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An Economic Analysis of the Environmental Impact of $PM_{2.5}$ Exposure on Health Status in Three Northwestern Mexican Cities

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Abstract: Introduction: This study provides an economic assessment of the health effects due to exposure to particulate matter $PM_{2.5}$ in three medium-size cities of northwestern Mexico: Los Mochis, Culiacan and Mazatlán. People in these cities are exposed to high pollutant concentrations that exceed limits suggested in domestic and international guidelines. $PM_{2.5}$ is an air contaminant negatively associated with people's health when is highly concentrated in the atmosphere; its diameter is below 2.5 µm and causes the air to appear hazy when levels are elevated. To account for the economic impact of air pollution, a Health Impact Assessment (HIA) was used by the means of the European Aphekom Project. We figured the cost-savings of complying with current environmental standards and computed gains in life expectancy, total avoidable premature mortality, preventable cardiovascular disease, and the economic costs of air pollution related to $PM_{2.5}$. A formal analysis of air pollution epidemiology is not pursued in this paper. Results: The cost of reducing $PM_{2.5}$ pollution associated with negative health outcomes was based on two different scenarios: Official Mexican Standard (NOM, Spanish acronym) and World Health Organization (WHO) environmental standards. The mean $PM_{2.5}$ concentrations in 2017 were 22.8, 22.4 and 14.1 $\mu g/m^3$ for Los Mochis, Mazatlán and Culiacan, respectively. Conclusions: The mean avoidable mortality for all causes associated to $PM_{2.5}$ exposure in these cities was 638 for the NOM scenario (i.e., with a reduction to 12 $\mu g/m^3$) compared to 739 for the WHO scenario (reduction to 10 $\mu g/m^3$). Complying with the WHO guideline of 10 $\mu g/m^3$ in annual $PM_{2.5}$ mean would add up to 15 months of life expectancy at age 30, depending on the city. The mean economic cost per year of the $PM_{2.5}$ effects on human life in these three cities was USD 600 million (NOM scenario) and USD 695 million (WHO scenario). Thus, effective public health and industrial policy interventions to improve air quality are socially advantageous and cost-saving to promote better health.

Keywords: Value of Statistical Life; human health; avoidable mortality; life expectancy; air pollution

1. Introduction

Air pollution caused by industrialization and population growth is a major public health problem worldwide. Evidence shows that current levels of air pollution in major urban areas place a considerable risk for human health [1]. The Global Burden of Disease Study [2] estimates that 7.2 million premature deaths in 2017 were due to environmental factors, of which 3.4 million were due to ambient fine particulate matter ($PM_{2.5}$) and ozone pollution [3]. Particulate matters can travel long distances from their sources. Due to different chemical and microbial characteristics, they can potentially impact on public health and ecosystems [4]. According to the Institute for Health Metrics and Evaluation (IHME) [5], air pollution is the fourth leading cause of mortality worldwide, and the $PM_{2.5}$ is one of the most harmful pollutants. Moreover, ambient air can be a potential source for exposure to PM_{10} and $PM_{2.5}$ and increase the risk of respiratory diseases and cardiovascular problems among exposed people [6]. The $PM_{2.5}$ particles are either solid or liquid microparticulates suspended in the air with an aerodynamic diameter of less than 2.5 micrometers (μm) [7–12]. The existing literature on environmental studies uses Health Impact Assessment (HIA) methods and comprises a combination of procedures by which a policy or program is evaluated as to its potential effects on people's health status and the distribution of those effects within the population [13]. Analyses of environmental pollution in North America [14] and Europe [15] reveal that chronic exposure to $PM_{2.5}$ is associated with increased mortality in the long run. The World Health Organization (WHO) [16] estimates that around 7 million people die from exposure to breathing particulate matter every year. $PM_{2.5}$ travels through the airways into the lungs, stays in the alveoli, affecting the cardiovascular system and triggering cerebrovascular events, heart diseases, lung cancer, chronic obstructive lung disease and respiratory infections [17–21].

Furthermore, evidence shows the links between cardiometabolic and mental diseases to related to specific levels of $PM_{2.5}$ in cities with a high human concentration and industrial activity. The current literature has documented the positive relationship between $PM_{2.5}$ and a wide range of diseases such as stroke [22]; Alzheimer's disease and dementia [23]; asthma [24]; atopic dermatitis and rhinitis [25]; low birth weight [26]; breast cancer [27]; melanogenesis [28]; chronic obstructive pulmonary disease [29]; autism spectrum disorders [30]; depression [31]; sleep loss [32]; aggressive behavior [33]; type 2 diabetes [34]; Parkinson [35] and chronic kidney disease [36]. Premature mortality attributable to air pollution around the world increased from 2.2 million deaths per year in 1990 to 4.2 million deaths in 2020 [5]. Premature mortality is adjusted according to regions, countries and is contingent on emission levels, urban concentration, meteorological conditions, government policies on the environment, and other factors. According to World Bank (WB) and the IHME, air pollution and chronic exposure to $PM_{2.5}$ caused around 48 premature deaths per 100,000 inhabitants worldwide [5]. Norway, Australia and Ireland were the countries achieving the highest reductions of air pollution, but Afghanistan, Turkmenistan and Yemen were the countries with the highest risk of dying from $PM_{2.5}$ exposures.

The economic cost of the air pollution from fossil fuels worldwide was around USD 2.9 trillion in 2018, which corresponds to 3.3% of global Gross Domestic Product (GDP) [5]. During the same year, environmental degradation caused by poor air quality in Mexico was associated with 26,484 deaths with estimated losses of USD 37.7 billion, which is equivalent to a 1.9% reduction in the Mexican GDP [5]. Elevated pollution levels experienced in several Mexican regions require strong and clear policy actions to improve air quality and population health. Thus, policymakers should aim to reduce $PM_{2.5}$ emissions below the Mexican Official Standard (NOM, Spanish acronym) [37] of 12 $\mu g/m^3$ or the WHO [38] air quality guideline (10 $\mu g/m^3$). The National Institute of Statistics and Geography (INEGI, Spanish acronym) reported investments to combat environmental pollution equivalent to 2.8% of the Mexican GDP in 2017, the highest share directed to public health in a single year [39].

The National Institute of Ecology and Climate Change (INECC, Spanish acronym) [40] reported that in 2014, at least 753 premature deaths of people 30 years of age and older could be prevented in the Mexico City area if the minimum pollution levels required by law were observed. These economic costs were estimated at USD 1.3 billion according to the NOM [37]. Likewise, under the WHO environmental standards [38], the number of avoidable premature deaths was estimated at 1421, with an economic cost of USD 2.4 billion. For Guadalajara and Monterrey, these statistics were very similar. The central region of Mexico showed a mean yearly $PM_{2.5}$ concentrations of 24.6 $\mu g/m^3$ during 2017, affecting major cities, experiencing twice the normal levels of permissible pollution according to the Mexican standard [37] and 2.5 higher using the WHO guideline [38]. Under these levels of air pollution, an estimated number of 8464 and 9767 could have been avoided with economic benefit estimated at USD 8.8 billion and USD 10.1 billion dollars considering the Mexican standard and WHO metrics, respectively [41]. Trejo-Gonzalez et al. [42] implemented an HIA in 15 Mexican cities showing decreasing $PM_{2.5}$ concentration levels to 12 $\mu g/m^3$ and 10 $\mu g/m^3$ would have avoided 12,722 and 14,666 deaths with an estimated economic cost of USD 20.9 and USD 24.1 billion, respectively. A significant source of environmental pollution is the thermal power plant in Tuxpan (Mexico) since 1991. Pollution emission in this thermoelectrical facility is associated with more than 30 deaths per year and a social cost of USD 9 million [43]. The $PM_{2.5}$ is also associated with labor productivity problems that cause economic losses when this pollutant exceeds the permissible limits. Becerra-Pérez et al. [44] found for three cities from Mexico a total of 261 (NOM) and 354 (WHO) deaths associated to exposure of high levels of air pollution, estimating an economic cost of USD 24 million and USD 34 million for 2017, respectively.

In this study, we hypothesize that the proper implementation of the current environmental policy is crucial to avoid premature mortality due to air pollution and $PM_{2.5}$ emissions. The endpoints of this study are the number of avoidable deaths and the economic cost of air pollution, using both the NOM [37] and WHO guidelines [38]. This examination is noteworthy since there is an absence of HIA evidence at the local level regarding $PM_{2.5}$, health status, and human populations. Environmental problems are highly prevalent in large urban settlements with medium-size cities experiencing similar and even worse air pollution problems. Thus, comprehensive control efforts will be required in addition to local initiatives to improve the air quality in cities [45].

2. Methods

2.1. Study Cities and Data

The three cities considered in this study are located in the state of Sinaloa, Mexico: Culiacan (24°48′32″ latitude and 107°23′38″ longitude), Los Mochis (25°47′00″ latitude and 108°59′40″ longitude), and Mazatlán (23°12′01″ latitude and 106°25′20″ longitude) [46]. These three urban concentrations (Figure 1) account for 63% of the state population, being Culiacan the largest city with a population ~1 million inhabitants (32% of the total state) and population density of 143.6 inhabitants per km^2. Los Mochis and Mazatlán have populations of less than 500,000 each (31% of the total state) with population densities of 112.4 and 198.5 inhabitants per km^2 [47,48].

Figure 1. Location of the three cities examined: Culiacan, Los Mochis and Mazatlán adapted from [49].

Atmospheric emissions records were obtained from Sinaloa State's environmental monitoring system, which has a fixed station in each of the selected cities measuring air quality and $PM_{2.5}$; this monitoring system uses the Tapered Element Oscillating Microbalance (TEOM). Although this method underestimates the semi-volatile components of $PM_{2.5}$, it is used in many cities around the world. To be able to apply Concentration-Response Function (CRF) to data collected by gravimetric methods, it is necessary to correct TEOM data [50]. The local monitoring system applies a correction factor to solve the problem of underestimation of volatile $PM_{2.5}$. The valid average concentration per year of $PM_{2.5}$ in 2017 was selected as the exposure values and were computed based on the daily concentration (hour/day) in the stations. These values align with the NOM regarding the number of observations stating that no more than 25% of the daily measurements should be missed to be acceptable [37]. Demographic and health data of 2017 were obtained from official sources; the INEGI [51] registered mortality based on the main cause of death among residents in our area of study, providing the monthly number of deaths of people 30 years and older. Our HIA included health and demographic information of people 30 years and older. In all cases, we applied the criteria of the International Classification of Diseases (ICD-10), selecting code A00-R99 to classify total mortality (external included) and code I00-I99 to classify cardiovascular diseases only. Population data were retrieved from the 2010 National Population and Housing Census and updated to 2017 using the population growth rates estimates by the Mexico's National Council for Population [52].

2.2. The Concentration-Response Function

The relationship between the concentration of air pollutants with total mortality and cardiovascular diseases helps quantify public health risks. Our sample of cities was chosen on the basis of CRF's data availability, according to the American Cancer Society (ACS) [53]. Our CRF's metrics are based on the long-run average $PM_{2.5}$ concentrations recorded from these sites. We also used the Harvard Six Cities cohort re-analysis [54] as well as the ACS follow up and space analysis, which relates to environmental pollution by particulate matter and mortality rates [53]. These studies provide a reliable estimation of uncertainty and decrease the variability among the exposed populations regarding individual susceptibility, $PM_{2.5}$ composition, minimum and maximum pollution concentrations, and exposition frequency. Pope et al. [55,56] estimated that, for the population >30 years old, the average relative risk (RR) per 10 $\mu g/m^3$ to total mortality of 1.06 [1.02–1.11] and the RR for cardiovascular mortality of 1.12 [1.08–1.15]. In HIA studies, the RR is understood as the relative response at the point of health (e.g., relative mortality) to an increase of 10 $\mu g/m^3$ in the concentration of pollutants. In our case, the RR was selected from previous epidemiological studies to estimate the long-term effects of $PM_{2.5}$ on total and cardiovascular mortality [55,56]. Although the HIA methodology has been standardized in international studies, several local decisions regarding data points and risk factors need to be considered during the estimation of avoidable deaths. In addition, an important variable for this analysis is the coefficient (β value) of the CRF, which directly influences the measurement of avoidable deaths. Following the Aphekom guidelines [50], the health impacts are estimated using the Function (1):

$$\Delta y = y_o \left(1 - e^{-\beta \Delta x}\right) \tag{1}$$

where Δy represents the change (decrease) in avoidable premature deaths associated with the decrease in pollution concentrations; y_o is the baseline health outcome (deaths); e is the Napier constant; Δx is the change (decrease) in the pollution concentrations in a given scenario; β is the coefficient of the CRF. In HIA β, it is defined as $(lnRR/\Delta x)$; in our case, it has the value of 0.0058269 for total mortality [55] and 0.0056664 for cardiovascular mortality [56]. According to this methodology [50], a confidence interval (CI) of Δy can be estimated using the CI of β coefficient. For example, for a $IC_{95\%} = (-1.96; +1.96)$ the following formulas can be applied [50]:

$$\Delta y_{sup} = y_o \left(1 - e^{-(\beta\ -\ 1.96s)\Delta x}\right) \tag{2}$$

$$\Delta y_{sup} = y_o \left(1 - e^{-(\beta\ +1.96s)\Delta x}\right) \tag{3}$$

where Δy_{sup} is CI of Δy; s is an estimate of the standard error of β. In summary, the health impacts are estimated with Formula (1) and its CI with Formulas (2) and (3). It is necessary to clarify that the CI only takes into account the uncertainty in the original β (original research), leaving for outside other local factors of our study area.

2.3. HIA and the European Aphekom Project

The health impacts use different platforms, but the HIA tool developed in the framework of the European Aphekom Project [57] was chosen because it provides meaningful estimates of life expectancy and avoidable deaths that are relevant for this study. A search in PubMed shows the relevance of this tool in the design of HIA studies across different countries. Aphekom was developed to improve knowledge and communication for decision-making on air pollution and health in Europe [57]. This tool has been widely used in several long-run studies in European cities and provided seminal findings that served as the baseline in the design of environmental policies aiming to ameliorate the effects of $PM_{2.5}$ pollution [58–63]. Aphekom tool simulates outputs on how the number of deaths per 100,000 inhabitants would decrease if $PM_{2.5}$ declined under specific predetermined values. This platform also computes the average gains in life expectancy of those exposed to air pollution.

We analyzed the impact of pollution on health under two scenarios: (i) scenario NOM [37], which imply the reduction in the $PM_{2.5}$ average concentration value per year down to 12 μg/m^3 in each of the selected cities. We categorized the variables to estimate gains in life expectancy with standardized mortality rates computed for each 5 years of age; and (ii) scenario WHO [38], which imply the reduction in the $PM_{2.5}$ average concentration value per year down to10 μg/m^3 in each of the appraised cities. The model restrictions were set at $PM_{2.5}$ < 12 μg/m^3 for the NOM and $PM_{2.5}$ < 10 μg/m^3 in the WHO simulation. Furthermore, we used the same β value in all age groups in which the population was classified. Aphekom shows the results as the "number of proposed premature deaths", understood as avoidable and "years of life lost" understood as gains in life expectancy (see Appendix A).

Our economic evaluation requires money values for total avoidable deaths and other effects derived from exposure to poor air quality to understand the tradeoff between the risk of death and money, the so-called Value of a Statistical Life (VSL). We multiplied VSL values by the number of avoidable deaths, which is required to better understand the money cost of the number of deaths by total and cardiovascular mortality. The VSL estimator compares, under a common unit of value, the cost and the benefits of introducing public policy aiming to reduce mortality rates due to air pollution [64]. Although VSL is debatable for ascribing monetary value to human life, this approach quantifies life for statistical and resource allocation purposes, allowing to explain the cost of death. The VSL index has been extensively applied in several economic studies to assess the cost of events. The Organization for Economic Co-operation and Development (OECD) [65] provides a useful framework to estimate the VSL for Mexico, which was applied to the estimated avoidable deaths in our sample of three cities. To compute these values, we used the following formula:

$$VSL_{Mex} = VSL_{OECD}\ (GDPP_{Mex}/GDPP_{OECD})^{\kappa} \quad (4)$$

where VSL_{Mex} is the Mexico's VSL in USD; VSL_{OECD} is the OECD's VSL in USD; $GDPP_{Mex}$ is the Mexico's GDP per capita in 2017; $GDPP_{OECD}$ is the OECD's GDP per capita in 2017; and κ is for income elasticity. Hammit et al. [66] suggested values > 1 for income elasticity (κ) aiming to estimate VSL in developing countries based on VSL of developed countries. We used κ = 1.5 because this is the elasticity value that better expresses social and economic conditions of Mexico with respect to the rest of the OECD countries. All values were normalized and inflated to 2017 using inflationary indexes and were compared with other existing estimations globally. GDP information was retrieved from the World Bank data base [67].

3. Main Results

The analyzed population was stratified by age groups of five years in each class. We accounted for people 30 years and older exposed to air pollution cause by $PM_{2.5}$ during 2017 in three Mexican cities. Table 1 depicts the results per city and the total of the sample in which we can observe that as we move along of the stratified age groups, the number of people potentially affected by air pollution decreases. The median age in the state of Sinaloa is 29 years, and although the state is made up of young people, the effects of $PM_{2.5}$ on older populations can be noticeable. As the person ages, the risk associated with pollution exposure increases due to the presence of multiple comorbidities, loss of mental abilities and the deterioration of physical functioning. Older adults become even more affected by exposure to pollution as they age.

Table 1. Population 30 years and older (2017).

	Age Group (Years)											
City	**30–34**	**35–39**	**40–44**	**45–49**	**50–54**	**55–59**	**60–64**	**65–69**	**70–74**	**75–79**	**80–84**	**85+**
Culiacan	68,995	65,734	64,240	51,435	47,383	35,481	28,357	19,886	15,003	10,199	7522	3168
Los Mochis	30,199	34,642	34,146	29,504	24,159	17,865	14,811	11,730	9143	6200	4050	2061
Mazatlán	37,353	35,686	35,351	32,380	28,990	24,235	18,727	12,634	10,133	7524	3015	2341
Total	136,547	136,062	133,737	113,319	100,532	77,581	61,895	44,250	34,279	23,923	14,587	7570

Figure 2 shows the estimated average concentration per day of $PM_{2.5}$ for each city. Data for Culiacan and Mazatlán display a uniform increasing tendency of $PM_{2.5}$ over time (2017), while in Los Mochis there is an erratic pattern, which may be caused by climatic factors, included changing winds patterns. The $PM_{2.5}$ average concentration per year was estimated at 22.8 (σ = 5) μg/m^3 for Los Mochis; 22.4 (σ = 3) μg/m^3 for Mazatlán; and 14.1 (σ = 2) μg/m^3 for Culiacan. When comparing these results with the maximum levels of established by the domestic [37] and international [38] guidelines, these cities exceed those benchmarks by far. These levels of air pollution are likely putting these communities at higher risk for cardiovascular diseases and lung cancer. These values show that Los Mochis exceeded the maximum levels of pollution by 10.8 and 12.8 μg/m^3 when compared to the NOM and WHO criterions, respectively. Similarly, Mazatlán surpassed these targets by 10.4 and 12.4, as well as Culiacan by 2.1 and 4.1 μg/m^3, correspondingly.

Figure 3 depicts the HIA results showing that the total avoidable mortality rate for both scenarios. Estimates show that the avoidable mortality rate (per 10,000 inhabitants) in the three cities is lower in the NOM scenario than in the WHO scenario. This is because the maximum $PM_{2.5}$ limit allowed by the NOM is higher (12 μg/m^3) than that of the WHO (10 μg/m^3). The results also show the classification of cities by the number of avoidable mortality due to $PM_{2.5}$ pollution: Mazatlán, Los Mochis and Culiacan. Although the city of Culiacan is the largest city (Sinaloa's Capital), it registered the lowest mortality rate, which could indicate, in advance, that it has fewer fixed sources and/or there is better control over them (see Figure 3).

These findings support the idea that life expectancy would increase with a reduction in the $PM_{2.5}$ average concentration per year below the national [37] and international [38] recommended guidelines. Using the NOM measures, we sustain that mean increases in the life expectancy would be 13 months for Los Mochis and Mazatlán, and 5 months for Culiacan. Under the WHO scenario, mean increases in the life expectancy would be 15 months for Los Mochis and Mazatlán, and 7 months for Culiacan. These results are consistent with the estimated rate of avoidable deaths per city because higher reductions in $PM_{2.5}$ concentrations are expected to yield greater gains of life expectancy.

Premature avoidable deaths per year in 2017 associated with $PM_{2.5}$ occurring among people 30 years and older were estimated per each city of our sample. We measured three variables per location to include total deaths, cardiovascular deaths and gains in life expectancy. According to the NOM simulation, in Culiacan, the average of total avoidable mortality and cardiovascular deaths were 158 and 85 individuals, respectively. In Los Mochis, total avoidable death had a mean of 227 people and for cardiovascular death was 132 persons, while in Mazatlán avoidable death averaged 253 people and for cardiovascular deaths was 127 people. These results indicate that total number of avoidable deaths in the three cities for all causes were 638, avoidable cardiovascular deaths were 344 and gains in life expectancy would be 12 months, being Los Mochis and Mazatlán the cities with the largest gains (Table 2).

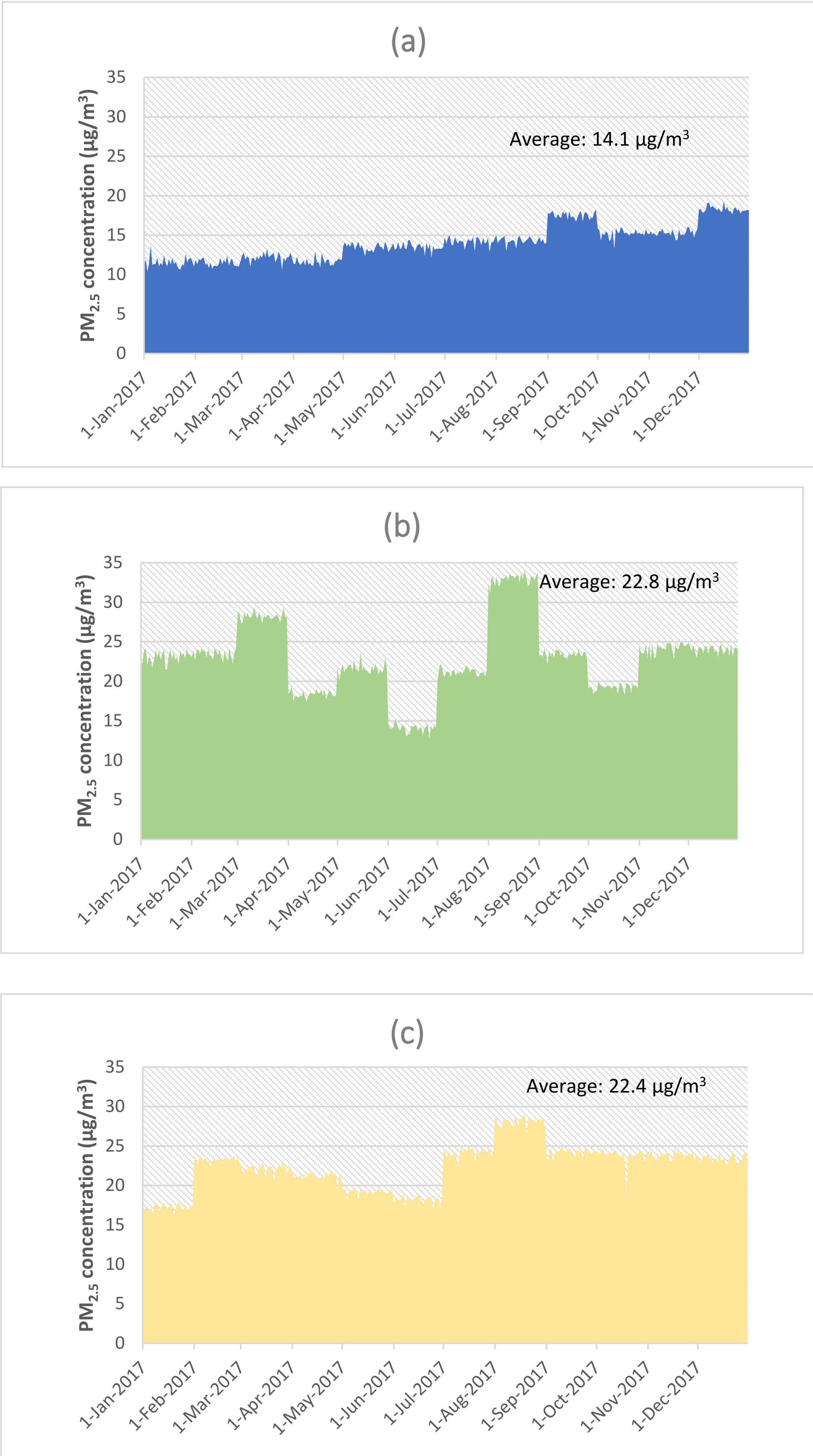
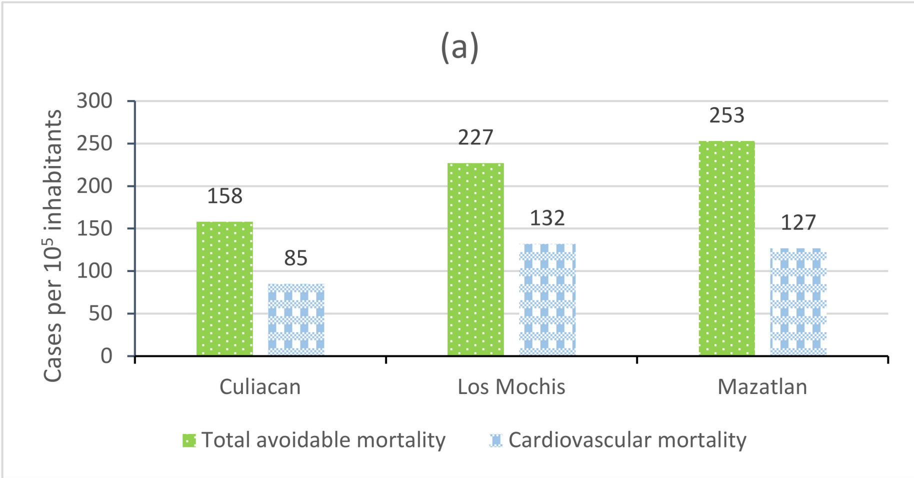


Figure 2. $PM_{2.5}$ Daily average concentrations (µg/m^3) in participating cities: (**a**) Culiacan; (**b**) Los Mochis; (**c**) Mazatlán.



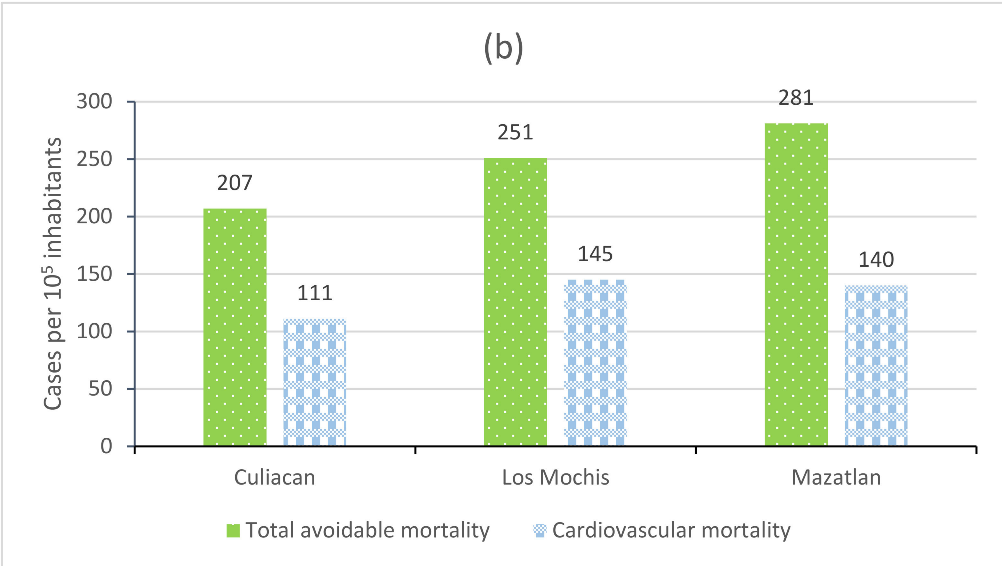


Figure 3. Avoidable mortality rate due to the reduction in $PM_{2.5}$ concentration (cases per 100,000 inhabitants). Chart (**a**): NOM scenario. Chart (**b**): WHO scenario.

Table 2 also shows the result for the WHO scenario. In Culiacan, the mean of the total avoidable mortality was 207 people, and for cardiovascular death, 111 individuals. Under these same variables, Los Mochis had a mean of 251 avoidable deaths and 145 cardiovascular deaths. Mazatlán could have avoided an average of 281 and 140 cardiovascular deaths. Considering average estimations only, the total number of avoidable deaths in the three cities was 396 with potential gains in life expectancy of 15 months, having the largest gains in Los Mochis and Mazatlán. According to these average values and aggregating the data for the three cities, the total avoidable fatalities associated to high levels of $PM_{2.5}$ for 2017 in Sinaloa were estimated as 638 and 739, depending on the metric (NOM [37] or WHO [38]) considered.

An Economic Assessment of the Impact of Air Pollution in Northwestern Mexico

The VSL calculated for Mexico was between \$453,435 USD (minimum), \$939,894 USD (mean) and USD 1,948,243 (maximum) with an income elasticity equal to 1.5. Under the NOM scenario, the economic impact due to total mortality was USD 148.6, USD 213.3 and USD 237.8 million for Culiacan, Los Mochis and Mazatlán, respectively. The total cost of total mortality for the three cities was USD 599.7 million. Using the NOM scenario, the economic cost of cardiovascular deaths was USD 79.9, USD 124.1 and USD 119.4 million for Culiacan, Los Mochis and Mazatlán with a total cost equivalent to USD 323.3 million (Table 3). Using the WHO scenario, the economic impact caused by total mortality (mean) was USD 194.6, USD 235.9 and USD 264.1 million for Culiacan, Los Mochis and Mazatlán, respectively, totaling USD 694.6 million for these three cities. For cardiovascular death, the economic cost was USD 104.3 for Culiacan, USD 136.2 for Los Mochis and USD 131.6 for Mazatlán with a total amount of USD 372.2 million (Table 3). The overall economic cost per year of the $PM_{2.5}$ effects on human life in these three Sinaloa's cities was estimated on about USD 599.7 and USD 694.6 million, for the NOM and WHO scenarios, respectively.

Table 2. Total Avoidable and Cardiovascular Death and Gains in Life Expectancy Due to Reduction in $PM_{2.5}$ concentration.

Cities	Scenario NOM			Scenario WHO		
	Min.	**Mean**	**Max.**	**Min.**	**Mean**	**Max.**
			Total mortality (number of deaths)			
Culiacan	105	158	212	138	207	276
Los Mochis	154	227	303	167	251	335
Mazatlán	169	253	337	187	281	375
Total	428	638	852	492	739	986
			Cardiovascular mortality (number of deaths)			
Culiacan	57	85	113	74	111	148
Los Mochis	88	132	176	97	145	193
Mazatlán	85	127	169	94	140	189
Total	230	344	458	265	396	530
			Gain in life expectancy (months)			
Culiacan	3	5	7	5	7	9
Los Mochis	8	13	19	9	15	22
Mazatlán	8	13	19	9	15	22

Table 3. Economic Impacts of Mortality by Avoidable and Cardiovascular Death (Millions, USD) [a].

Cities	Scenario NOM			Scenario WHO		
	Min.	**Mean**	**Max.**	**Min.**	**Mean**	**Max.**
			Total mortality			
Culiacan	98.7	148.5	199.2	129.7	194.5	259.4
Los Mochis	144.7	213.3	284.8	156.9	235.9	314.8
Mazatlán	158.8	237.7	316.7	175.7	264.1	352.4
Total	402.2	599.6	800.7	462.3	694.5	926.6
			Cardiovascular mortality			
Culiacan	53.6	79.9	106.2	69.5	104.3	139.1
Los Mochis	82.7	124.1	165.4	91.1	136.3	181.4
Mazatlán	79.9	119.3	158.8	88.3	131.6	177.6
Total	216.2	323.3	430.4	248.9	372.2	498.1

[a] The calculated VSL value for Mexico is USD 939,894 (2017).

These costs were elevated because air pollution levels in these Sinaloa's cities significantly exceeded the NOM [37] and WHO [38] permissible levels. Further examination of air quality and pollution would include a cost-benefit analysis to compare these estimated costs with the benefits of allocating monetary resources to public policy, aiming to mitigate and control this environmental deterioration.

4. Discussion

There is a shortage of HIA studies exploring the environmental impact caused by poor air quality in Mexican cites and developing countries in general. Our work focused on settlements with less than one million residents in a sample of three cities in the northwestern

(Sinaloa), Mexico. We identified that these cities have $PM_{2.5}$ average concentrations way above the recommended national [37] and international [38] guidelines, causing harm to human health that can be prevented. It is worth mentioning that the city with the largest population (Culiacan) experience the lowest economic impact, compared to the other two cities. A plausible explanation is that Culiacan, as the state capital, has few fix sources of emission such as low levels of industrialization, low population density (144 inhabitants per km^2), favorable geographic location and compass rose among other factors. Conversely, Los Mochis and Mazatlán have substantially higher rates of avoidable death than Culiacan. These two cities have thermal power stations to produce electricity operating with a toxic pollutant fossil fuel known as "combustoleo", a by-product in the oil refining process. Besides, Mazatlán and Los Mochis are heavy traffic seaports moving high volumes of containerized and in bulk cargo; these cities are also the headquarters of local companies and have pipelines that facilitate environmental pollution caused by oil. In Los Mochis, this situation is worsening due to the ongoing installation of an ammonia production plant near the city (~20 km), at the margin of the Ohuira-Topolobampo lagoon complex. This plant will produce 770,000 tons of ammonia per year using natural gas, a less toxic than other fossil fuels, however, is expected to increase the emission of H_2, CO_2, NH_3, CO, H_2S and $PM_{2.5}$ [68], adding this impact to that caused by the thermal power plant.

Although the HIA methodology is solid [55,56], some features were not captured in this analysis, such as the representativeness of the population and other possible forms of the CRF. We argue that value of the impact to chronic exposure of $PM_{2.5}$ on health was likely underestimated because of the variations of the pollutant within a city with heavy traffic, source of pollution from specific industries and the thermal power plants. Our findings suggest that variations in air quality within a city can be wider than those variations across cities [69,70]. Also, the use of TEOM technologies to measure particulate matter may underestimate the real exposure because of its intermittence, even when using a factor for local correction. The abovementioned CRF analysis performed by the US American Cancer Society shed important light regarding the long-term effect of chronic pollution exposure by $PM_{2.5}$ [53–55]. Similarly, European cohort studies [71] and Canadian analyses have found similar relative risk ratios [72].

Our HIA results show estimations of the number of avoidable deaths in three different cities in northwestern Mexico as well as its corresponding money values, demonstrating the benefits of reducing pollution levels at or below the NOM [37] and WHO [38] recommended guidelines, thus our initial hypothesis was accomplished. The findings of this study can contribute policy on the economic and human cost of air pollution; thus, complying with the Official Mexican Standard and the "ProAire" program guidelines implemented by the Mexico's Secretariat of Environment and Natural Resources [73] would decrease the number of avoidable deaths with its commensurate gains in life expectancy in these three Mexican cities. Estimating the economic cost of pollution may have a great social impact and is beneficial in terms of public health.

5. Conclusions

Using the HIA strategy, we estimate the total avoidable deaths associated with air pollution and computed the economic costs for three northwestern Mexican cities. These findings allow us to derive the total cost derived from air pollution attributable to $PM_{2.5}$ and better understand the benefits of reducing environmental pollution below the maximum allowed under two scenarios. Under the NOM scenario [37], we determined that 638 deaths could be avoided (158 in Culiacan, 227 in Los Mochis and 253 in Mazatlán). We also established that life expectancy would increase by 5, 13 and 13 months for people in these cities, respectively. Regarding the WHO scenario [38], total avoidable deaths were 739 in our sample of cities, being 207 in Culiacan, 251 in Los Mochis and 281 in Mazatlán, with a corresponding gain in the mean life expectancy of 7, 15 and 15, respectively. We quantified the average cost of the impact on health as a result of $PM_{2.5}$ with a value around USD 600 and 695 million. However, we consider that the figures aforesaid were underestimated because it does not itemize important evaluation features such as morbidity, loss of productivity, number of days absent at work, and population younger than 30 years of age. Our results contribute to the existing empirical body of evidence emphasizing the economic and social benefits of abiding federal and state environmental policies aiming to reduce current levels of environmental pollution by $PM_{2.5}$ in these three Mexican cities. Efforts to continuously reduce airborne pollution are socially beneficial and economically advantageous. The role of proactive environmental and public policies is key to ameliorate the effect of the $PM_{2.5}$ pollutants.

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Appendix A. Procedure to Estimate Gains in Life Expectancy

Long-term Health Impact Assessment (HIA) can also be estimated in terms of life expectancy gains. The procedure shown below was made following the guidelines for assessing the health impacts of air pollution in European cities developed by Aphekom [50] to estimate gains in life expectancy. The data for this exercise correspond to Culiacan (Sinaloa, Mexico) for the year 2017. The selected fatalities were total mortality (code A00-R99) and cardiovascular diseases (code 100–199) according to the criteria of the International Classification of Diseases (ICD-10). This estimator was computed based on a hypothetical cohort of 100,000 people of 30 years and older. The first step is to estimate mortality rate on each interval of the population as follows in Formula (A1):

$$ {}_{n}M_{x} = {}_{n}D_{x}/({}_{n}N_{x})(Y) \tag{A1} $$

where:

x is the duration interval of each age group;
x is the starting age in each group;
${}_{n}M_{x}$ is is the mortality rate in each age group;
${}_{n}D_{x}$ is the total number of deaths in each age group averaged over Y years (increasing 5 years starting at 30 years), according to the International Classification of Diseases (ICD-10);
${}_{n}N_{x}$ is the population in each age group;
Y is the number of years used in the HIA.

In our assessment, n adopts a value of 5 to represent the different classes and n_{ax} is the average number of years lived by a person who died during interval [... + n], which is estimated by $(n/2)$. The next step is to calculate the probability of dying in each age group $({}_{n}q_{x})$, as shown in Formula (A2):

$$ {}_{n}q_{x} = (n)\ ({}_{n}M_{x})/[1 + (n - n_{ax})\ ({}_{n}M_{x})] \tag{A2} $$

In the last age category (85+) ${}_{n}q_{x} = 1$, because the likelihood of dying is almost eminent.

The estimation process of gains in life expectancy assumes that the first age interval is the beginning of the cycle and the whole cohort is alive (n = 100,000) as defined in l_x, but for the rest of the process, we calculate this value using Formula (A3):

$$l_{x+n} = l_x\ (1 - {}_nq_x) \tag{A3}$$

where:

l_{x+n} is the number of people alive in each age group, excluding the first interval.

The following step is to estimate the number of people who died in each age group (${}_nd_x$) using Formula (A4):

$${}_nd_x = l_x\ ({}_nq_x) \tag{A4}$$

Then, we compute the number of years/persons lived within each age group (${}_nL_x$) by the means of Formula (A5):

$${}_nL_x = (n)\ (l_{x+n} + n_{ax})\ ({}_nd_x) \tag{A5}$$

We obtain the last age group value (${}_nL_x$) as follows (A6):

$${}_nL_x = l_x / {}_nM_x \tag{A6}$$

From the above Formula (A6), we repeatedly estimated the number of years/persons who live after reaching age x, called them T_x by the means of Formula (A7):

$$T_x = T_{x+n} + {}_nL_x \tag{A7}$$

The life expectancy of the current period (e_x, where x = 30) is estimated. This Formula (A8) is very important because determines the main input to obtain life expectancy:

$$e_x = T_x / l_x \tag{A8}$$

Likewise, we estimated life rates at each age interval (S_x) as follows (A9):

$$S_x = l_x / 100{,}000 \tag{A9}$$

The life tables capturing the impact of changes in air pollution was based on the previous procedure but ${}_nD_x$ is replaced by the dependent variable in the following specification (A10):

$${}_nD_x{}^{impacted} = ({}_nD_x)\ (e^{-\Delta_x(\beta)}) \tag{A10}$$

where:

${}_nD_x{}^{impacted}$ is the total number of deaths in each age group modified according to the ICD-10.

In summary, the life tables estimated (base and impacted) are the inputs to compute gains in life expectancy using the Aphekom tool [50] (see Table A1).

Table A1. Exercise to estimate the gain in life expectancy, Culiacan city (2017).

Age	${}_nN_x$	${}_nD_x$	n	n_{ax}	${}_nM_x$ (A1)	${}_nq_x$ (A2)	l_{x+n} (A3)	${}_nd_x$ (A4)	${}_nL_x$ (A5, A6)	T_x (A7)	e_x (A8)	S_x (A9)
30–34	68,995	239	5	2.5	0.003	0.017	100,000	1717.139	495,707.152	4,638,382.221	46.384	1
35–39	65,734	206	5	2.5	0.003	0.016	98,282.861	1528.043	487,594.196	4,142,675.068	42.151	0.983
40–44	64,240	241	5	2.5	0.004	0.019	96,754.818	1798.042	479,278.982	3,655,080.872	37.777	0.968
45–49	51,435	221	5	2.5	0.004	0.021	94,956.775	2018.317	469,738.085	3,175,801.890	33.445	0.950
50–54	47,383	231	5	2.5	0.005	0.024	92,938.459	2238.173	459,096.859	2,706,063.805	29.117	0.929
55–59	35,481	328	5	2.5	0.009	0.045	90,700.285	4097.641	443,257.323	2,246,966.946	24.774	0.907
60–64	28,357	332	5	2.5	0.012	0.057	86,602.644	4925.494	420,699.486	1,803,709.623	20.827	0.866
65–69	19,886	397	5	2.5	0.020	0.095	81,677.150	7765.364	388,972.342	1,383,010.137	16.933	0.817

Table A1. *Cont.*

Age	$_nN_x$	$_nD_x$	n	n_{ax}	$_nM_x$ (A1)	$_nq_x$ (A2)	l_{x+n} (A3)	$_nd_x$ (A4)	$_nL_x$ (A5, A6)	T_x (A7)	e_x (A8)	S_x (A9)
70–74	15,003	404	5	2.5	0.027	0.126	73,911.787	9323.787	346,249.465	994,037.794	13.449	0.739
75–79	10,199	525	5	2.5	0.051	0.228	64,587.999	14,728.185	286,119.534	647,788.330	10.030	0.646
80–84	7522	496	5	2.5	0.066	0.283	49,859.815	14,112.342	214,018.218	361,668.796	7.254	0.499
85+	3168	767			0.242	1	35,747.473	35,747.473	147,650.578	147,650.578	4.130	0.357

Note: the parentheses in the column headings indicate the applied formula number.

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