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The Effect of Air Pollution-Related Deaths in Malaysia: Evaluating Disease Burden Mortality and Economic Impact

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Abstract

Background: In 2016, the World Bank Group estimated that health costs related to PM2.5 pollution totalled approximately $5.7 trillion worldwide. Information on the estimated health costs from the environmental burden of disease caused by ambient air pollutant PM2.5 in Malaysia is limited. Therefore, this study aimed to estimate the environmental health costs associated with PM2.5 for all-cause and respiratory mortality at the national level. Methods: The population-weighted exposure level (PWEL) of PM10 concentrations across all Malaysian states for 2000, 2008, and 2013 was calculated using publicly available remote sensing data, air quality data from the Department of Environment, and burden-of-disease mortality statistics from the Institute of Public Health. The PWEL was then converted to PM2.5 using the World Health Organization's ambient air conversion factors. The AirQ+ 2.2.4 software was used to calculate mortality proportions for all-cause mortality, chronic obstructive pulmonary disease (COPD), lung cancer (LC), and acute lower respiratory infection (ALRI) in children under five, based on the National Burden of Disease data from 2000, 2008, and 2013. Results: The cost per disability-adjusted life-year (DALY) ranged from one (low estimate) to three times the Gross Domestic Product (GDP) per capita (high estimate). These costs were projected for 2022 using a GDP deflator. The estimated PWEL for PM2.5 in 2000, 2008, and 2013 was 22μg/m³, 18μg/m³, and 24μg/m³, respectively. The mortality cost of all-cause deaths increased from MYR 3.3 billion in 2000 to MYR 5.1 billion in 2008, and then to MYR 12.8 billion in 2013, accounting for nearly 1% of Malaysia''s 2013 GDP. Conclusions:This indicates a rise in disease burden and mortality costs due to ambient air PM2.5 levels. Therefore, policymakers should remain highly vigilant. (298 words)

Keywords: PWEL; ambient PM2.5; burden of disease; DALY; mortality cost

1. Background

Air pollution represents a pressing global crisis that extends beyond public health to encompass environmental, social, and economic dimensions, demanding urgent and coordinated action. It is among the most pervasive environmental health threats worldwide, primarily driven by vehicular emissions, industrial activities, and residential combustion sources (Department of Environment, 2022; Li et al., 2023; Mazeli, Pahrol, Abdul Shakor, et al., 2023b). Alarmingly, over 90% of the global population is exposed to ambient air pollutant levels exceeding the WHO guideline of 5 μg/m³ for $PM_{2.5}$, a threshold established in 2021, emphasizing the widespread degradation of air quality (WHO, 2021; Yu et al., 2023). Among various pollutants, fine particulate matter ($PM_{2.5}$)—airborne particles

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with diameters smaller than 2.5 μm—poses the greatest risk to human health (Afroz et al., 2003; Crouse et al., 2015; Liu et al., 2016; Pope III et al., 2002). The classification of mortality resulting from exposure to $PM_{2.5}$, referred to as deaths attributable to $PM_{2.5}$ pollution, highlights the severe implications of this environmental hazard (Yue et al., 2020). Both short-term and long-term exposure to $PM_{2.5}$ has been robustly linked to increased morbidity and mortality from cardiovascular and respiratory diseases, such as ischemic heart disease, stroke, and chronic obstructive pulmonary disease (Arregocés et al., 2023; Brook et al., 2024).

In 2019, it was estimated that ambient air pollution was responsible for approximately 4.2 million premature deaths (WHO, 2022). Notably, the Western Pacific and Southeast Asia regions experienced the highest disease burdens attributable to air pollution. The morbidity associated with air pollution is chiefly attributable to several cardiovascular and respiratory conditions. Specifically, stroke and heart attack (IHD) accounted for 68% of deaths linked to ambient air pollution. Chronic obstructive pulmonary disease (COPD) constituted 14%, acute lower respiratory tract infections (ALRI) were responsible for 14% of the deaths, and lung cancer (LC) contributed to 4%. Similarly, the Global Burden of Disease (GBD) 2019 report estimated that deaths associated with ambient and household $PM_{2.5}$ pollution rose to approximately 6.45 million (World Bank Group, 2022a). In the hierarchy of health risk factors, $PM_{2.5}$ exposure ranks as the fifth most significant global health risk, following high blood pressure, dietary risks, tobacco smoking, and diabetes, according to the GBD 2019 study. This growing evidence underscores the urgent need for comprehensive air quality management strategies and public health interventions targeting $PM_{2.5}$ exposure, given its significant contribution to global mortality. Further investigation is warranted to elucidate the mechanisms by which $PM_{2.5}$ influences health outcomes and to develop effective policy measures to reduce air pollution and its associated health risks.

1.1. Quantifying the Monetary Cost of Health

The economic burden attributable to air pollution encompasses an assessment of both individual and societal costs, specifically delineating those linked to mortality and morbidity. Commonly employed methodologies for quantifying the monetary value of life include (1) the Value of Statistical Life (VSL), which reflects the monetary value individuals assign to a marginal change in their probability of death, and (2) the Value of Life, wherein a financial value is ascribed to Disability-Adjusted Life Years (DALYs). This valuation yields a quantifiable amount that individuals are willing to pay for an additional year of healthy life (Robinson et al., 2019).

The interplay between VSL and the Value of Life is well documented, with the latter often derived from estimates of the former. A notable limitation of these methodologies is their variability across different national contexts, which can impede the comparability of results. Complementary frameworks for evaluating the economic burden of disease include the Cost of Illness (COI) approach, which captures both direct and indirect costs and accounts for productivity loss. Additionally, the Value of Lost Output (VLO) quantifies the economic consequences of the loss of capital and labor. In contrast to these traditional approaches, assigning a monetary value to DALYs enables comparisons beyond the health sector, equipping policymakers with the critical insights needed to prioritize interventions at the national level (Arias et al., 2022). Such a comprehensive valuation framework is essential for informed decision-making on public health strategies to mitigate the adverse impacts of air pollution.

1.2. Global Health Costs Due to Air Pollution

The global economic burden associated with air pollution is substantial and warrants significant attention from policymakers and researchers alike. Globally, the burden of $PM_{2.5}$-related mortality is predominantly linked to ambient air pollution (64% of total deaths), with the remaining 36% attributable to household air pollution stemming from the use of solid fuels. Of the comprehensive health costs associated with $PM_{2.5}$, approximately 85% are attributed to premature mortality, with the remaining 15% linked to morbidity (World Bank Group, 2022b). An examination of data from India

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reveals that air pollution contributed to economic losses ranging from USD 8.0 billion to USD 28.8 billion in 2019, primarily due to morbidity and premature mortality, constituting approximately 1.36% of India''s gross domestic product (GDP) (Pandey et al., 2021) In a broader context, estimates for the year 2000 indicate that air pollution incurred costs between € 276 billion and € 790 billion in Europe alone, associated with premature deaths and hospital admissions (Franchini et al., 2015). Moreover, the Organization for Economic Co-operation and Development (OECD) identified a rising trend in the economic costs associated with mortality due to air pollution, which increased by 7% during the period from 2005 to 2010, ultimately reaching US. In 2019, the global health costs associated with mortality and morbidity from $PM_{2.5}$ exposure approximated USD 8.1 trillion, representing 6.1% of global GDP (Envirotec, 2023). Regional disparities are evident, with costs ranging from approximately 1.7% of GDP in North America to 10.3% in South Asia and 12.9% in China. In low-income countries, the cost amounts to around 5.9% of their GDP, escalating to between 8.9% and 9.0% in lower- and upper-middle-income nations.

In the Malaysian context, there is a paucity of studies that leverage Malaysian Burden of Disease (BOD) data to elucidate the national burden of disease attributable to ambient $PM_{2.5}$ exposure. This study aims to quantify the burden of ischemic heart disease (IHD), stroke, LC, COPD, and acute lower respiratory tract infections (ALRI) among children under 5 years of age for 2000, 2008, and 2013. By estimating the economic costs associated with these health outcomes, this research aims to provide a robust foundation for policymakers, facilitating informed investment decisions to mitigate air pollution, guiding public health priorities, and informing budget allocations for necessary interventions.

2. Methods

2.1. Site Description

Malaysia, a developing Southeast Asian nation, has rapidly grown in industry and transportation, increasing PM10 air pollution (Murray et al., 2012). Comprising thirteen states and three federal territories, it experiences a tropical climate influenced by atmospheric pressure. The Northeast Monsoon from November to February and the Southwest Monsoon from June to August shape its seasons. Open burning and forest fires contribute 3-5% of air pollution, while transboundary haze has significantly impacted air quality since 1994, according to the Department of Environment report (Department of Environment, 2022).

2.2. Baseline Population and Mortality Data

Malaysia''s biannual population censuses for the years 2000, 2008, and 2013 were obtained from the Department of Statistics Malaysia website (Department of Statistics Malaysia, 2022). Data from the Centre for International Earth Science Information Network were utilised for Putrajaya, as data for 2008 and 2013 were unavailable. The numbers of medically certified deaths and DALYs in 2000, 2008, and 2013 were obtained from the Institute for Public Health, National Institutes of Health, Malaysia, database. The data referred to all natural causes (ICD-10 A00-R99), except for external causes of death not due to environmental factors (Chapter XIX ICD-10 S00-T98 and Chapter XX of ICD-10, V01-Y98), such as traffic accidents, homicides, suicides, IHD (ICD10 I20–I25), stroke (ICD10 I60-I69), COPD (ICD10 J40–J44, J47), LC (ICD10 C33-C34, D02.1-D02.2, D38.1) and acute lower respiratory infections (ALRI) (ICD10 J10-J22, P23, U04).

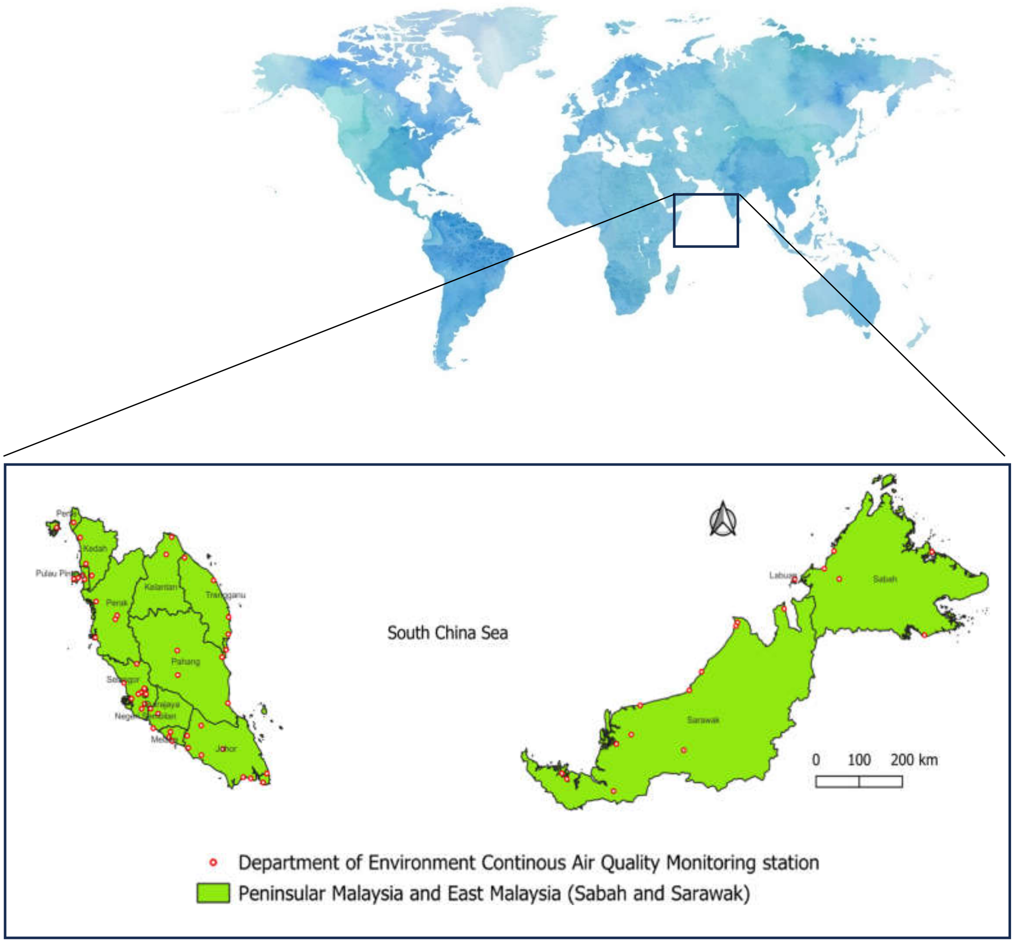

Figure 1. Location of Department of Environment Continuous Air Quality Monitoring stations in Malaysia (source from Department of Environment, 2024).

2.3. *Exposure Assessment*

We used aerosol products of Level 2 Terra-MODIS (satellite surveillance data) from the National Aeronautics and Space Administration's (NASA) Level-1 and Atmosphere Archive and Distribution System (LAADS) Distributed Active Archive Centre (DAAC) website over Malaysia for the years 2000, 2008, and 2013 to calculate the population exposure to $PM_{2.5}$ as described in detailed by Abdul Shakor et al. (2020); Mazeli, et al., (2023) and Kamarul Zaman et al. (2017).

We calculated the population-weighted $PM_{2.5}$ concentrations from the PM_{10} estimation using the methods by Mazeli et al., 2023 and Sun et al., 2013 for the years 2000, 2008, and 2013 using Eq. (1) with P as population and C as the mean annual PM_{10} concentration. PWEL:

$$PWEL = \sum(P \times C)/\sum P \quad (1)$$

2.4. *Attributable Proportion Estimation*

We calculated the attributable proportion (AP) by using the relative risk (RR) function for all-cause, cardiovascular, and respiratory mortality in adults and children under 5, using annual-average $PM_{2.5}$ concentrations as the exposure indicator based on this equation:

$$RR = \exp.\ [\beta\ (X - X_0)] \quad (2)$$

Where β controls the rate of RR increase, with X ($\mu g/m^3$) as pollutant concentration and X_0 ($\mu g/m^3$) as the background level without reported health effects. A relative risk (RR) of 1 indicates no

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increased health impact for each 10 μg/m³ rise in $PM_{2.5}$. The Attributable Proportion (AP) calculated from the RR (Burnett et al., 2014; Ostro, 2004). We used Eq. (3) for the AP calculation:

$$AP = \frac{\Sigma\{[RR(c) - 1] \times P(c)\}}{\Sigma\{RR(c) \times P(c)\}} \quad (3)$$

RR is the relative risk for a health endpoint in exposure category "c," obtained from epidemiological studies. P(c) is the population proportion in exposure category "c."

2.5. Attributable Disability-Adjusted Life Year (Daly) Estimates

To calculate the attributable DALY due to ambient $PM_{2.5}$, we used the Malaysian National Burden of Disease (NBD) years of life lost (YLL) data for 2000, 2003, and 2013. NBD studies are a valuable source of data for the Environmental Burden of Disease (EBD) assessments, as they estimate the disease burden of the major diseases or disease groups at the country level (generally, in terms of deaths (YLL) and DALYs. YLL is years of life lost, representing the mortality of disease, and YLD is the years lived in disability, representing the morbidity of disease. The estimated disease-burden mortality cost can be measured using DALYs, which combine the burden of disability and death into a single index. We adopted the calculation principle from Cui et al. (2016) and Prüss-Üstün et al. (2003).

The attributable burden for an environmental risk factor was obtained by multiplying the attributable disease proportion for the risk factor by the total disease burden or disease burden for the corresponding mortality assessed in the National Burden of Disease study (Eq. 5).

$$\text{Attributable burden} = \text{Attributable Proportion} \times \text{Total burden} \quad (5)$$

In this study, the attributable YLL due to air pollution was estimated using the attributable proportion for $PM_{2.5}$ derived from the burden-of-disease calculation with the AirQ+ software and the national YLL value (Eq. 6).

$$\text{Attributable YLL} = \text{Attributable proportion due to } PM_{2.5} \times \text{National YLL value} \quad (6)$$

We then calculated the attributable YLD using country-specific factors, which were the YLL to YLD ratio and attributable YLL (Eq. 7). The suggested country-specific factor values are based on available data by WHO (2022).

$$\text{Attributable YLD} = \text{country-specific factors} \times \text{Attributable YLL} \quad (7)$$

2.6. Economic Burden Calculation

The economic cost of mortality from air pollution is estimated by assigning monetary values to the attributable DALYs. This process, grounded in rigorous research methodologies, is a crucial step toward understanding the economic burden of air pollution. There are multiple approaches to assigning monetary values to mortality. The value of statistical life (VSL) approach, which assigns a value to the small reduction in mortality risks, has been adapted by earlier studies to estimate the economic cost of diseases in low- and middle-income countries. However, the VSL approach does not consider the value of full life years or years lived with disabilities. Alternatively, various studies have previously used Gross Domestic Product (GDP) per capita as a proxy for the monetary value of DALY (Arias et al., 2022). The value of one to three times GDP per capita has been used as a proxy for DALY's value (Blizard, Z. 2023). Hence, this study used one GDP per capita as the base case (low estimates) and three times GDP per capita as the high estimates. The GDP per capita values for 2000, 2008, and 2013 were retrieved from the Department of Statistics Malaysia (DOSM): MYR 15,169, MYR 27,929, and MYR 33,714, respectively. The estimated values were presented in both nominal and constant terms, with 2022 used as the base year, as it was the most recent deflator available at the time of analysis. Constant value was calculated using a GDP deflator. The GDP deflator value for the three years was estimated using a splicing method to the GDP data retrieved from DOSM (2020). A constant value adjusts the current or nominal value to offset the inflation effect. Hence, it allows for a more meaningful comparison across time.

3. Results

3.1. Baseline Mortality and Estimated Particulate Matter Data

The mid-year population census, DALY, and the number of deaths due to all-natural causes, IHD, stroke, COPD, LC, and ALRI (0–4 years) for the year 2000, 2008, and 2013 in Malaysia are shown in Table 1. These findings underscore the urgent need to address air pollution in Malaysia. There has been an overall increase in the mid-year population census, DALYs, and mortality from all causes, including IHD and stroke, from 2000 to 2013. Similar trends were shown for COPD and LC mortality, but with a slight reduction in 2008.

Table 1. National mid-year population census, national mortality cases, and Disability Adjusted Life Years (DALY) value for 2000, 2008 and 2013.

Year	2000		2008		2013	
	Numbers	DALY	Numbers	DALY	Numbers	DALY
Mid-year population census (0-85+ years old)	23,494,900	-	27,567,600	-	30,213,700	-
All-cause (natural)[a]	93,232	1,751,891	118,539	1,903,996	128,008	1,964,529
IHD	22,158	278,733	22,892	279,529	20,295	412,552
Stroke	11,290	180,431	13,430	205,254	22,282	359,994
COPD	3,949	60,728	3,156	51,129	9,376	108,308
LC	2,154	26,932	2,103	45,754	3,696	71,220
ALRI (0-4 years old)	198	15,203*	231	13,197*	352	27,307*

[a] Excluding deaths due to accidents and suicide. *DALY at the age of 0 to 4 years old. **The table represents DALY at more than 25 years of age, except those indicated otherwise.

In this study, we used the estimated annual average PWEL $PM_{2.5}$ values provided by Mazeli et al. (2023) for the years 2000, 2008, and 2013, which were 22 μg/m³, 18 μg/m³, and 24 μg/m³, respectively. The Malaysian Department of Environment's Environmental Quality Report confirmed this increasing trend of ambient air PM_{10} from 2000, 2008, and 2013 (Department of Environment, 2001, 2009, 2013).

3.2. Burden of Disease Due to Estimated Pwel Pm2.5

We assessed attributable proportions and cases of all-cause, COPD, LC, ALRI in children under five years old, IHD, and stroke due to estimated PWEL of $PM_{2.5}$ for the years 2000, 2008, and 2013 (Table 2). The estimated proportion of attributable deaths from natural causes, ALRI in children under five, IHD, and stroke ranged from 9% to 27%, depending on the disease and year.

In this study, we estimated an excess of 6,288 all-cause deaths in the population when comparing burden-of-disease estimates for 2013 with those for 2008. The stroke showed an excess of 2,082. The ALRI for those below five years old, COPD, and LC showed excesses of 23, 1,143, and 351, respectively. Interestingly, although the national trend of IHD showed a decline from 2000 to 2013, the attributable IHD mortality in 2000 and 2013 was almost the same. This may be due to higher $PM_{2.5}$ levels in 2013, which offset the lower value in the national IHD mortality data.

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Table 2. Estimated Burden of Disease Attributable Proportion, Attributable Mortality, and Attributable cases per 100,000 People in 2000, 2008, and 2013 due to $PM_{2.5}$ exposure for Natural, COPD, LC, ALRI (0-4 years old), IHD, and Stroke mortality.

Year	2000			2008			2013		
Mortality	Estimated attributable proportion (percent)	Estimated attributable deaths	Estimated Attributable cases per 100,000 people	Estimated attributable proportion (percent)	Estimated attributable deaths	Estimated Attributable cases per 100,000 people	Estimated attributable proportion (percent)	Estimated attributable deaths	Estimated Attributable cases per 100,000 people
All (natural) cause**	14.00 (10.79-15.54)	11,848 (9,133-13,151)	129.52 (99.83-143.76)	11.31 (8.69-12.58)	12,259 (9,415-13,631)	106.44 (81.75-118.35)	15.32 (11.83-16.98)	18,547 (14,321-20,568)	138.28 (106.78-153.35)
ALRI	11.55 (6.16-18.32)	23 (12-36)	0.81 (0.43-1.28)	9.28 (4.72-15.12)	21 (11-35)	0.85 (0.43-1.39)	12.62 (6.86-19.78)	44 (24-70)	1.74 (0.94-2.72)
COPD	15.25 (10.39-20.07)	563 (383-740)	5.08 (3.46-6.69)	12.38 (8.13-16.79)	389 (255-527)	2.78 (1.82-3.76)	16.60 (11.45-21.61)	1,532 (1,057-1,996)	9.32 (6.43-12.14)
LC	15.80 (10.44-21.13)	339 (224-453)	3.06 (2.02-4.09)	13.15 (8.35-18.02)	275 (175-377)	1.96 (1.25-2.69)	16.99 (11.40-22.46)	626 (420-828)	3.81 (2.56-5.04)
IHD**	25.24 (17.04-31.18)	5,593 (3,776-6,908)	50.53 (34.11-62.41)	20.67 (13.82-25.72)	4,717 (3,153-5,870)	33.65 (22.49-41.88)	27.43 (18.61-33.75)	5,538 (3,757-6,814)	33.68 (22.85-41.45)
Stroke**	18.50 (7.40-27.70)	2,088 (835-3,128)	18.87 (7.55-28.26)	15.02 (5.94-22.76)	1,993 (787-3,018)	14.22 (5.62-21.53)	20.18 (8.12-30.06)	4,075 (1,640-6,069)	24.79 (9.98-36.91)

*Values in parentheses are lower and upper limits (95% CI). ** RR from Chen & Hoek, 2020.

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3.3. Cost of Daly Mortality

Figure 2 and Figure 3 present the estimated attributable DALY trend of all-cause and the five disease mortality trends, akin to the attributable number and proportion mortality trend in Table 2. The DALY for each disease in Figure 3 decreased from 2000 to 2008, followed by a significant surge in 2013, underscoring the profound influence of ambient air PWEL $PM_{2.5}$ on DALY values, except for LC. The only noticeable difference across diseases was the magnitude of the DALYs over time.

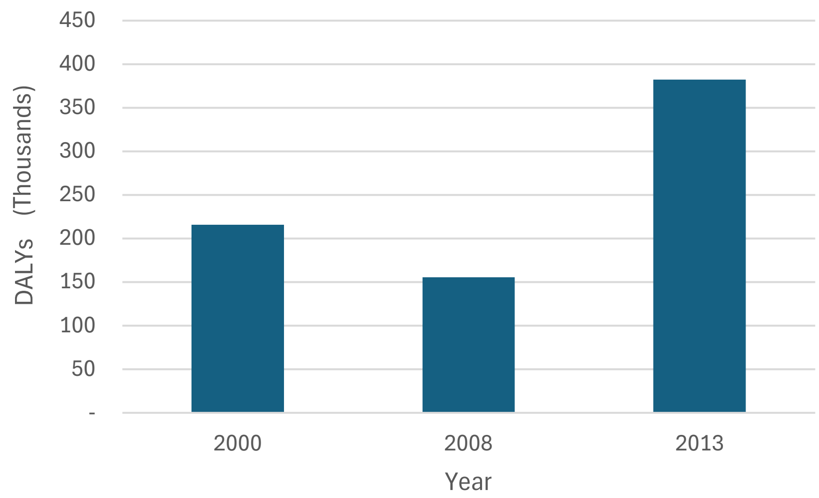

Figure 2. Disability-adjusted Life Years value (thousands) for all-cause mortality for 2000, 2008 and 2013.

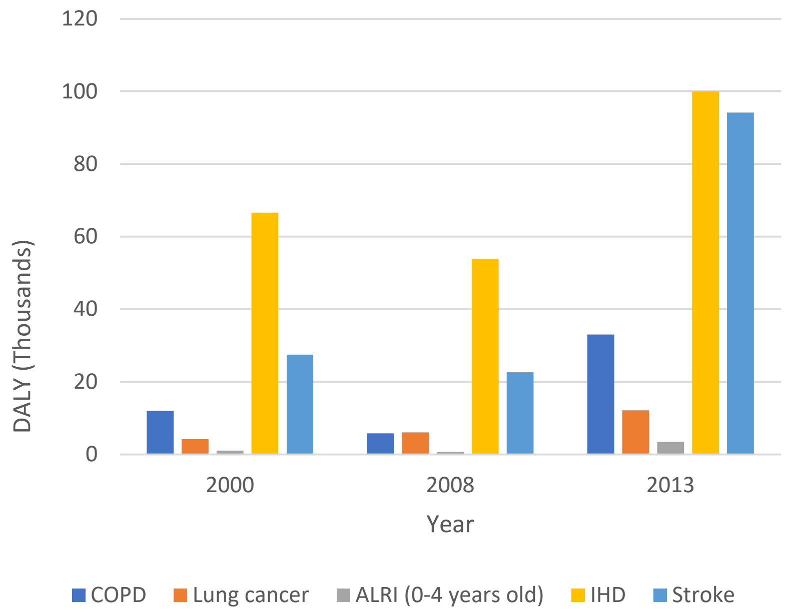

Figure 3. Disability-adjusted Life Years value (thousands) for COPD, LC, ALRI under 5 years old, IHD, and Stroke for 2000, 2008 and 2013.

The DALY cost calculation reveals notable trends regarding the economic burden of all-cause mortality. An upward trajectory is observed in low-cost estimates, from MYR 3.3 billion in 2000 to MYR 4.3 billion in 2008, followed by a further increase to MYR 12.8 billion in 2013, equivalent to MYR 15.8 billion when adjusted to 2022 constant prices (Table 3). This sustained increase is evident across mortality rates for five distinct diseases.

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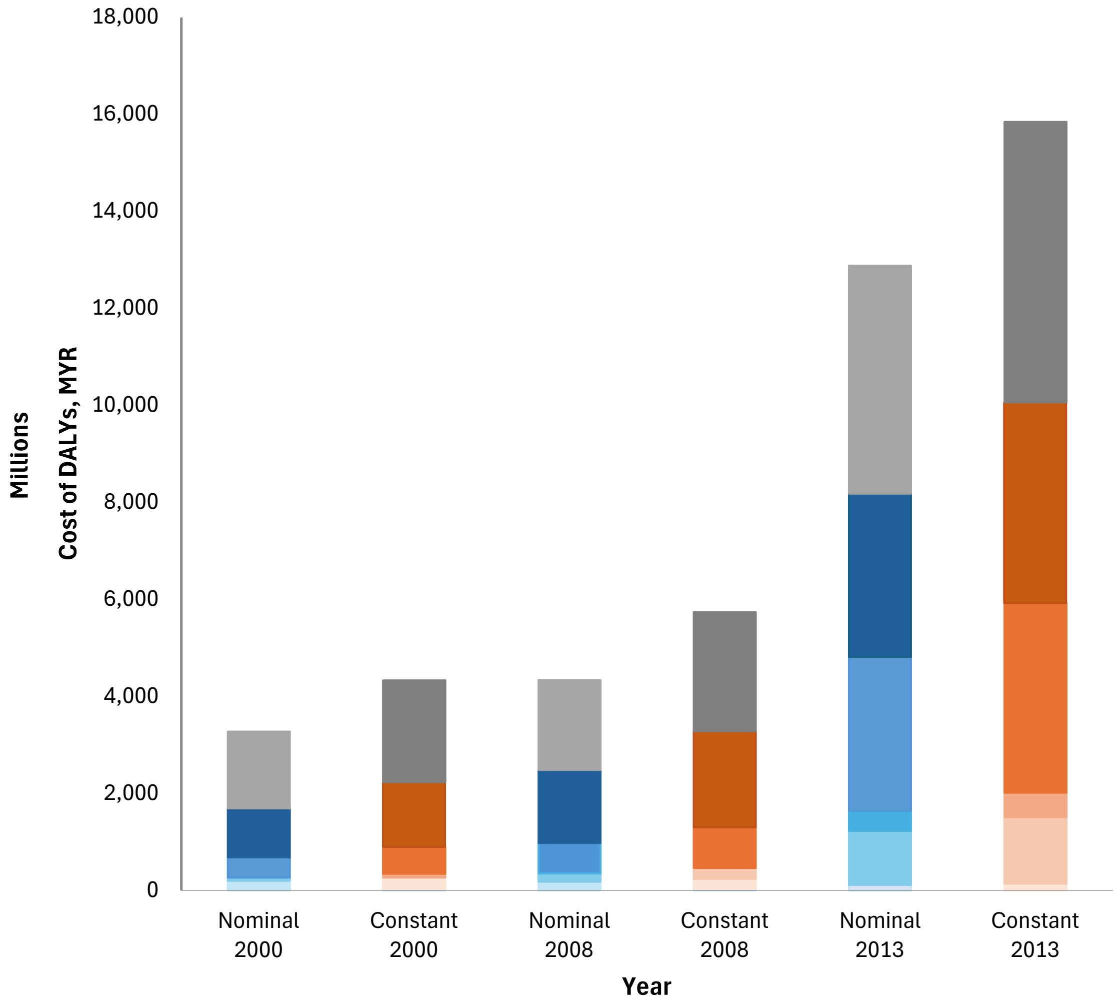
Table 3. Estimated Burden of Disease Attributable DALY and Attributable Low and High Estimates Mortality Cost in the Year 2000, 2008, and 2013 due to $PM_{2.5}$ exposure for All-Causes (Natural), COPD, LC, ALRI, IHD, and Stroke.

	2000					2008					2013				
		Cost of DALYs in MYR (nominal)(millions)		Cost of DALYs in MYR (constant[d])(millions)			Cost of DALYs in MYR (nominal)(millions)		Cost of DALYs in MYR (constant[d])(millions)			Cost of DALYs in MYR (nominal)(millions)		Cost of DALYs in MYR (constant[d])(millions)	
Mortality	DALY	Low Estimates[b]	High Estimates[c]	Low Estimates[b]	High Estimates[c]	DALY	Low Estimates[b]	High Estimates[c]	Low Estimates[b]	High Estimates[c]	DALY	Low Estimates[b]	High Estimates[c]	Low Estimates[b]	High Estimates[c]
All-Cause	215,781.00 (166,306.00 - 239,517.00)	3,273.18 (2,522.70- 3,633.23)	9,819.55 (7,568.09- 10,899.70)	6,294.58 (4,851.34- 6,986.99)	18,883.74 (14,554.01- 20,960.96)	155,213.00 (119,257.00 - 172,642.00)	4,334.94 (3,330.73- 4,821.72)	13,004.83 (9,992.19- 14,465.16)	5,734.05 (4,405.73- 6,377.93)	17,202.16 (13,217.18- 19,133.80)	382,114.00 (295,066.00 - 423,518.00)	12,882.59 (9,947.86- 14,278.49)	38,647.77 (29,843.57- 42,835.46)	15,845.75 (12,235.98- 17,562.71)	47,537.24 (36,707.95- 52,688.14)
ALRI	1,013.77 (540.68- 1,607.99)	15.38 (8.20- 24.39)	46.13 (24.60- 73.17)	29.57 (15.77- 46.91)	88.72 (47.32- 140.72)	665.14 (338.30 - 1,083.72)	18.58 (9.45- 30.27)	55.73 (28.35- 90.80)	24.57 (12.50- 40.04)	73.72 (37.49- 120.11)	3,399.07 (1,847.67- 5,327.55)	114.60 (62.29 179.61)	343.79 (186.88- 538.84)	140.96 (76.62- 220.93)	422.87 (229.86- 662.78)
COPD	11,991.54 (8,169.97- 15,781.65)	181.90 (123.93- 239.39	545.70 (371.79- 718.18)	349.81 (238.33- 460.37)	1,049.42 (714.98- 1,381.11)	5,823.23 (3,824.14- 7,897.58)	162.64 (106.80- 220.57)	487.91 (320.41- 661.71)	215.13 (141.28- 291.76)	645.38 (423.83- 875.28)	33,020.59 (22,776.25 - 42,986.44)	1,113.26 (767.88- 1,449.24)	3,339.77 (2,303.64- 4,347.73)	1,369.32 (944.50- 1,782.59)	4,107.96 (2,833.50- 5,347.77)
Lung cancer	4,219.55 (2,788.11- 5,642.98)	64.01 (42.29- 85.60)	192.02 (126.88- 256.79)	123.09 (81.33- 164.61)	369.27 (244.00_ 493.84)	6,017.41 (3,820.94- 8,245.91)	168.06 (106.72- 230.30)	504.18 (320.15- 690.90)	222.30 (141.16- 304.63)	666.91 (423.47- 913.89)	12,140.42 (8,146.02 - 16,049.08)	409.30 (274.63- 541.08)	1,227.91 (823.90- 1,623.24)	503.45 (337.80- 665.53)	1,510.34 (1,013.41- 1,996.60)
IHD	66,583.78 (44,951.96 - 82,253.65)	1,010.01 (681.88- 1,247.71)	3,030.03 (2,045.63- 3,743.12)	1,942.33 (1,311.30- 2,399.43)	5,826.98 (3,933.90- 7,198.30)	53,755.55 (35,941.06- 66,888.86)	1,501.34 (1,003.80- 1,868.14)	4,504.02 (3,011.39- 5,604.42)	1,985.90 (1,327.77- 2,471.08)	5,957.69 (3,983.32- 7,413.25)	99,993.97 (67,841.33- 123,033.05)	3,371.20 (2,287.20- 4,147.94)	10,113.59 (6,861.61- 12,443.81)	4,146.61 (2,813.29- 5,102.01)	12,439.84 (8,439.86- 15,306.04)
Stroke	27,467.23 (10,986.89 - 41,126.61)	416.65 (166.66- 623.85)	1,249.95 (499.98- 1,871.55)	801.25 (320.50- 1,199.71)	2,403.75 (961.50- 3,599.13)	22,574.74 (8,927.69- 34,207.79)	630.49 (249.34- 955.39)	1,891.47 (748.02- 2,866.17)	833.98 (329.82- 1,263.74)	2,501.94 (989.45- 3,791.23)	94,148.48 (63,875.44- 115,840.73)	3,174.12 (2,153.50- 3,905.45)	9,522.37 (6,460.49- 11,716.36)	3,904.21 (2,648.83- 4,803.76)	11,712.63 (7,946.48- 14,411.27)

*Values in parentheses are lower and upper limits (95% CI). [a] GDP per capita based on source from Department of Statistics Malaysia (DOSM, n.d). [b] low estimates were calculated based on value of one (1) GDP per capita (WHO, 2001). [c] high estimates were calculated based on value of three (3) GDP per capita (WHO, 2001). [d] constant value using 2022 as base year (DOSM, n.d). GDP per capita for year 2000 is MYR 15,169. GDP per capita for year 2008 is MYR 27,929. GDP per capita for year 2013 is MYR 33,714.

The year 2013 witnessed the highest cost estimation associated with the burden of disease attributable to all-cause mortality due to ambient particulate matter ($PM_{2.5}$), with a calculated constant price mortality cost ranging between MYR 15.8 billion and MYR 47.5 billion (Figure 4). This figure represented approximately one to four percent of Malaysia's gross domestic product (GDP), valued at MYR 1,018.6 billion that year. The substantial DALY cost incurred during this period underscores the profound economic burden of elevated mortality rates associated with ambient $PM_{2.5}$ exposure. The economic implications of this burden necessitate a concerted response, underscoring the urgent need to formulate and implement effective public health policies. The mortality costs attributed to IHD emerged as the predominant contributor to the overall economic burden, accounting for approximately 0.41% of the total cost, translating to around MYR 4.1 billion in 2013 (constant prices 2022). Stroke-related mortality was the second most significant contributor, accounting for roughly 0.38% of the total burden (equivalent to MYR 3.9 billion in 2013 at the 2022 constant price). Furthermore, respiratory-related mortality from conditions such as LC, COPD, and ALRI in children aged zero to four years old collectively contributed 0.19% to the total economic burden. Within this category, LC and COPD accounted for approximately 0.01% to 0.13% of the total burden cost in 2013. The implications of these findings highlight the necessity for targeted interventions to mitigate the adverse health effects of ambient $PM_{2.5}$ and enhance public health outcomes in Malaysia.



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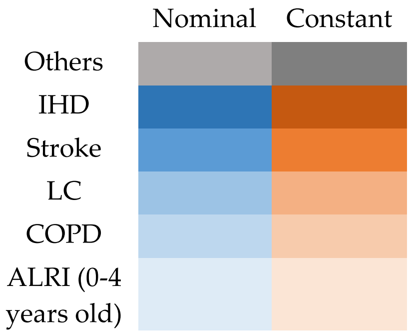

Figure 4. Estimated Trend of DALY Mortality cost in Malaysian Ringgit due to Ambient $PM_{2.5}$ exposure in year 2000, 2008 and 2013 (Low estimates). *Each column represents the total all-cause mortality cost due to $PM_{2.5}$.

4. Discussion

In this study, the PWEL $PM_{2.5}$ findings by Mazeli, Pahrol, Shakor, et al. (2023) and the Malaysian Department of Environment's Environmental Quality Report confirmed the increasing trend of ambient air PM_{10} from 2000, 2008, and 2013 (Department of Environment, 2001, 2009, 2013). This trend worsened in 2013 due to transboundary haze. This led to higher mortality estimates in 2013 than in 2000 and 2008, indicating a potentially greater impact of increased ambient air PWEL $PM_{2.5}$ exposure on patients with these diseases. On the other hand, in 2008, the nation experienced lower ambient air $PM_{2.5}$ estimates and lower estimated deaths due to $PM_{2.5}$ due to higher precipitation and economic slowdown (Abdul Shakor et al., 2020; NOAA, 2009).

Our analysis showed how rising levels of estimated ambient PWEL $PM_{2.5}$ in Malaysia may affect the mortality costs for the country's population. The findings revealed that higher levels of ambient air $PM_{2.5}$ have a major influence on mortality costs, especially those related to IHD and stroke, as well as the overall national disease burden. For 2000, 2008, and 2013, the IHD mortality cost accounts for the largest share of the overall burden of disease and mortality costs, followed by stroke, with an increasing trend over the years. These findings emphasize the potential impact of effective environmental health and air quality policies in reducing the national burden of disease mortality costs. Our results align with those of other researchers, such as Meisner et al. (2023) and Mueller et al. (2021).

To contextualize the economic valuation of $PM_{2.5}$-related mortality in Malaysia, it is useful to compare the GDP-per-capita-per-DALY method used in this study, which assigns a monetary value of 1–3 times the national GDP per capita to each DALY lost (Table 4), with two alternative valuation approaches: the Value of Statistical Life (VSL) and Willingness to Pay (WTP). The GDP-per-capita per DALY method provides a transparent, standardized valuation approach, especially suited for national-level burden estimation and budget planning (Drummond et al., 2015). For instance, with Malaysia's 2013 GDP per capita at MYR 33,714, each DALY was valued between MYR 33,714 and MYR 101,142. In contrast, the VSL method estimates the economic value of a life lost based on individuals' willingness to accept small risks of death in exchange for money, often using labor market data or stated preferences (Robinson et al., 2019). The World Bank (2020) estimated a VSL for Malaysia of approximately USD 1.3 million, translating to MYR 5.9 million per premature death. VSL is often used in regulatory cost-benefit analyses but may face ethical and methodological challenges in LMICs due to income disparities. As noted by Landrigan (2012), incorporating the hidden costs of environmental contamination into economic evaluations is vital for understanding the full societal impact of pollution-related health outcomes.

Lastly, the WTP approach assesses how much individuals are willing to pay to reduce health risks, often based on contingent valuation surveys or behavioral data. While WTP is less frequently used in Malaysia due to limited local studies, regional haze-related avoidance behavior suggests values ranging from MYR 20–50 per person per day. Although context-specific and income-sensitive, WTP estimates are valuable for microeconomic appraisals of environmental interventions. Each method offers complementary insights. The GDP-per-capita DALY valuation supports national burden costing, VSL informs broader cost-benefit evaluations, and WTP captures individual risk preferences. Integrating these approaches may enhance future economic analyses of environmental health policies in Malaysia.

Table 4. Comparison of Economic Valuation Methods in Health Costing.

Aspect	GDP-per-Capita per DALY	Value of Statistical Life (VSL)	Willingness to Pay (WTP)
Definition	Assigns a monetary value to a DALY based on a country's GDP per capita, usually multiplied by 1–3x	Estimates the value of a statistical life based on trade-offs people make between money and small changes in risk of death	Estimates how much people are willing to pay to reduce health risks, via surveys or observed behavior
Unit of Valuation	Cost per DALY	Cost per life lost	Cost per risk unit avoided
Basis of Calculation	National income proxy (e.g., MYR 33,714 per DALY in Malaysia, 2013)	Meta-analysis of labor market/survey data (e.g., MYR 1.8–3.6 million per life)	Survey- or behavior-based preferences (e.g., MYR 20–50/day during haze)
Common Usage	WHO-CHOICE, GBD DALY monetization	World Bank, OECD, U.S. EPA CBA	Environmental tax design, clean air policies
Strengths	Simple, transparent, applicable in LMICs	Captures societal value of mortality risk reduction	Captures individual utility and non-market values
Limitations	May underestimate non-fatal burden, doesn't reflect WTP	Needs calibration; may seem inconsistent in LMICs	Survey-based, may be biased by income or context
Malaysia Example	GDP/capita in 2013 = MYR 33,714 → DALY value = MYR 33.7k–101k	World Bank (2020) VSL ≈ USD 1.3–2.6 million (MYR 5.9M–11.8M)	Haze-related avoidance behavior: MYR 20–50/day (estimates vary)
Policy Implication	Useful for budgeting and burden studies	Powerful for regulatory and intersectoral decisions	Useful for program-specific valuation and communication

In 2019, the global health damages caused by $PM_{2.5}$ air pollution were estimated at approximately USD 8.1 trillion, representing 6.1 percent of the global gross domestic product (GDP) adjusted for purchasing power parity (PPP) (World Bank Group, 2022). This total was broken down into different categories, with ambient air $PM_{2.5}$ contributing approximately

USD 6.43 trillion, accounting for 4.8 percent of the global GDP (PPP-adjusted). The estimated health damage costs from $PM_{2.5}$ air pollution in 2019 show a significant increase, specifically a 40 percent rise compared to the figures reported in 2013 by the Institute for Health Metrics and Evaluation (IHME) (2016). Several factors have been suggested to explain this sharp rise in health cost estimates. Notably, changes in IER functions used in the AirQ+ software, along with substantially higher global estimates for ambient air $PM_{2.5}$ exposure, are considered major contributors. Additionally, the current estimates include morbidity-related costs, offering a more complete picture of the health effects of $PM_{2.5}$ exposure. The rise in estimated global ambient air $PM_{2.5}$ levels can also be attributed to advances in methodology and the improved availability of ground-level monitoring data. However, it is essential to acknowledge that accurately attributing the contribution of these factors remains challenging. Furthermore, a 2020 World Bank Group report estimated that ambient air pollution was responsible for 10,551 premature deaths in Malaysia in 2019, with health damage costs of USD 13,977 million using the value of statistical life (VSL) method. Notably, the World Bank estimated the ambient air $PM_{2.5}$ concentration in Malaysia for 2019 at 16.6 µg/m³. This figure led to a lower estimate of health-related mortality than the 2013 estimate.

Integrating economic considerations into public health epidemiology is crucial for developing a comprehensive understanding of the impacts of environmental degradation and the associated health costs resulting from exposure to toxic chemicals. This discussion argues that quantifying these economic costs offers both an analytical framework and a persuasive tool for disease prevention efforts. Empirical research has confirmed that the economic burden of environmental health issues, such as lead exposure, can be enormous, with estimates suggesting that costs related to lost productivity and healthcare exceed billions of dollars (Landrigan, 2012; Wang et al., 2024). Additionally, economic evaluations, especially cost-effectiveness analyses, are becoming increasingly important in evaluating public health interventions. These analyses provide a detailed understanding of the return on investment in preventive measures, thereby improving decision-making (Drummond et al., 2005). The significance of economic data is further underscored when countering the often-narrow arguments of business and industry stakeholders, who may prioritize economic interests over public health concerns (Woodward et al., 2001). By providing public health officials and advocates with solid economic evidence, a compelling case can be made for prioritizing health initiatives and allocating resources efficiently. For example, integrating health economics into policy discussions can highlight the long-term cost savings from preventive strategies, such as reducing air pollution. This approach not only decreases morbidity but also significantly reduces healthcare costs over time (U.S. EPA, 2014). In summary, using economic data is crucial for informing policymaking and promoting a comprehensive approach that aligns economic realities with public health objectives. Such integration is expected to enhance decision-making and yield more effective public health outcomes (Arrow et al., 1996; Landrigan, 2012). The severe financial and health consequences of $PM_{2.5}$ air pollution highlight the urgent need for stronger regulations and public health measures to reduce exposure and prevent related illnesses and deaths worldwide.

Our findings exceed the estimates by Mazeli et al. (2023), likely due to our lower $PM_{2.5}$ cutoff of 2.4 µg m-3 in this study (WHO, 2022). Furthermore, we utilized the latest version of the AirQ+ software, employing the most current Integrated Exposure-Response (IER) functions in the WHO model. This updated model likely improves the accuracy of burden-of-disease assessments across various health conditions.

Our evaluation indicated that ambient air $PM_{2.5}$ exposure has shown a progressive upward trend in burden-of-disease estimates from 2000 to 2013. These results align with findings from studies by Arregocés et al. (2023) and Brito et al. (2022)reinforcing the trend of rising health impacts related to air quality. However, our study could not show the actual year-to-year trend due to a lack of annual burden-of-disease data between 2000 and 2013. Thus, the trend from 2000 to 2013 is only partially observable, and the missing elements between 2000, 2008, and 2013 may obscure important variations.

This study is specifically designed to assist policymakers in implementing effective mitigation measures to reduce ambient $PM_{2.5}$ concentrations. Achieving reductions in air pollution levels comparable to those observed in 2008 or lower could significantly alleviate the avoidable disease burden. This hypothetical scenario assumes that both population size and mortality rates remain unchanged. Such proactive strategies promise public health benefits and represent a crucial step toward sustainable improvements in air quality.

This relationship between DALY trends and ambient air $PM_{2.5}$ exposure echoes the findings of Du et al. (2021) and Al-Hemoud et al. (2018). The DALY approach provides a measure that can be applied across any demographic and allows for comparisons at any time. Thus, it is feasible to convert time-loss estimates into monetary values. The disease burden is measured in DALYs, which combine the burden from disability and death into a single index. Using this index, the burden of different environmental risk factors can be juxtaposed with other risk factors. The primary benefits of the DALY approach are the ability to convert years of life into monetary terms and to compare estimates across countries and diseases. The primary constraints stem from the lack of morbidity data, which

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necessitates simplifications and typically underestimates the actual impact. At the very least, it is a tool that can quantify the effects of certain diseases or risk factors on health (Miraglia et al., 2005)

It is critical to note that although overall mortality and DALY values decreased in 2008, this did not translate into a proportional reduction in the cost per DALY. The higher DALY cost in 2008 compared to 2000 can be attributed to the increase in GDP per capita from 2000 to 2008. The economic implications of the 2008 GDP effectively mitigate the influence of the relatively low DALY value observed that year. Consequently, while ambient particulate matter levels, represented as PWEL $PM_{2.5}$, may affect BOD mortality metrics, it is essential to acknowledge that the financial ramifications of BOD mortality are highly contingent on the economic context, particularly the annual GDP used in the cost calculation. This highlights the need for a nuanced understanding of how economic factors intersect with public health data when assessing the overall burden of disease and mortality.

The current study has several limitations that need to be acknowledged. First, we employed a simplified method to assess the health impact of ambient air pollution using the AirQ+ software. This method did not account for exposure to multiple pollutants simultaneously, as noted by the World Health Organization (WHO, 2022). As a result, our findings may underestimate the actual effects of particulate matter ($PM_{2.5}$) and other pollutants on the health burden and related costs in Malaysia. Second, the analysis did not distinguish data by sex because the AirQ+ software lacked gender-specific IER functions. This limitation restricts our ability to analyze potential differences in health impacts and exposure-response between genders. Third, the AirQ+ model used to estimate health outcomes related to $PM_{2.5}$ exposure has inherent limitations. The estimates produced by this model involve uncertainties because they rely on IER functions that are based on assumptions and limited evidence for specific diseases (WHO, 2022).

Our assessment primarily focused on the indirect costs associated with health outcomes, specifically mortality resulting from air pollution. However, this study did not include direct costs, such as hospitalization, diagnostic tests, medications, or non-health expenses, including time lost, childcare responsibilities, and transportation costs (Jo, 2014). Consequently, the estimate of mortality-related costs may be underestimated, particularly since patient expenses and productivity losses were not factored in. Future research should aim to address these gaps by examining the costs associated with productivity loss and patient expenses related to $PM_{2.5}$ mortality, thereby providing a more comprehensive estimate of the economic burden of air pollution on society. Additionally, our study did not cover remote sensing data, analyses, or their limitations, as previously discussed in the literature (Mazeli, Pahrol, Shakor, et al. (2023)).

5. Conclusion

This study highlights a significant increase in the estimated mortality burden related to higher levels of ambient fine particulate matter ($PM_{2.5}$) from 2000 to 2013. Our thorough assessment shows clear public health benefits from reducing this estimated disease burden, especially when comparing $PM_{2.5}$ levels in 2008 with those in 2000 and 2013. The findings also suggest that the economic costs of disease mortality attributable to increased ambient $PM_{2.5}$ may reach up to 4% of the national Gross Domestic Product (GDP). This significant economic burden places considerable pressure on healthcare budgets and may lead to adverse outcomes at the national level. Therefore, policymakers must remain committed to initiatives to reduce ambient $PM_{2.5}$ levels. Such actions are crucial for improving public health and maintaining a sustainable fiscal balance. We believe the insights from this study can help policymakers develop and implement effective environmental health strategies and air quality regulations. These measures are vital for protecting future health and strengthening the overall public health infrastructure.

Conflicts of Interest: There was no conflict of interest in writing this article.

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References

Abdul Shakor, A. S., Pahrol, M. A., & Mazeli, M. I. (2020). Effects of Population Weighting on PM10 Concentration Estimation. *Journal of Environmental and Public Health*, *2020*. https://doi.org/10.1155/2020/1561823

Afroz, R., Hassan, M. N., & Ibrahim, N. A. (2003). Review of air pollution and health impacts in Malaysia. *Environmental Research*, *92*(2), 71–77. https://doi.org/10.1016/S0013-9351(02)00059-2

Al-Hemoud, A., Gasana, J., Al-Dabbous, A. N., Al-Shatti, A., & Al-Khayat, A. (2018). Disability adjusted life years (DALYs) in terms of years of life lost (yll) due to premature adult mortalities and postneonatal infant mortalities attributed to PM2.5 and PM10 exposures in Kuwait. *International Journal of Environmental Research and Public Health*, *15*(11), 1–15. https://doi.org/10.3390/ijerph15112609

Arias, D., Saxena, S., & Verguet, S. (2022). Quantifying the global burden of mental disorders and their economic value. *EClinicalMedicine*, *54*, 101675. https://doi.org/10.1016/J.ECLINM.2022.101675

Arregocés, H. A., Rojano, R., & Restrepo, G. (2023). Health risk assessment for particulate matter: application of AirQ+ model in the northern Caribbean region of Colombia. *Air Quality, Atmosphere and Health*, *16*(5), 897–912. https://doi.org/10.1007/s11869-023-01304-5

arrow, kenneth j., cropper, maureen l., eads, george c., hahn, robert w., lave, lester b., noll, roger g., portney, paul r., russel, milton, schmalensee, richard, smith, v. kerry, & stavins, robert n. (1996). Is There a Role for Benefit-Cost analysis in environmental, health, and safety regulation? *Science*, *272*, 221–222.

Brito, J., Bernardo, A., & Gonçalves, L. L. (2022). Atmospheric pollution and mortality in Portugal: Quantitative assessment of the environmental burden of disease using the AirQ+ model. *Science of the Total Environment*, *815*. https://doi.org/10.1016/j.scitotenv.2022.152964

Brook, R. D., Rajagopalan, S., & Al-Kindi, S. (2024). Public Health Relevance of US EPA Air Quality Index Activity Recommendations. *JAMA Network Open*, E245292. https://doi.org/10.1001/jamanetworkopen.2024.5292

Burnett, R. T., Arden Pope, C., Ezzati, M., Olives, C., Lim, S. S., Mehta, S., Shin, H. H., Singh, G., Hubbell, B., Brauer, M., Ross Anderson, H., Smith, K. R., Balmes, J. R., Bruce, N. G., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M. C., Gapstur, S. M., … Cohen, A. (2014). An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, *122*(4), 397–403. https://doi.org/10.1289/EHP.1307049

Crouse, D. L., Peters, P. A., Hystad, P., Brook, J. R., van Donkelaar, A., Martin, R. V., Villeneuve, P. J., Jerrett, M., Goldberg, M. S., Arden Pope, C., Brauer, M., Brook, R. D., Robichaud, A., Menard, R., & Burnett, R. T. (2015). Ambient PM2.5, O3, and NO2 exposures and associations with mortality over 16 years of follow-up in the Canadian Census Health and Environment Cohort (CanCHEC). *Environmental Health Perspectives*, *123*(11), 1180–1186. https://doi.org/10.1289/ehp.1409276

Cui, F., Zhang, L., Yu, C., Hu, S., & Zhang, Y. (2016). Estimation of the disease burden attributable to 11 risk factors in Hubei Province, China: A comparative risk assessment. *International Journal of Environmental Research and Public Health*, *13*(10). https://doi.org/10.3390/ijerph13100944

Department of Environment. (2001). *Environmental Quality Report 2000*.

Department of Environment. (2009). *Environmental Quality Report 2008*.

Department of Environment. (2013). ENVIRONMENTAL QUALITY REPORT 2013 contents.

Department of Environment. (2022). *Environmental Quality Report 2022*.

Du, J., Yang, J., Wang, L., Wu, X., Cao, W., & Sun, S. (2021). A comparative study of the disease burden attributable to PM2.5 in China, Japan and South Korea from 1990 to 2017. *Ecotoxicology and Environmental Safety*, *209*. https://doi.org/10.1016/j.ecoenv.2020.111856

Franchini, M., Mannucci, P. M., Harari, S., Pontoni, F., & Croci, E. (2015). The Health and Economic Burden of Air Pollution. *The American Journal of Medicine*, *128*(9), 931–932. https://doi.org/10.1016/J.AMJMED.2015.03.021

Jo, C. (2014). Cost-of-illness studies: concepts, scopes, and methods. In *Clinical and molecular hepatology* (Vol. 20, Number 4, pp. 327–337). https://doi.org/10.3350/cmh.2014.20.4.327

Kamarul Zaman, N. A. F., Kanniah, K. D., & Kaskaoutis, D. G. (2017). Estimating Particulate Matter using satellite based aerosol optical depth and meteorological variables in Malaysia. *Atmospheric Research*, *193*(November), 142–162. https://doi.org/10.1016/j.atmosres.2017.04.019

Landrigan, P. J. (2012). The hidden costs of environmental contamination. *European Respiratory Journal*, *40*(2), 286–288. https://doi.org/10.1183/09031936.00006112

Li, C., van Donkelaar, A., Hammer, M. S., McDuffie, E. E., Burnett, R. T., Spadaro, J. V., Chatterjee, D., Cohen, A. J., Apte, J. S., Southerland, V. A., Anenberg, S. C., Brauer, M., & Martin, R. V. (2023). Reversal of trends in global fine particulate matter air pollution. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-41086-z

Liu, C.-J., Liu, C.-Y., Mong, N., & Chou, C. (2016). Spatial Correlation of Satellite-Derived PM2.5 with Hospital Admissions for Respiratory Diseases. *Remote Sensing*, *8*(11), 914. https://doi.org/10.3390/rs8110914

Mazeli, M. I., Pahrol, M. A., Abdul Shakor, A. S. ad, Kanniah, K. D., & Omar, M. A. (2023a). Cardiovascular, respiratory and all-cause (natural) health endpoint estimation using a spatial approach in Malaysia. *Science of the Total Environment*, *874*. https://doi.org/10.1016/j.scitotenv.2023.162130

Mazeli, M. I., Pahrol, M. A., Abdul Shakor, A. S., Kanniah, K. D., & Omar, M. A. (2023b). Cardiovascular, respiratory and all-cause (natural) health endpoint estimation using a spatial approach in Malaysia. *Science of The Total Environment*, *874*, 162130. https://doi.org/10.1016/J.SCITOTENV.2023.162130

Mazeli, M. I., Pahrol, M. A., Abdul Shakor, A. S., Kanniah, K. D., & Omar, M. A. (2023c). Cardiovascular, respiratory and all-cause (natural) health endpoint estimation using a spatial approach in Malaysia. *Science of The Total Environment*, *874*, 162130. https://doi.org/10.1016/J.SCITOTENV.2023.162130

Mazeli, M. I., Pahrol, M. A., Shakor, A. S. A., Kanniah, K., & Omar, M. (2023). Cardiovascular, respiratory and all-cause (natural) health endpoint estimation using a spatial approach in Malaysia. *The Science of the Total Environment*, *null*, 162130. https://doi.org/10.2139/ssrn.4306133

Meisner, C., Gjorgjev, D., & Tozija, F. (2023). Estimating health impacts and economic costs of air pollution in the Republic of Macedonia. *South Eastern European Journal of Public Health*. https://doi.org/10.56801/seejph.vi.63

Miraglia, S. G. E. K., Nascimento Saldiva, P. H., & Böhm, G. M. (2005). An evaluation of air pollution health impacts and costs in São Paulo, Brazil. *Environmental Management*, *35*(5), 667–676. https://doi.org/10.1007/s00267-004-0042-9

Mueller, W., Vardoulakis, S., Steinle, S., Loh, M., Johnston, H. J., Precha, N., Kliengchuay, W., Sahanavin, N., Nakhapakorn, K., Sillaparassamee, R., Tantrakarnapa, K., & Cherrie, J. W. (2021). A health impact assessment of long-term exposure to particulate air pollution in Thailand. *Environmental Research Letters*, *16*(5). https://doi.org/10.1088/1748-9326/abe3ba

Ostro, B. (2004). Outdoor air pollution: assessing the environmental burden of disease at national and local levels. *Environmental Burden of Disease Series*, (5), 1–54.

Pandey, A., Brauer, M., Cropper, M. L., Balakrishnan, K., Mathur, P., Dey, S., Turkgulu, B., Kumar, G. A., Khare, M., Beig, G., Gupta, T., Krishnankutty, R. P., Causey, K., Cohen, A. J., Bhargava, S., Aggarwal, A. N., Agrawal, A., Awasthi, S., Bennitt, F., … Dandona, L. (2021). Health and economic impact of air pollution in the states of India: the Global Burden of Disease Study 2019. *The Lancet Planetary Health*, *5*(1), e25–e38. https://doi.org/10.1016/S2542-5196(20)30298-9

Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *JAMA*, *287*(9), 1132. https://doi.org/10.1001/jama.287.9.1132

Prüss-üstün, A., Prüss-üstün, A., Campbell-lendrum, D., Corvalán, C., & Woodward, A. (2003). *Introduction and methods Assessing the environmental burden of disease at national and local levels*. (1).

Robinson, L. A., Hammitt, J. K., & O'Keeffe, L. (2019). Valuing Mortality Risk Reductions in Global Benefit-Cost Analysis. *Journal of Benefit-Cost Analysis*, *10*, 15–50. https://doi.org/10.1017/bca.2018.26

Sun, Z., An, X., Tao, Y., & Hou, Q. (2013). Assessment of population exposure to PM10 for respiratory disease in Lanzhou (China) and its health-related economic costs based on GIS. *BMC Public Health*, *13*(1). https://doi.org/10.1186/1471-2458-13-891

Wang, S., Song, R., Xu, Z., Chen, M., Di Tanna, G. L., Downey, L., Jan, S., & Si, L. (2024). The costs, health and economic impact of air pollution control strategies: a systematic review. In *Global Health Research and Policy* (Vol. 9, Number 1). BioMed Central Ltd. https://doi.org/10.1186/s41256-024-00373-y

WHO. (2021). WHO Air quality guidelines 2021 - Aiming for healthier air for all.

World Bank Group. (2022a). *The Global Health Cost of PM2.5 Air Pollution: A Case for Action Beyond 2021*. The World Bank. https://doi.org/10.1596/978-1-4648-1816-5

World Bank Group. (2022b). *The Global Health Cost of PM2.5 Air Pollution: A Case for Action Beyond 2021*. The World Bank. https://doi.org/10.1596/978-1-4648-1816-5

Yu, W., Ye, T., Zhang, Y., Xu, R., Lei, Y., Chen, Z., Yang, Z., Zhang, Y., Song, J., Yue, X., Li, S., & Guo, Y. (2023). Global estimates of daily ambient fine particulate matter concentrations and unequal spatiotemporal distribution of population exposure: a machine learning modelling study. *The Lancet Planetary Health*, *7*(3), e209–e218. https://doi.org/10.1016/S2542-5196(23)00008-6

Yue, H., He, C., Huang, Q., Yin, D., & Bryan, B. A. (2020). Stronger policy required to substantially reduce deaths from PM2.5 pollution in China. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-15319-4