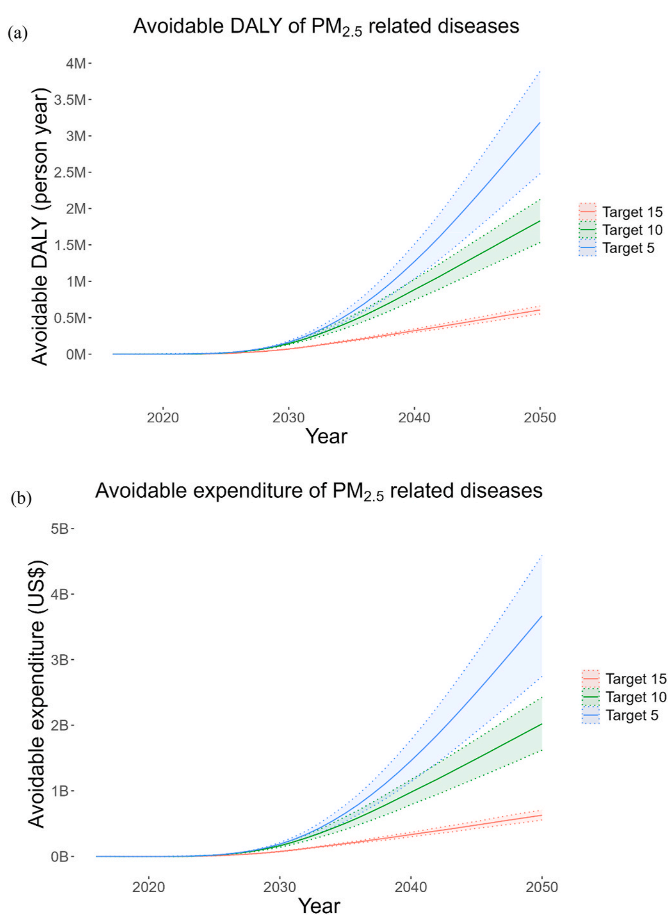


**Fig. 2.** The potential health benefits in each scenario projection. The cumulative avoidable DALYs (a) and health expenditures (b) in Target 15, Target 10, and Target 5 scenarios. Solid lines indicate the estimates of cumulative health burden, and dotted lines indicate 95% confidence interval.

## 4. Discussion

In this study, we developed a predictive model that integrates the CRA framework to forecast the health effects and healthcare costs resulting from long-term $PM_{2.5}$ exposure in Taiwan. Our findings indicate that reducing ambient air pollution in Taiwan would considerably decrease disease burden and healthcare expenditures. By 2030, the simulated predictions of the four air quality target scenarios reveal no significant difference in the disease burden associated with $PM_{2.5}$ exposure. However, considering the cumulative effects of long-term exposure, the impact will become significant. Extrapolating these trends to 2050, it is clear that sustained efforts to mitigate $PM_{2.5}$ pollution will lead to even greater benefits in terms of reducing healthcare expenditures and improving overall population health. Specifically, the Target 5 scenario would achieve the greatest health benefits, with 3.19 million DALYs avoided (95% CI: 2.48–3.89) and US$ 3.67 billion of expenditure saved from 2016 to 2050 (95% CI: 2.74–4.59). Our findings underscore the need for effective policy measures and actions to improve air quality and reduce the disease burden due to ambient air pollution in Taiwan.

In addition, our analysis revealed significant geographic disparities in $PM_{2.5}$ exposure and its associated disease burden in Taiwan. Metropolitan areas such as Kaohsiung City, Tainan City, and New Taipei City exhibit the highest health benefits in terms of avoidable DALYs and healthcare expenditures. Notably, central and southwestern regions experience the most severe impact, characterized by high DALY rates and healthcare expenditures per capita (see more detailed information in Tables S6–S7). Several global studies have reported an uneven spatial distribution of air pollution health risks, whether through population-level or individual-level exposure assessments (Huang et al., 2019; Martenies et al., 2018; Romero-Lankao et al., 2013). Exposure to $PM_{2.5}$ in central and southwestern Taiwan places residents of these regions at an increased risk for IHD, stroke, lung cancer, COPD, and DM. These variations are attributable to differences in population size, urbanization, air pollutant emissions, and geographical location. However, the differences in $PM_{2.5}$ exposure and its health effects across Taiwan underscore major environmental and health disparities. For instance, eastern counties have the lowest air pollution, whereas Yunlin County

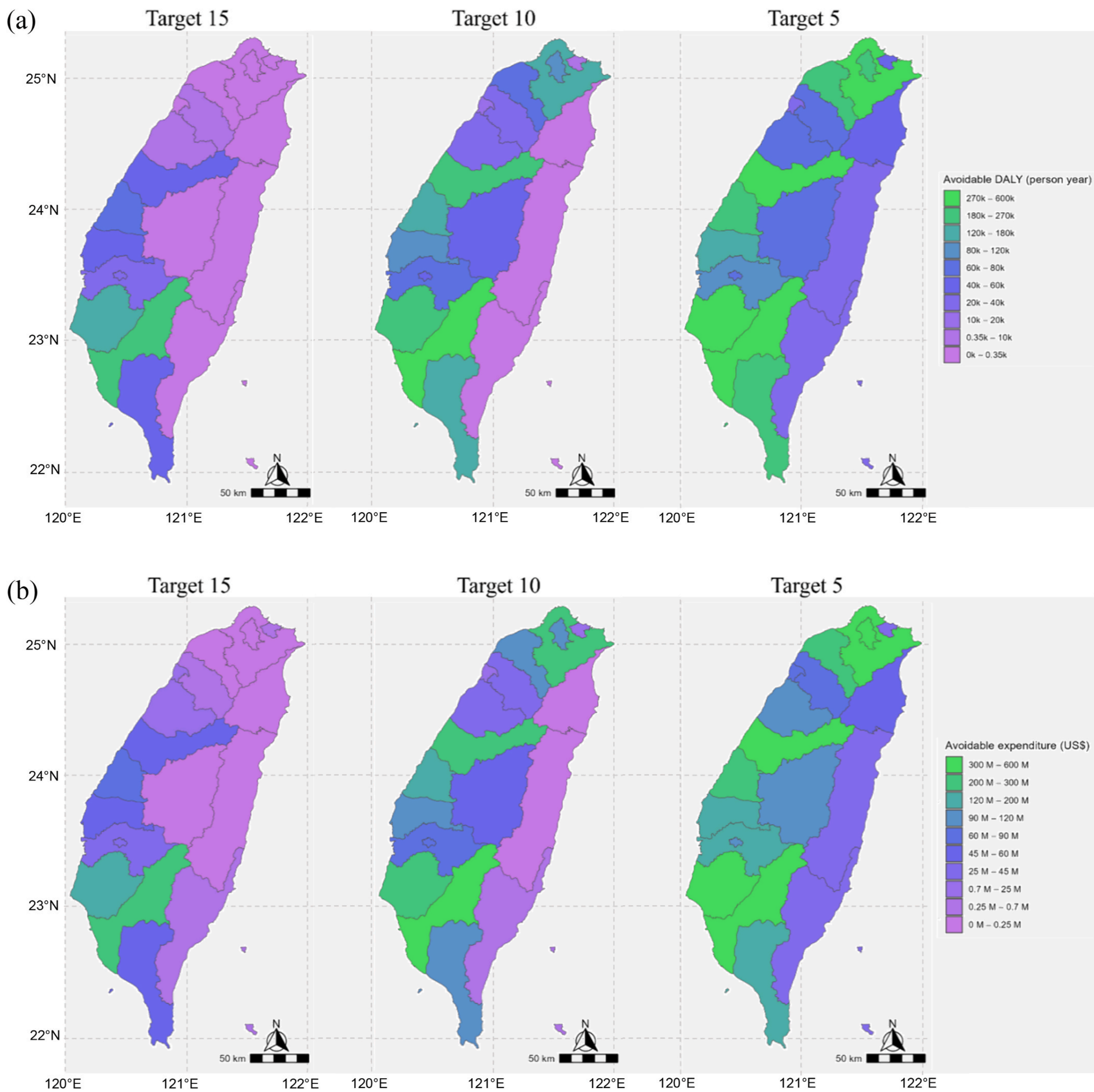


**Fig. 3.** The geographical distribution of avoidable health burden due to $PM_{2.5}$ reduction across scenario projection. The cumulative avoidable DALYs (a) and health expenditures (b) from 2022 to 2050.

and Kaohsiung City have the highest air pollution. Although air quality appears to be improving nationally, no encouraging results have yet been reported.

In Taiwan, each city has its own challenges in facing air pollution, and the proportion of emission sources in each city is different (Taiwan Environmental Protection Administration, 2023; Kaohsiung City Government, 2022; Taichung City Government, 2022). For instance, both central and southwestern regions of Taiwan have high levels of $PM_{2.5}$ exposure, primarily due to energy-intensive industrial areas, such as emissions from coal-fired power plants and heavy industrial factories (Lin et al., 2020). The impact of stationary pollution sources is quite important. According to Wu et al. (2021), coal-fired power plants and petrochemical industries are major sources of air pollution in central Taiwan. Also, Liang et al. (2023) estimated the annual incidence rate growth rate of respiratory-related diseases, emphasizing the considerable effect of fine particulate matter exposure on respiratory disease incidence, particularly in urban areas compared to rural areas. Over the past few decades, Kaohsiung City, a seaport city in southern Taiwan, has been the hub of heavy industry, which has affected not only the city itself but also its neighboring counties and cities. There is still a lot of room for improvement in the south-central region in order to achieve a health status comparable to other regions. Therefore, a regional strategy must be developed to control the concentrations of air pollution from all sources in the south-central region to reduce $PM_{2.5}$ exposure of residents.

Taiwan's standard annual mean $PM_{2.5}$ concentration is currently set at 15 μg/m$^3$, which is still far from the optimal WHO Guidelines of 5 μg/m$^3$. Therefore, to address the complex and urgent problem of air pollution and health, we urge a coordinated multisectoral effort involving the Ministry of Health and Welfare, the EPA, and the Ministry of Economy. In an effort to address this problem, the EPA has formulated 58 sub laws and regulations, which are subject to review and revision depending on actual requirements. To expedite the improvement of air quality, the EPA developed the Air Pollution Prevention and Control Plan (2020–2023) to promote four major aspects of air pollution control: stationary pollution source control, mobile pollution source control, and policy support. By 2023, the annual mean $PM_{2.5}$ concentration is expected to be 15 μg/m$^3$ if the relevant ministries and local government agencies work in close coordination. However, the international community has already made major strides in this area, and Taiwan must pursue a more ambitious goal.

Although previous studies on the health effects of air pollution have largely focused on morbidity and mortality, the associated healthcare expenditures have been rather overlooked. Healthcare expenditures serve as a universal language that is widely understood across various fields. Williams et al. (2020) discovered that high-income countries spend over 300 times more on diabetes-related health matters than do low-income countries. Du et al. (2021) analyzed the healthcare expenditures attributable to $PM_{2.5}$ in Jing-Jin-Ji and their share in gross domestic product. The study found that the healthcare expenditures related to $PM_{2.5}$ pollution accounted for approximately 2.15% of the region's GDP. In addition, Xie et al. (2023) used data from China in 2016 and 2017 to assess the economic impact of $PM_{2.5}$ pollution on healthcare spending. They found that each 10 μg/m$^3$ increase in $PM_{2.5}$ concentrations was associated with a significant increase in monthly costs of lower respiratory infection, coronary heart disease, and stroke. However, the impact of air pollution control on healthcare expenditures requires longer-term investigations. Haseeb et al. (2019) investigated the relationship between environmental pollution, healthcare expenditures, and economic growth and reported that the effect of environmental pollution on healthcare expenditures may not be immediate. Khan et al. (2020) reported that increased public health spending and poor environmental performance may negatively affect economic growth and labor productivity. Therefore, by analyzing healthcare expenditures, policymakers can better plan and allocate resources to achieve sustainable development goals, energy policies, and pollution control measures.

In Taiwan, the exploration of the relationship between air pollution and healthcare expenditures are relatively limited, representing a missed opportunity, as healthcare expenditures can serve as an indicator of policy effectiveness. The primary objective of public health is to enhance health outcomes and prevent disease. Therefore, if policies targeting air pollution reduction yield a decline in disease burden and healthcare expenditures, they can bolster confidence in environmental protection measures. Moreover, examining the geographical distribution of attributable healthcare expenditures can unveil regions burdened with high disease prevalence and limited medical resources. This analysis enables the government to allocate resources strategically, mitigating health inequality and promoting equitable access to healthcare services.

According to our results, the most stringent scenario for reducing $PM_{2.5}$ exposure, known as Target 5, has the potential to yield substantial health benefit of 3.19 million DALYs (95% CI: 2.48–3.89) avoided and an expenditure reduction of US\$ 3.67 billion (95% CI: 2.74–4.59) by 2050. These findings emphasize the importance of setting ambitious targets and implementing effective policies to reduce air pollution and safeguard public health. By adopting the Target 5 scenario, Taiwan can substantially improve the health and well-being of its citizens and serve as an example in promoting sustainable development and environmental protection. Therefore, we strongly urge the government to prioritize air quality improvement measures and commit to achieving the most stringent target as early as possible.

Recognizing the significance of controlling long-term $PM_{2.5}$ exposure in Taiwan for public health, several emerging technologies hold promise in reducing air pollutants. Among these, carbon capture technology, blue hydrogen, and wind power demonstrate significant potential. Carbon capture technologies aim to capture and store carbon dioxide emissions from various sources, such as power plants and industrial facilities, potentially mitigating the formation of $PM_{2.5}$ and reduce greenhouse gas emissions. Likewise, blue hydrogen produced from natural gas through carbon capture and storage offers an opportunity to transition to clean energy, reducing reliance on fossil fuels. However, it is important to note that current studies, such as Marks (2019), indicate relatively low net capture rates of $CO_2$-equivalent emissions in both the short and long term. On the other hand, substituting wind power for coal without carbon capture has shown considerable potential in reducing $CO_2$-equivalent emissions, air pollution, and overall societal costs. By examining these technologies, their effectiveness, cost implications, and potential synergies with existing air pollution control measures can be better understood. In addition to the introduction of new control technologies, previous studies have shown slow declines in air pollution, attributed to improvements in transportation systems in Taiwan (Wong et al., 2023). We believe that with corresponding technological advancements and continued improvements in the future, it's expected that the downward trends in air pollution will persist. Our model also hints at the possibility of achieving lower concentrations of air pollution in the future with the assistance of new technologies. Furthermore, the work of Coccia and Bontempi (2023) emphasizes that the development of new technologies focused on pollutant elimination can facilitate co-evolutionary growth pathways and contribute positively to the transition towards a circular and sustainable economy. These technological advancements can provide valuable support for policymakers in making informed decisions regarding research and development investments, ultimately leading to fruitful technology directions that align with environmental goals and promote sustainable development. This highlights the potential for significant improvements in air quality through technological advancements and underscores the importance of continued efforts in developing and implementing effective pollution control measures.

Overall, this study has several strengths that enhance its contribution to the understanding of the effects of air pollution on health and healthcare expenditures in Taiwan. Firstly, the utilization of the GBD research framework and the adoption of DALYs as an indicator allowed for a comprehensive evaluation of the burden of air pollution–related diseases. Secondly, the analysis of healthcare expenditures provided valuable insights into resource allocation and reflected the commitment of local governments to long-term medical treatment of related diseases. Lastly, the results shed light on the uneven distribution of attributable disease burden across different geographical regions, highlighting the potential health inequality. These insights can inform policy decisions aimed at reducing air pollution–related diseases and promoting equitable access to healthcare resources.

However, this study also has several limitations. The estimation of nonfatal burden of disease and healthcare expenditures relied on data from the NHIRD, which includes registration files and original reimbursement claims data. Although previous studies have verified the coding validity of the NHIRD, the possibility of disease misclassification or coding errors cannot be completely ruled out (Cheng et al., 2015; Ho et al., 2018; Kao et al., 2018; Lin et al., 2005). The use of Airbox sensors to estimate $PM_{2.5}$ concentrations may be limited due to the lack of information on sampling height above the ground. In addition, the GBD classification did not differentiate between acute and chronic ischemic manifestations in IHD, limiting the ability to discern between these subtypes (Khan et al., 2020). Moreover, the relative risks for air pollution and outcomes in our analysis were based on systematic reviews of studies from various countries, and the applicability of these relative risks to Taiwan might be uncertain. Also, we assumed that the prediction of PAFs in the unattributable disease rate was constant may introduce additional uncertainty. The aggregation of each 5-yr age group into four age groups for future predictions may have reduced precision. Furthermore, our analysis considered $PM_{2.5}$ exposure exclusively and did not account for other air pollutants. In addition, we employed an ARIMA model to predict the unattributable disease burden rate and per capita unattributable healthcare expenditures, which primarily considers the time series itself. We believe that existing trends can provide us with a credible source of information. Choo et al. (2023) also mentioned that the number of past disease cases has a significant impact on the current number of cases, indicating a common change in the number of cases. While this simplification of the forecasting process may overlook certain factors, it can still provide a useful evaluation of general policies or standards. For instance, the study conducted by (Vyas et al., 2023) explored the relationship between toxic air pollution, healthcare expenditures, and India's GDP using a comprehensive dataset spanning 44 years and employing various models. The findings revealed that the association between these variables is complex and highlights the challenges of considering real-world dynamics. These results serve as a reminder that formulating effective strategies requires careful consideration and cautious interpretation, it can be challenging to provide policymakers with concise and straightforward recommendations. We acknowledge that there are inherent uncertainties associated with the PAF and ARIMA models used in this study. While the research primarily focuses on parameter uncertainties based on past evidence, it should be recognized that uncertainties related to broader environmental factors, such as technological advancements and economic trends, are challenging to analyze and may not be addressed adequately within the scope of this model. The primary objective of this research is not to provide precise estimates, but rather to offer a general direction and emphasize the importance of considering the long-term effects of disease burden, even if new technologies are developed to mitigate the impacts of $PM_{2.5}$. In this context, the research remains valuable in providing insights and informing decision-making processes. Therefore, although the ARIMA model may not capture all the complexities of the real-world scenario, it can still offer valuable insights into the potential future trend of $PM_{2.5}$ concentrations and serve as a starting point for policymakers to make informed decisions.

## 5. Conclusion

In this study, we assess the impact of $PM_{2.5}$ reductions on population health and healthcare spending in Taiwan. Our projections reveal that maintaining the current status quo could lead to 11.06 DALYs and approximately US$13.18 billion in healthcare spending by 2050. However, embracing ambitious targets, such as the 5 $\mu g/m^3$ recommended by the WHO guidelines for $PM_{2.5}$ concentrations, could significantly reduce disease burden and associated healthcare costs. We identify notable regional variations in $PM_{2.5}$ exposure and related health impact, with the central and southwestern regions most affected. Addressing these disparities requires targeted interventions and policies.

While our study relies on strong assumptions enabling efficient estimation of population health impacts, we acknowledge escalating complexities as more parameters are considered. The PAF algorithm's quantitative estimates have limitations in addressing specific questions. Recognizing study limitations, including modeling uncertainties and challenges in incorporating technology advancements and economic trends, is crucial. Thus, while our study sheds light on potential health benefits, refined methodologies in future research are essential for nuanced understanding. In conclusion, our study enhances the understanding of potential health and economic co-benefits of $PM_{2.5}$ pollution control in Taiwan. The findings provide evidence-based guidance for policymakers to prioritize air quality improvement and technology advancement, fostering population health and sustainable healthcare practices.

## Credit author statement

All authors contributed extensively to the work presented in this paper. W.C. Lo, W.C. Lee, and H.H. Lin conceived and designed the study. C.C. Ho and J.S. Hwang provided exposure data. Y.H. Chen, B.C. Liu, T.H. Huang, and P.C. Yang did the data analysis and prepared the figures and tables. J.S. Hwang, W.C. Lee, and H.H. Lin provided the comments. Y.H. Chen and W.C. Lo wrote the manuscript. All authors contributed to the interpretation of data and the revision of the manuscript and approved the final manuscript.

## 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.

## Acknowledgments

This work was supported by grants from the Sustainability Science Research Program, Academia Sinica in Taiwan (project grants AS–SS–107-01), the Higher Education Sprout project, Ministry of Education in Taiwan (project grant NTU-CC-108L891601), and the Foresight 2050: Developing a Decision Support System for a Sustainability Transition of Taiwan (IV) (MOST-110-3011-F002-001). We would like to express our sincere appreciation for the financial support provided by these projects. It has allowed us to pursue our research goals and contribute to the field of sustainability science. This research was approved by the Institutional Review Board on Biomedical Science Research of Academia Sinica (AS-IRB02-107267).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.122405.

## References

Atella, V., Piano Mortari, A., Kopinska, J., Belotti, F., Lapi, F., Cricelli, C., Fontana, L., 2019. Trends in age-related disease burden and healthcare utilization. Aging Cell 18 (1), e12861.

Baldwin, S., Myers, A., O'Boyle, M., Wooley, D., 2021. Accelerating Clean, Electrified Transportation by 2035: Policy Priorities. Policy.

Brusselaers, N., Macharis, C., Mommens, K., 2023. The health impact of freight transport-related air pollution on vulnerable population groups. Environ. Pollut. 329, 121555.

Cheng, C.-L., Chien, H.-C., Lee, C.-H., Lin, S.-J., Yang, Y.-H.K., 2015. Validity of in-hospital mortality data among patients with acute myocardial infarction or stroke in National Health Insurance Research Database in Taiwan. Int. J. Cardiol. 201, 96–101.

Chio, C.-P., Lo, W.-C., Tsuang, B.-J., Hu, C.-C., Ku, K.-C., Chen, Y.-J., Lin, H.-H., Chan, C.-C., 2019. Health impact assessment of PM2. 5 from a planned coal-fired power plant in Taiwan. J. Formos. Med. Assoc. 118 (11), 1494–1503.

Choo, E.L.W., Janhavi, A., Koo, J.R., Yim, S.H., Dickens, B.L., Lim, J.T., 2023. Association between ambient air pollutants and upper respiratory tract infection and pneumonia disease burden in Thailand from 2000 to 2022: a high frequency ecological analysis. BMC Infect. Dis. 23 (1), 379.

Coccia, M., Bontempi, E., 2023. New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment. Environ. Res. 229, 115938.

Dhamo, E., Puka, L., 2010. Using the R-Package to Forecast Time Series: ARIMA Models and Application. INTERNATIONAL CONFERENCE Economic & Social Challenges and Problems.

Dieleman, J.L., Baral, R., Birger, M., Bui, A.L., Bulchis, A., Chapin, A., Hamavid, H., Horst, C., Johnson, E.K., Joseph, J., 2016. US spending on personal health care and public health, 1996-2013. JAMA 316 (24), 2627–2646.

Du, P., Wang, J., Niu, T., Yang, W., 2021. PM2. 5 prediction and related health effects and economic cost assessments in 2020 and 2021: case studies in Jing-Jin-Ji, China. Knowl. Base Syst. 233, 107487.

Evans, J., van Donkelaar, A., Martin, R.V., Burnett, R., Rainham, D.G., Birkett, N.J., Krewski, D., 2013. Estimates of global mortality attributable to particulate air pollution using satellite imagery. Environ. Res. 120, 33–42.
Ghosh, R., Causey, K., Burkart, K., Wozniak, S., Cohen, A., Brauer, M., 2021. Ambient and household PM2. 5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories. PLoS Med. 18 (9), e1003718.
Haseeb, M., Kot, S., Hussain, H.I., Jermsittiparsert, K., 2019. Impact of economic growth, environmental pollution, and energy consumption on health expenditure and R&D expenditure of ASEAN countries. Energies 12 (19), 3598.
He, Y., Jiang, W., Gao, X., Lin, C., Li, J., Yang, L., 2023. Short-term effects and economic burden of air pollutants on acute lower respiratory tract infections in children in Southwest China: a time-series study. Environ. Health 22 (1), 1–11.
Ho, T.-W., Ruan, S.-Y., Huang, C.-T., Tsai, Y.-J., Lai, F., Yu, C.-J., 2018. Validity of ICD9-CM codes to diagnose chronic obstructive pulmonary disease from National Health Insurance claim data in Taiwan. Int. J. Chronic Obstr. Pulm. Dis. 3055–3063.
Ho, C.-C., Chen, L.-J., Hwang, J.-S., 2020. Estimating ground-level PM2. 5 levels in Taiwan using data from air quality monitoring stations and high coverage of microsensors. Environ. Pollut. 264, 114810.
Huang, G., Zhou, W., Qian, Y., Fisher, B., 2019. Breathing the same air? Socioeconomic disparities in PM2. 5 exposure and the potential benefits from air filtration. Sci. Total Environ. 657, 619–626.
Hyndman, R.J., Athanasopoulos, G., Bergmeir, C., Caceres, G., Chhay, L., O'Hara-Wild, M., Petropoulos, F., Razbash, S., Wang, E., 2020. Package 'forecast'. https://cran.r-project.org/web/packages/forecast/forecast.pdf.
Kao, W.H., Hong, J.H., See, L.C., Yu, H.P., Hsu, J.T., Chou, I.J., Chou, W.C., Chiou, M.J., Wang, C.C., Kuo, C.F., 2018. Validity of cancer diagnosis in the national health insurance database compared with the linked national cancer registry in taiwan. Pharmacoepidemiol. Drug Saf. 27 (10), 1060–1066.
Kaohsiung City Government, 2022. 2022 Kaohsiung City Voluntary Local Review. Kaohsiung City: Kaohsiung City Government Retrieved from. https://ksepb.kcg.gov.tw/FileDownLoad/FileUpload/20221228153710793712.pdf.
Karimi, A., Shirmardi, M., Hadei, M., Birgani, Y.T., Neisi, A., Takdastan, A., Goudarzi, G., 2019. Concentrations and health effects of short-and long-term exposure to PM2. 5, NO2, and O3 in ambient air of Ahvaz city, Iran (2014–2017). Ecotoxicol. Environ. Saf. 180, 542–548.
Ke, W., Zhang, S., He, X., Wu, Y., Hao, J., 2017. Well-to-wheels energy consumption and emissions of electric vehicles: mid-term implications from real-world features and air pollution control progress. Appl. Energy 188, 367–377.
Khan, M.A., Hashim, M.J., Mustafa, H., Baniyas, M.Y., Al Suwaidi, S.K.B.M., AlKatheeri, R., Alblooshi, F.M.K., Almatrooshi, M.E.A.H., Alzaabi, M.E.H., Al Darmaki, R.S., 2020. Global epidemiology of ischemic heart disease: results from the global burden of disease study. Cureus 12 (7).
Ku, L., Li, C., Li, C., 2018. The establishment and application of healthcare utilization database in Taiwan. J. Health Sci. 2018, 11–23.
Kumar, M., Patel, A.K., Shah, A.V., Raval, J., Rajpara, N., Joshi, M., Joshi, C.G., 2020. First proof of the capability of wastewater surveillance for COVID-19 in India through detection of genetic material of SARS-CoV-2. Sci. Total Environ. 746, 141326.
Lai, H.-C., Hsiao, M.-C., Liou, J.-L., Lai, L.-W., Wu, P.-C., Fu, J.S., 2020. Using costs and health benefits to estimate the priority of air pollution control action plan: a case study in Taiwan. Appl. Sci. 10 (17), 5970.
Landrigan, P.J., Fuller, R., Acosta, N.J., Adeyi, O., Arnold, R., Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., 2018. The Lancet Commission on pollution and health. Lancet 391 (10119), 462–512.
Li, T., Guo, Y., Liu, Y., Wang, J., Wang, Q., Sun, Z., He, M.Z., Shi, X., 2019. Estimating mortality burden attributable to short-term PM2. 5 exposure: a national observational study in China. Environ. Int. 125, 245–251.
Liang, C.-J., Lin, P.-Y., Chen, Y.-C., Liang, J.-J., 2023. Effects of regional air pollutants on respiratory diseases in the basin metropolitan area of central Taiwan. Sustainable Environment Research 33 (1), 1.
Lin, C.-C., Lai, M.-S., Syu, C.-Y., Chang, S.-C., Tseng, F.-Y., 2005. Accuracy of diabetes diagnosis in health insurance claims data in Taiwan. J. Formos. Med. Assoc. 104 (3), 157–163.
Lin, W.-Y., Hsiao, M.-C., Wu, P.-C., Fu, J.S., Lai, L.-W., Lai, H.-C., 2020. Analysis of air quality and health co-benefits regarding electric vehicle promotion coupled with power plant emissions. J. Clean. Prod. 247, 119152.
Lo, W.-C., Shie, R.-H., Chan, C.-C., Lin, H.-H., 2017. Burden of disease attributable to ambient fine particulate matter exposure in Taiwan. J. Formos. Med. Assoc. 116 (1), 32–40.
Lo, W.-C., Ho, C.-C., Tseng, E., Hwang, J.-S., Chan, C.-C., Lin, H.-H., 2022. Long-term exposure to ambient fine particulate matter (PM2. 5) and associations with cardiopulmonary diseases and lung cancer in Taiwan: a nationwide longitudinal cohort study. Int. J. Epidemiol. 51 (4), 1230–1242.
Marks, A.B., 2019. Carbon) farming our way out of climate change. Denv. L. Rev. 97, 497.
Martenies, S.E., Milando, C.W., Batterman, S.A., 2018. Air pollutant strategies to reduce adverse health impacts and health inequalities: a quantitative assessment for Detroit, Michigan. Air Quality, Atmosphere Health 11 (4), 409–422.
Murray, C.J., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F., Abdelalim, A., Abdollahi, M., Abdollahpour, I., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10258), 1223–1249.
Ng, T.-C., Lo, W.-C., Ku, C.-C., Lu, T.-H., Lin, H.-H., 2020. Improving the use of mortality data in public health: a comparison of garbage code redistribution models. Am. J. Publ. Health 110 (2), 222–229.
R Core Team, R., 2022. R: a language and environment for statistical computing. In: R Foundation for Statistical Computing. https://www.R-project.org/.
Romero-Lankao, P., Qin, H., Borbor-Cordova, M., 2013. Exploration of health risks related to air pollution and temperature in three Latin American cities. Soc. Sci. Med. 83, 110–118.
Rosofsky, A., Levy, J.I., Zanobetti, A., Janulewicz, P., Fabian, M.P., 2018. Temporal trends in air pollution exposure inequality in Massachusetts. Environ. Res. 161, 76–86.
Stanaway, J.D., Afshin, A., Gakidou, E., Lim, S.S., Abate, D., Abate, K.H., Abbafati, C., Abbasi, N., Abbastabar, H., Abd-Allah, F., 2018. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392 (10159), 1923–1994.
Taichung City Government, 2022. 2022 Taichung Fine Suspended Particulate Sampling and Empty Sample Forecasting Plan. Taichung City. Taiwan Retrieved from. https://www.epb.taichung.gov.tw/media/896812/111%E5%B9%B4_%E8%87%BA%E4%B8%AD%E5%B8%82%E7%B4%B0%E6%87%B8%E6%B5%AE%E5%BE%AE%E7%B2%92%E6%8E%A1%E6%A8%A3%E8%88%87%E7%A9%BA%E5%93%81%E9%A0%90%E5%A0%B1%E8%A8%88%E7%95%AB_%E7%A9%BA%E5%99%AA%E7%A7%91.pdf.
van Oostrom, S.H., Gijsen, R., Stirbu, I., Korevaar, J.C., Schellevis, F.G., Picavet, H.S.J., Hoeymans, N., 2016. Time trends in prevalence of chronic diseases and multimorbidity not only due to aging: data from general practices and health surveys. PLoS One 11 (8), e0160264.
Vos, T., Lim, S.S., Abbafati, C., Abbas, K.M., Abbasi, M., Abbasifard, M., Abbasi-Kangevari, M., Abbastabar, H., Abd-Allah, F., Abdelalim, A., 2020. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10258), 1204–1222.
Vyas, V., Mehta, K., Sharma, R., 2023. The nexus between toxic-air pollution, health expenditure, and economic growth: an empirical study using ARDL. Int. Rev. Econ. Finance 84, 154–166.
Wang, Y.-S., Chang, L.-C., Chang, F.-J., 2021. Explore regional PM2. 5 features and compositions causing health effects in Taiwan. Environ. Manag. 67 (1), 176–191.
WHO, 2021. WHO Global Air Quality Guidelines: Particulate Matter (PM2. 5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization.
Wilson, N., Cleghorn, C., Nghiem, N., Blakely, T., 2023. Prioritization of intervention domains to prevent cardiovascular disease: a country-level case study using global burden of disease and local data. Popul. Health Metrics 21 (1), 1.
Williams, R., Karuranga, S., Malanda, B., Saeedi, P., Basit, A., Besançon, S., Bommer, C., Esteghamati, A., Ogurtsova, K., Zhang, P., 2020. Global and regional estimates and projections of diabetes-related health expenditure: results from the international diabetes federation diabetes atlas. Diabetes Res. Clin. Pract. 162, 108072.
Wong, Y.J., Yeganeh, A., Chia, M.Y., Shiu, H.Y., Ooi, M.C.G., Chang, J.H.W., Shimizu, Y., Ryosuke, H., Try, S., Elbeltagi, A., 2023. Quantification of COVID-19 impacts on NO2 and O3: systematic model selection and hyperparameter optimization on AI-based meteorological-normalization methods. Atmos. Environ. 301, 119677.
Wu, Y.-S., Tsai, C.-Y., Chang, K.-H., Chiang, C.-F., 2021. Impact of air pollutants emitted by taichung power plant on atmospheric PM2. 5 in central taiwan. Aerosol Air Qual. Res. 20.
Xiao, Q., Liang, F., Ning, M., Zhang, Q., Bi, J., He, K., Lei, Y., Liu, Y., 2021. The long-term trend of PM2. 5-related mortality in China: the effects of source data selection. Chemosphere 263, 127894.
Xie, Y., Zhong, H., Weng, Z., Guo, X., Kim, S.E., Wu, S., 2023. PM2. 5 concentration declining saves health expenditure in China. Front. Environ. Sci. Eng. 17 (7), 90.
Yang, X., Zhang, T., Zhang, Y., Chen, H., Sang, S., 2021. Global burden of COPD attributable to ambient PM2. 5 in 204 countries and territories, 1990 to 2019: a systematic analysis for the Global Burden of Disease Study 2019. Sci. Total Environ. 796, 148819.
Yazdi, M.D., Wang, Y., Di, Q., Zanobetti, A., Schwartz, J., 2019. Long-term exposure to PM2. 5 and ozone and hospital admissions of Medicare participants in the Southeast USA. Environ. Int. 130, 104879.
Yuan, S., Wang, J., Jiang, Q., He, Z., Huang, Y., Li, Z., Cai, L., Cao, S., 2019. Long-term exposure to PM2. 5 and stroke: a systematic review and meta-analysis of cohort studies. Environ. Res. 177, 108587.
Zhang, X., Xia, Q., Lai, Y., Wu, B., Tian, W., Miao, W., Feng, X., Xin, L., Miao, J., Wang, N., 2022. Spatial effects of air pollution on the economic burden of disease: implications of health and environment crisis in a post-COVID-19 world. Int. J. Equity Health 21 (1), 1–16.
National Development Council,, 2022. Taiwan's population projection 2022–2070 report (In Mandarin). National Development Council, Taipei. https://www.ndc.gov.tw/en/#Group_1380.
Taiwan Environmental Protection Administration,, 2023. Taiwan Emission Data System 11.1. Retrieved n.d. from. https://air.epa.gov.tw/EnvTopics/AirQuality_6.aspx.