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

Luis Armando Becerra-Pérez (✉ becerra@uas.edu.mx)

Autonomous University of Sinaloa: Universidad Autonoma de Sinaloa <https://orcid.org/0000-0001-6919-0621>

Roberto A. Ramos-Álvarez

Autonomous University of Sinaloa: Universidad Autonoma de Sinaloa

Juan J. DelaCruz

Lehman College of CUNY Division of Natural and Social Science

Benjamín García-Páez

UNAM Facultad de Economía: Universidad Nacional Autónoma de México Facultad de Economía

Federico Páez-Osuna

Instituto de Ciencias del Mar y Limnología: Universidad Nacional Autónoma de México Instituto de Ciencias del Mar y Limnología

Guillermo Cedeño-Laurent

Harvard University T H Chan School of Public Health

Elena Boldo

Carlos III Health Institute: Instituto de Salud Carlos III

Research

Keywords: Value of a statistical life, Human health, Avoidable mortality, Life expectancy, Air pollution

Posted Date: June 1st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-559152/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

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

Luis A. Becerra-Pérez ^{a, *}, Roberto A. Ramos-Álvarez ^b, Juan J. DelaCruz ^c, Benjamín García-Páez ^d, Federico Páez-Osuna ^e, J. Guillermo Cedeño-Laurent ^f, Elena Boldo ^g

^a Economics and Social Sciences Faculty, Autonomous University of Sinaloa; Blvd. Universitarios y Av. de las Américas, Módulo III, C.U., 80010 Culiacán, Sinaloa, México.

^b Program in Social Sciences, Autonomous University of Sinaloa; Blvd. Universitarios y Av. de las Américas, Módulo III, C.U., 80010 Culiacán, Sinaloa, México.

^c Lehman College, The City University of New York; 250 Bedford Park Boulevard West, Bronx, NY 10468, USA.

^d Faculty of Economy, Division of Postgraduate Studies, National Autonomous University of Mexico; Interior s/n Ciudad Universitaria, Coyoacán, 04510 CDMX, México.

^e Institute of Sciences of the Sea and Limnology, National Autonomous University of Mexico; Cap. Joel Montes Camarena s/n, Cerro del Vigía 82000, Mazatlán, Sinaloa, México.

^f Harvard T.H. Chan School of Public Health, Harvard University; 677 Huntington Ave, Boston, MA 02115, USA.

^g Consortium for Biomedical Research in Epidemiology and Public Health (CIBERESP), Carlos III Institute of Health and, Environmental Health Department, Madrid City Council, Madrid, Spain. Avenida Mediterráneo 62, planta 1ra 28007, Madrid, España.

* Corresponding author: becerra@uas.edu.mx

Abstract

Background: This study provides an assessment of the health effects due to exposure to particulate matter PM_{2.5} (diameter < 2.5 µm that cause the air to appear hazy when levels are elevated) in three medium size cities of north western Mexico (Los Mochis, Culiacan and Mazatlan). We computed the total avoidable premature mortality, avoidable cardiovascular disease, gains in life expectancy, as well as the economic costs by air contamination corresponding to PM_{2.5}. To achieve this goal, the Health Impacts Assessment (HIA) methodology provided by the European Aphekom Project was used. People in these cities are exposed to high PM_{2.5} concentrations that exceed limits implemented in domestic and international guidelines.

Results: We determined the cost of the PM_{2.5} pollutant associated with health outcomes under two different scenarios: Official Mexican Standard (NOM, Spanish acronym) and World Health Organization (WHO). The mean PM_{2.5} concentrations in 2017 were 22.8, 22.4 y 14.1 µg/m³ for the cities Los Mochis, Mazatlan and Culiacan, respectively. The mean avoidable mortality for all causes associated to the exposure to PM_{2.5} in the three cities was 638 for the NOM scenario (i.e., with a reduction to 12 µg/m³) compared to 739 for the WHO scenario (reduction to 10 µg/m³). Complying with the WHO guideline of 10 µg/m³ in annual PM_{2.5} mean would add up to 15 months of life expectancy at age 30, depending on the city.

Conclusions: The mean economic cost per year of the PM_{2.5} effects on human life in these three cities was \$600 (NOM scenario) and \$695 million dollars (WHO scenario). Effective public health and industrial policy interventions are socially advantageous and cost-saving to promote better health.

Keywords: Value of a statistical life, Human health, Avoidable mortality, Life expectancy, Air pollution

Background

Air pollution caused by industrialization and population growth is a major public health issue worldwide. Empirical evidence shows that current levels of air pollution in major urban areas place a considerable risk for human health [5]. The Global Burden of Disease Study [23] 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 [44]. This particulate matter is an air pollutant that is negatively associated with people's health when is highly concentrated in air. According to the Institute for Health Metrics and Evaluation [33], air pollution is the fourth leading cause of mortality worldwide, and the PM_{2.5} is one of the most harmful pollutants. The PM_{2.5} are either solid or liquid microparticulate suspended in the air with an aerodynamic diameter of at most 2.5 micrometers (μm), which is equivalent to one thousandth of a millimeter [13, 15, 32, 34, 58, 67]. Health Impact Assessments (HIA) methods are often used in environmental studies. HIA comprises a combination of procedures by which a policy or program is evaluated as to its potential effects on people's health and the distribution of those effects within the population [20].

Studies of environmental pollution in North America [63] and in Europe [8] reveal that chronic exposure to PM_{2.5} is associated with increased mortality in the long run. The World Health Organization [68] estimates that around 7 million people die from exposure to breathing particulate matter every year. These fine particulate travels through the airways into the lungs, stay in the alveoli and affect the cardiovascular system, causing cerebrovascular events, heart diseases, lung cancer, chronic obstructive lung disease and respiratory infections [1, 17, 22, 48, 68, 70].

Furthermore, empirical evidence shows the links between cardiometabolic and mental diseases to related to specific levels of PM_{2.5} in cities with high human concentration and industrial activity.

82 The current literature has documented the positive relationship between PM_{2.5} and a wide range of
83 diseases such as stroke [72]; Alzheimer and dementia [61]; asthma [4]; atopic dermatitis and
84 rhinitis [28]; low birth weight [62]; breast cancer [73]; melanogenesis [54]; chronic obstructive
85 pulmonary disease [27]; autism spectrum disorders [12]; depression [21]; sleep loss [31];
86 aggressive behavior [9]; type 2 diabetes [71]; Parkinson [26] and chronic kidney disease [69].
87 Premature mortality attributable to air pollution around the world increased 32% from 2.2 million
88 deaths per year in 1990 to 2.9 million deaths in 2013 [33]. Premature mortality is adjusted
89 according to regions, countries and is contingent on emission levels, urban concentration,
90 meteorological conditions (winds, sun, height, heat or relative humidity), government policies on
91 the environment and other factors. Based on World Bank (WB) and Institute for Health Metrics
92 and Evaluation (IHME) [33] estimations, air pollution and exposure to PM_{2.5} caused around 48
93 premature deaths per 100,000 inhabitants worldwide with Norway, Australia and Ireland being the
94 countries achieving the highest reduction of air pollution. Conversely, Afghanistan, Turkmenistan
95 and Yemen were the countries with the highest risk of dying from PM_{2.5} exposures. The economic
96 cost of the air pollution worldwide was estimated to be around \$5.1 trillion US dollars (USD) in
97 2013 [33]. During the same year, environmental degradation caused by poor air quality in Mexico
98 was associated to 26,484 deaths with estimated losses of \$37.7 billion USD, which is equivalent
99 to 1.9% reduction in the Mexican Gross Domestic Product (GDP) [33]. Elevated pollution levels
100 experienced in several Mexican regions require strong and clear policy actions to improve air
101 quality and population's health, thus policy makers should aim to reduce PM_{2.5} emissions below
102 the Mexican Official Standard NOM-025-SSA1-2014 [50] of 12 µg/m³ or the WHO [66] air
103 quality guideline (10 µg/m³). 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 [41].

The National Institute of Ecology and Climate Change (INECC, Spanish acronym) [35] reported environmental statistics for the three largest urban concentrations of Mexico. In 2014, 753 premature deaths of people 30 years of age and older could be prevented in the Mexico City and its metropolitan area if the minimum pollution levels required by law were observed with an economic cost estimated in \$1.3 billion USD according to the NOM [50]. Likewise, under the WHO environmental standards [66], the number of avoidable premature deaths were estimated at 1,421 with an economic cost of \$2.4 billion USD. For Guadalajara, this report [35] estimated 301 avoidable deaths with an economic impact of \$475 million USD (of 2010) under the Mexican standard [50] and 394 avoidable deaths with a cost of \$634 million USD (of 2010) under the WHO guideline [66]. For Monterrey, the number of avoidable deaths were 263 under the Mexican standard with a cost of \$396 million USD and the number of avoidable deaths were 355 with an economic impact of \$554 million USD of 2010, respectively [35]. Moreover, the central region of Mexico showed a mean yearly PM_{2.5} concentrations of 24.6 µg/m³ during 2017, affecting areas such as Mexico City, Toluca, Puebla, Hidalgo, Queretaro, Morelos and Tlaxcala. These places experienced twice the normal levels of permissible pollution according to the Mexican standard [50] and 2.5 higher using the WHO guideline as reference [66]. Under these levels of air pollution, an estimated number of 8,464 and 9,767 could have been avoided with economic benefit estimated as \$8.8 billion USD and \$10.1 billion dollars considering the Mexican standard and WHO metrics, respectively [36].

Trejo-Gonzalez et al. [60] implemented a HIA in 15 Mexican cities (Mexico City, Toluca, Guadalajara, Guanajuato, Monterrey, Queretaro, Puebla, Tlaxcala, Tepic, Merida, Leon, Silao,

Irapuato, Salamanca and Celaya), showing that the mean concentration of PM_{2.5} per year ranged between 9.4 µg/m³ and 32.3 µg/m³, being the lowest concentration in Tepic and the highest in Toluca. Under hypothetical scenarios, decreasing PM_{2.5} concentration levels to 12 µg/m³ y 10 µg/m³ would have avoided 12,722 and 14,666 deaths with an estimated economic cost of \$20.9 and \$24.1 billion USD respectively. A significant site of environmental pollution is located around the thermal power plant in Tuxpan (State of Veracruz); this plant has produced dangerous levels of pollution caused by the emission of PM_{2.5} since it was built in 1991. Pollution emission in this thermoelectrical facility is associated with more than 30 deaths per year and a social cost of \$9 million USD [74]. The PM_{2.5} is also associated with labor productivity problems that cause economic losses when this pollutant exceeds the permissible limits. From this perspective, Becerra-Pérez et al. [6] found for three cities in northwestern Mexico (Culiacan, Mazatlan, and Los Mochis) a total of 261 (NOM) and 354 (WHO) preventable deaths occur as result of the exposure to high levels of air pollution, estimating an economic cost of \$ 24 million and \$ 34 million for 2017, respectively.

The study uses the HIA framework to quantify the environmental effect on health outcomes and the economic costs of PM_{2.5} exposure in Culiacan, Los Mochis and Mazatlan, cities located in the northwestern State of Sinaloa, Mexico. 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 Official Mexican Standard (NOM-025-SSA1-2014) [50] and the WHO guideline [66]. This research is significant because there is an absence of HIA evidence at the local level regarding particulate matter, health status and human populations. Environmental

problems are highly prevalent in large urban settlements and medium size cities with similar and even worst air pollution issues.

Methods

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" length), Los Mochis (25°47'00" latitude and 108°59'40" length), and Mazatlan (23°12'01" latitude and -106°25'20" length) [40]. 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 km². Los Mochis and Mazatlan have populations of less than 500,000 each (31% of the total state) with population densities of 112.4 and 198.5 inhabitants per km² [37, 38, 42].

Fig. 1. Location of the three cities examined: Culiacan, Los Mochis and Mazatlan [38]

Atmospheric emissions records were obtained from the State of Sinaloa's environmental monitoring system, which has a fixed station in each of the selected cities measuring air quality and in particular PM_{2.5}. To measure these PM_{2.5}, this monitoring system uses the *Tapered Element Oscillating Microbalances* technology (TEOM), which is a widely used method to collect data on PM_{2.5} in real time. The valid average concentration per year of PM_{2.5} in 2017 were selected as the exposure values, which were computed based on the daily concentration (hour/day) in the stations. These values align with the Mexican standard (NOM-025-SSA1-2014) regarding the number of observations stating that no more than 25% of the daily measurements should be missed to be acceptable [50]. Demographic and health data of 2017 were obtained from official sources; the INEGI [39] 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 only included health and demographic information of people 30 years and older in the three cities of our sample. 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. Additionally, population data was 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 [14].

The Concentration-Response Function (CRF)

The relationship between the concentration of air pollutants with total mortality and cardiovascular diseases helps quantify public health risks. Our sample of cities were chosen on the basis of CRF's data availability according to the American Cancer Society (ACS) [56], the largest research assessing the effects of air pollution on human health. 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 [46] as well as the ACS follow up and space analysis, which relates environmental pollution by particulate matter to mortality rates [45]. These studies provide 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. [56,57] also estimated an average relative risk (RR) of general mortality of 1.06 [95% CI: 1.02-1.11] and a RR for cardiovascular disease equal to 1.12 with a [95% CI: 1.08-1.15]. A confidence interval (CI) describes the variability between the measure obtained in a study and the actual measure of the population (the true value) as well as indicates that within the given range is the real value of a parameter with 95% certainty [24, 49, 64].

Although the HIA methodology has been standardized in international studies, several local decisions regarding data points and risk factors need to be taken into account during the estimation of avoidable deaths. An important variable for this analysis is the CRF coefficient (β value) which directly influences the measurement of the impact of pollutant exposure on population given changes in the concentration level. This basic relationship can be expressed as follows [3]:

$$\Delta y = y_0 - e^{-\Delta x \beta} \dots\dots\dots (1)$$

Where Δy represents the change in avoidable premature deaths in the health result associated with the decrease in pollution concentrations at the baseline; y_0 is the base health outcome (deaths according to ICD-10); e is the Napier constant; Δx is the change of pollution concentrations in a given scenario; β is the concentration-response function (CRF) coefficient, which is calculated according to:

$$CRF = \frac{\ln(RR)}{\Delta C} \dots\dots\dots (2)$$

Where CRF is the concentration-response function; $\ln(RR)$ is the natural logarithm of the relative risk (RR), which was selected from previous epidemiological studies to estimate the long-term effects of $PM_{2.5}$ on overall and cardiovascular mortalities; ΔC captures deviations in pollution concentration from $10 \mu g/m^3$ [56, 57]. The Δ value was computed when variables in equation (2), representing the relationship between changes in the particulate matter concentration and changes in the impact on the exposed population.

Tool used: Aphekom

HIA is a robust methodology designed to quantify the impact of air pollution on human health as a result of air pollution by particulate matters. HIA uses different platforms and among them the one developed by the European Aphekom Project, which describes specific equations to estimate life expectancy and avoidable early deaths [2]. Aphekom is a European project developed to improve knowledge and communication for decision-making on air pollution and health in Europe [3]. This tool is based on MS Excel and has been widely used in several long run studies for 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 (*e.g.* 10, 11, 29, 30, 47, 55]. Aphekom 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 used Aphekom as a tool to analyze the impact of pollution on health under two scenarios: (i) scenario NOM, which imply the reduction in the $PM_{2.5}$ average concentration value per year down to $12 \mu g/m^3$ in each of the selected cities. Furthermore, Aphekom requires the classification of the population into categories to estimate gains in life expectancy, thus standardized mortality rates were computed for each 5 years of age. This simulation responds to the assumptions of the

Mexican normativity NOM-025-SSA1-2014, which establish $12 \mu\text{g}/\text{m}^3$ to be the maximum allowed level of air pollution [50]; and (ii) scenario WHO, which imply the reduction in the $\text{PM}_{2.5}$ average concentration value per year down to $10 \mu\text{g}/\text{m}^3$ in each of the appraised cities. This scenario abides to the WHO international benchmarks that requires emission below to $10 \mu\text{g}/\text{m}^3$ [66].

The model restrictions were set at $\text{PM}_{2.5} < 12 \mu\text{g}/\text{m}^3$ for the NOM and $\text{PM}_{2.5} < 10 \mu\text{g}/\text{m}^3$ in the WHO simulation. In both cases, the reduction in pollution concentration is equal to zero, assuming that total current deaths would not be attributed to the abovementioned pollutant. Furthermore, we used the same Δ 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).

Mexico’s value of a statistical life (VSL)

Our economic evaluation requires a method capable to quantify the money value of total avoidable deaths and other effects derived from exposure to poor air quality due to high levels of pollutants. There are different types of methodologies aiming to estimate the value of life, cost of disability and losses in productivity caused by air pollution. Independently of the approach, we multiplied the Value of a Statistical Life (VSL) by the number of avoidable deaths. In our study, the VSL was 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 [18]. Although VSL is debatable for ascribing money 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) [51] 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:

$$VSL\ Mexico = VSLOECD * \left(\frac{PIBpMexico}{PIBpOECD} \right)^e \dots\dots\dots (3)$$

Where *VSL México* is the Mexico's VSL in USD; *VSLOECD* is the OECD's VSL in USD; *PIBpMexico* is the Mexico's GDP per capita in 2017; *PIBpOECD* is the OECD's GDP per capita in 2017; and *e* is for income elasticity. Hammit et al. [25] suggested values > 1 for income elasticity (e) aiming to estimate VSL in developing countries based on VSL of developed countries. We used *e* = 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 [65].

Results

Avoidable deaths and life expectancy

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 a sample of three 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, which is explained by the natural tendency of biological age of the population. The median age in the state of Sinaloa is 29 years and although the state is mainly made out of young people, the effects of PM_{2.5} on older populations can be noticeable. As the person ages, the risk associated to pollution exposure increases due to the presence of multiple

comorbidities, loss of mental abilities and the deterioration of physical functioning. Older adults become the most susceptible to exposure to pollution as they age.

Table 1 Total population in the study cities over 30 years old in 2017

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	7,522	3,168
Los Mochis	30,199	34,642	34,146	29,504	24,159	17,865	14,811	11,730	9,143	6,200	4,050	2,061
Mazatlan	37,353	35,686	35,351	32,380	28,990	24,235	18,727	12,634	10,133	7,524	3,015	2,341
Total	136,547	136,062	133,737	113,319	100,532	77,581	61,895	44,250	34,279	23,923	14,587	7,570

Figure 2 shows the estimated average concentration per day of PM_{2.5} for each city. Data for Culiacan and Mazatlan display a uniform increasing tendency of PM_{2.5} over time, 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 ($\square=5$) $\mu\text{g}/\text{m}^3$ for Los Mochis; 22.4 ($\square=3$) $\mu\text{g}/\text{m}^3$ for Mazatlan; and 14.1 ($\square=2$) $\mu\text{g}/\text{m}^3$ for Culiacan. When comparing these results with the maximum levels of established by the domestic [50] and international [66] guidelines, these cities exceed by far those benchmarks. 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 $\mu\text{g}/\text{m}^3$ when compared to the NOM [50] and WHO [66] criterions, respectively. Similarly, Mazatlan surpassed these targets by 10.4 and 12.4, as well as Culiacan by 2.1 and 4.1 $\mu\text{g}/\text{m}^3$, correspondingly.

(a)

(b)

(c)

Fig. 2. PM_{2.5} Daily average concentrations (µg/m³) in cities participating in the study (a) Culiacan, (b) Los Mochis, (c) Mazatlan during 2017

Figure 3 depicts the HIA results showing that the total avoidable mortality rate under the NOM for Los Mochis was 104 cases per 10^5 inhabitants, 102 cases for Mazatlan and 38 cases for Culiacan. Also, under the NOM, avoidable cardiovascular mortality was estimated by 61 cases for Los Mochis, 51 cases for Mazatlan and 20 cases per 10^5 inhabitants for Culiacan. Under the WHO scenario, the total avoidable mortality rate for Los Mochis was 115 events per 10^5 inhabitants, 113 events for Mazatlan and 50 events for Culiacan. Likewise, under the WHO, avoidable cardiovascular mortality was estimated by 67 events for Los Mochis, 57 events for Mazatlan and 27 events per 10^5 inhabitants for Culiacan.

333
334 (a)

335
336
337
338
339 (b)

340
341
342 **Fig. 3.** Avoidable total and cardiovascular mortality due to the reduction in PM_{2.5} concentration
343 levels (a) (cases per 100,000 inhabitants) (b), for population older than 30 years in the three cities
344 examined
345

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 [50] and international [66] recommended guidelines. Using the NOM measures, we sustain that mean increases in the life expectancy would be 13 months for Los Mochis and Mazatlan, and 5 months for Culiacan. Under the WHO scenario, mean increases in the life expectancy would be 15 months for Los Mochis and Mazatlan, 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 associated with PM_{2.5} occurring among people 30 years and older were estimated per each city of our sample showing the minimum, mean and maximum. 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 total avoidable mortality ranged from 105 to 212 (mean = 158) people and cardiovascular death from 57 to 113 (mean = 85) people. In Los Mochis, total avoidable death fluctuated from 154 to 303 (mean = 227) people and cardiovascular death fluctuated between 88 and 176 (mean = 132) people, while in Mazatlan avoidable death oscillated between 169 and 337 (mean = 253) people and the range for cardiovascular deaths was 85 to 167 (mean = 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 Mazatlan the cities with the largest gains (Table 2).

Table 2 also shows result for the WHO scenario. In Culiacan, the total avoidable mortality ranged 138 and 276 (mean = 207) people and the number of deceased for cardiovascular illnesses fluctuated between 74 and 148 (mean = 111) people. Under these same variables, Los Mochis had

167 to 335 (mean = 251) avoidable deaths and 97 to 193 (mean = 145) cardiovascular deaths. Mazatlan could have avoided between 187 to 375 (mean = 281) and 94 to 189 (mean = 140) cardiovascular deaths. Considering average estimations only, the total number of avoidable deaths in the three cities were 396 with potential gains in life expectancy of 15 months, having the largest gains in Los Mochis and Mazatlan. According 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 or WHO) considered.

Table 2 Avoidable total and cardiovascular mortality due to the reduction in PM_{2.5} concentration levels (total cases), and increase in gain in life expectancy for population older than 30 years

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
Mazatlan	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
Mazatlan	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
Mazatlan	8	13	19	9	15	22

Economic evaluation

The VSL calculated for Mexico was between \$453,435 USD (minimum), \$939,894 USD (mean) and \$1,948,243 (maximum). With an income elasticity equal to 1.5, we decided to utilize the mean value to estimate the economic cost of air pollution by PM_{2.5}. Under the NOM scenario, the economic impact due to total mortality was \$148.6, \$213.3 and \$237.8 million USD for Culiacan, Los Mochis and Mazatlan, respectively. The total cost of total mortality for the three cities was \$599.7 million USD. Using the NOM scenario, the economic cost of cardiovascular deaths was \$79.9, \$124.1 and \$119.4 million USD for Culiacan, Los Mochis and Mazatlan with a total cost equivalent to \$323.3 million USD (Table 3). Using the WHO scenario, the economic impact caused by total mortality (mean) was \$194.6, \$235.9 and \$264.1 million USD for Culiacan, Los Mochis and Mazatlan, totaling \$694.6 million USD for these three cities. For cardiovascular death, the economic cost was \$104.3 for Culiacan, \$136.2 for Los Mochis and \$131.6 for Mazatlan with a total amount of \$372.2 million USD (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 \$599.7 and \$694.6 million USD, for the NOM and WHO scenarios, respectively.

Table 3 Economic impacts of mortality by avoidable total and cardiovascular mortality in the studied cities (USD)^a

Cities	Scenario NOM			Scenario WHO		
	Min.	Mean	Max.	Min.	Mean	Max.
Total mortality						
Culiacan	98,688,870	148,503,252	199,257,528	129,705,372	194,558,058	259,410,744
Los Mochis	144,743,676	213,355,938	284,787,882	156,962,298	235,913,394	314,864,490
Mazatlan	158,842,086	237,793,182	316,744,278	175,760,178	264,110,214	352,460,250
Total	402,274,632	599,652,372	800,789,688	462,427,848	694,581,666	926,735,484
Cardiovascular mortality						
Culiacan	53,573,958	79,890,990	106,208,022	69,552,156	104,328,234	139,104,312
Los Mochis	82,710,672	124,066,008	165,421,344	91,169,718	136,284,630	181,399,542
Mazatlan	79,890,990	119,366,538	158,842,086	88,350,036	131,585,160	177,639,966
Total	216,175,620	323,323,536	430,471,452	249,071,910	372,198,024	498,143,820

^a The calculated VSL value for Mexico is \$939,894 (USD, 2017).

These costs were elevated because air pollution levels in these Sinaloa's cities exceeded significantly the NOM [50] and WHO [66] 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.

Discussion

There is a shortage of HIA studies exploring the environmental impact caused by poor air quality in Mexican cities and developing countries in general. This work focused on settlements with less than one million residents to prove that a sample of three cities in the northwestern (Sinaloa), Mexico have PM_{2.5} average concentrations way above the recommended national [50] and international [66] guidelines, causing harm to human health that can be avoided. 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 km²), favorable geographic location and compass rose among other factors. Conversely, Los Mochis and Mazatlan have comparable and 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, Mazatlan 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 the case of Los Mochis city, this situation can worsen due to the planned 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 H₂, CO₂, NH₃, CO, H₂S and PM_{2.5} [52], adding this impact to that caused by the thermal power plant.

Although the HIA methodology is solid [56,57], there are some features that we were unable to capture in our 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, particularly in urban areas with heavy traffic and around specific industries and the thermal power plants, like in Mazatlan and Los Mochis. Our findings suggest that variations in air quality within a city can be wider than those variations across cities [43, 53]. 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 CRF of the US American Cancer Society provides the best available evidence regarding the long-term effect of chronic pollution exposure by PM_{2.5} [56, 45, 46]. European cohort studies [7] and Canadian analyses have found similar relative risk ratios [16]. 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 [50] and WHO [66] 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 [59] 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.

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 know 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 [50] scenario, we determined that 638 deaths could be avoided (158 in Culiacan, 227 in Los Mochis and 253 in Mazatlan). We also established that life expectancy would increase in 5, 13 and 13 months for people in these cities in the same order. Regarding the WHO [66] scenario, total avoidable deaths were 739 in our sample of cities, being 207 in Culiacan, 251 in Los Mochis and 281 in Mazatlan, with a corresponding gain in the mean life expectancy of 7, 15 and 15 in the same order. We quantified the average cost of the impact on health as a result of PM_{2.5} with value around \$600 and \$695 million USD. 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. Thus, controlling air pollution is socially beneficial and the role of environmental and public policies are key to ameliorate the effect of the PM_{2.5} pollutants.

Supplementary information accompanies this paper

Appendix A: Procedure to Estimate Gains in Life Expectancy

Abbreviations

ACS: American Cancer Society; Aphekom: Tool designed by the European Aphekom Project to quantify the impact of air pollution on human health; CI: Confidence Interval; CRF: Concentration-Response Function; GDP: Gross Domestic Product; HIA: Health Impacts Assessment; ICD-10: International Classification of Diseases; IHEM: Institute for Health Metrics and Evaluation, University of Washington, Seattle; INECC: National Institute of Ecology and Climate Change (Spanish acronym); INEGI: National Institute of Statistics and Geography (Spanish acronym); NOM scenario: 12 $\mu\text{g}/\text{m}^3$ (NOM-025-SSA1-2014); NOM: Official Mexican Standard (Spanish acronym); OECD: Organization for Economic Co-operation and Development; PM_{2.5}: particulate matter suspended in the air with an aerodynamic diameter of at most 2.5 micrometers (μm); RR: Relative Risk; TEOM: Tapered Element Oscillating Microbalances technology; US: United States of America; USD: United States of America Dollar; VSL: Value of a Statistical Life; WB: World Bank; WHO scenario: 10 $\mu\text{g}/\text{m}^3$ (WHO, 2006); WHO: World Health Organization; μm : micrometers.

Acknowledgements

We would like to thank the National Council of Science and Technology of Mexico for the scholarship awarded to RARA.

Authors' contributions

Conceptualization and study design: LABP and RARA; review of literature and drafting: LABP and RARA; writing-review and editing: LABP, JDC, FPO, BGP, JGCL and EB; field and laboratory work: LABP and RARA; software: EB; resources, funding acquisition, supervision, and project administration: LABP.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare no conflict of interest.

References

1. Anenberg SC, Horowitz LW, Tong DQ, West JJ (2010) An Estimate of the Global Burden of Anthropogenic Ozone and Fine Particulate Matter on Premature Human Mortality Using Atmospheric Modeling. *Environ Health Perspect* 118: 1189-1195. <https://doi.org/10.1289/ehp.0901220>
2. Aphekom Project (2013) Health Impact Assessment Tool Long Term. www.aphekom.org. Accessed 10 January 2020
3. Aphekom (2013) The Aphekom Project Improving knowledge and communication for decision making on air pollution and health in Europe. http://aphekom.org/c/document_library/get_file?uuid=3f436766-812c-4658-a901-ca52ee5d8e35&groupId=10347. Accessed 20 August 2019
4. Arriagada NB, Horsley JA, Palmer AJ, Morgan GG, Tham R, Johnston FH (2019) Association between fire smoke fine particulate matter and asthma-related outcomes: Systematic review and meta-analysis. *Environ Res* 179: 108777. <https://doi.org/10.1016/j.envres.2019.108777>
5. Barret RH, Speth RL, Eastham SD, Dedoussi IC, Ashok A, Malina R, Keith DV (2015) Impact of the Volkswagen emissions control defeat device on US public health. *Environ Res Lett* 10: 114005. <https://doi.org/10.1088/1748-9326/10/11/114005>
6. Becerra-Pérez LA, Ramos-Álvarez RA (2020) Evaluación del Impacto en la Salud por Partículas PM_{2.5} en Sinaloa, México. *Rev Int Contam Ambie* 36 (2): 249-259. <http://dx.doi.org/10.20937/RICA.53463>
7. Beelen R, Hoek G, van den Bravndt PA, Goldbohm RA, Fischer P, Schouten LJ, Jerret M, Hughes E, Armstrong B, Brunekreef B (2008) Long-term effects of traffic-related air

pollution on mortality in a Dutch cohort [NLCS-AIR study]. *Environ Health Perspect* 116: 196–202. <https://doi.org/10.1289/ehp.10767>

8. Brook RD, Rajagopalan S, Pope CA, Brook JR, Bhatnagar A, Diez-Roux AV, Holguin F, Hong Y, Luepker RV, Mittleman MA, Peters A, Siscovick D, Smith SC Jr, Whitsel L, Kaufman JD (2010) Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circ* 121: 2331-2378. <https://doi.org/10.1161/CIR.0b013e3181dbeece1>
9. Burkhardt J, Bayham J, Wilson A, Carter E, Berman JD, O'Dell K, Ford B, Fischer EV (2019) The effect of pollution on crime: evidence from data on particulate matter and ozone. *Journal of Environmental Economics and Management* 98: 102267
10. Chanel O, Henschel S, Goodman P, Analitis A, Atkinson RW, Le Tertre A, Zeka A, Medina S, Aphekom group (2014). Economic valuation of the mortality benefits of a regulation on SO₂ in 20 European cities. *Eur J Public Health* 24: 631-637. <https://doi.org/10.1093/eurpub/cku018>
11. Chanel O, Perez P, Künzli K, Medina S, Aphekom Group (2016) The hidden economic burden of air pollution-related morbidity: evidence from the Aphekom project. *Eur J Health Econ* 17: 1101-1115. <https://doi.org/10.1007/s10198-015-0748-z>
12. Chun H, Leung C, Wen SW, McDonald J, Shin HH (2020) Maternal exposure to air pollution and risk of autism in children: A systematic review and meta-analysis. *Environ Pollut* 256: 113307. <https://doi.org/10.1016/j.envpol.2019.113307>
13. Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, Balakrishnan K, Brunekreef B, Dandona L, Dandona R, Feigin V, Freedman G, Hubbell B, Jobling A, Kan H, Knibbs L, Liu Y, Martin R, Morawska L, Pope CA, Shin H, Straif K, Shaddick G,

- Thomas M, Dingenen R, Van Donkelaar A, Van Vos T, Murray C JL, Forouzanfar MH (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389: 1907–1918. [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6)
14. CONAPO (2017) Proyección de la población de México y de las Entidades Federativas, 2016-2050. Consejo Nacional de Población, México. <https://www.gob.mx/conapo/acciones-y-programas/conciliacion-demografica-de-mexico-1950-2015-y-proyecciones-de-la-poblacion-de-mexico-y-de-las-entidades-federativas-2016-2050>. Accessed 20 April 2019
15. Crippa M, Janssens-Maenhout G, Guizzardi D, Van Dingenen R, Dentener F (2019) Contribution and uncertainty of sectorial and regional emissions to regional and global PM_{2.5} health impacts. *Atmos Chem Phys* 19: 5165–5186. <https://doi.org/10.5194/acp-19-5165-2019>
16. Crouse L, Peters PA, Van Donkelaar A, Goldberg MS, Villeneuve PJ, Brion O, Khan S, Atari DO, Jerret M, Pope CA, Brauer M, Brook JR, Martin RV, Stieb D, Burnett RT (2012) Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study. *Environ Health Perspect* 120: 708–714. <https://doi.org/10.1289/ehp.1104049>
17. De Keijzer C, Agis D, Ambrós A, Arévalo G, Baldasano JM, Bande S, Barrera-Gómez J, Benach J, Cirach M, Dadvand P, Ghigo S, Martínez-Solanas E, Nieuwenhuijsen M, Cadum E, Basagaña X (2017) The association of air pollution and greenness with mortality and life expectancy in Spain: A small-area study. *Environ Int* 99: 170–176. <https://doi.org/10.1016/j.envint.2016.11.009>

18. De Lima M (2019) The value of a statistical life in México. J Environ Econ Policy 9: 140-166. <https://doi.org/10.1080/21606544.2019.1617196>
19. Declercq C, Pascal M, Corso M, Ung M, Medina S, on behalf of the Aphekom WP5 team (2011) Health impacts of urban air pollution in 25 European cities. http://www.aphekom.org/c/document_library/get_file?uuid=4f388abf-61e5-415d-ae22-e437a4e25937&groupId=10347. Accessed 17 August 2020
20. European Centre for Health Policy (1999) Health Impact Assessment: main concepts and suggested approach. Gothenburg consensus paper, Brussels. <https://web.archive.org/web/20061007033923/http://www.who.dk/document/PAE/Gothenburgpaper.pdf>. Accessed 15 February 2020
21. Fan SJ, Heinrich J, Bloom MS, Zhao TY, Shi TX, Feng WR, Sun Y, Shen JC, Yang ZC, Yang BY, Dong GH (2020) Ambient air pollution and depression: A systematic review with meta-analysis up to 2019. Sci Total Environ 701: 134721. <https://doi.org/10.1016/j.scitotenv.2019.134721>
22. Forouzanfar MH, Alexander L, Anderson HR, Bachman VF, Biryukov S, Brauer M, Burnett R, Casey D, Coates MM, Cohen A, Delwiche K, Estep K, Frostad JJ, Astha KC, Kyu HH, Moradi-Lakeh M, Ng M, Slepak EL, Thomas BA, Wagner J, Murray CJ (2015) Global, regional, and national comparative risk assessment of 79 behavioral, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet 386: 2287–2323. [https://doi.org/10.1016/S0140-6736\(15\)00128-2](https://doi.org/10.1016/S0140-6736(15)00128-2)
23. GBD Results (2017) Global Burden of Disease Study, 2017. <https://vizhub.healthdata.org/gbd-compare/>. Accessed 28 May 2020

24. Guyatt G, Jaeschke R, Heddle N, Cook D, Shannon H, Walter S (1995) Basic statistics for clinicians [Interpreting study results: confidence intervals]. CMAJ [Canadian Medical Association Journal] 152(2): 169–173.
25. Hammitt JK, Robinson LA (2011) The income elasticity of the value per statistical life: transferring estimates between high and low income populations. J Benefit-Cost Anal 2: 1-29. <https://doi.org/10.2202/2152-2812.1009>
26. Han C, Lu Y, Cheng H, Wang C, Chan P (2020) The impact of long-term exposure to ambient air pollution and second-hand smoke on the onset of Parkinson disease: a review and meta-analysis. Public Health 179:100-110. <https://doi.org/10.1016/j.puhe.2019.09.020>
27. Han F, Yang X, Xu D, Wang Q, Xu D (2019) Association between outdoor PM_{2.5} and prevalence of COPD: a systematic review and meta-analysis. Post Med J 95: 612-618. <https://doi.org/10.1136/postgradmedj-2019-136675>
28. Hassoun Y, James C, Bernstein DI (2019) The effects of air pollution on the development of atopic disease. Clin Rev Allergy Immun 57: 403-414. <https://doi.org/10.1007/s12016-019-08730-3>
29. Henschel S, Atkinson R, Zeka A, Le Tertre A, Analitis A, Katsouyanni K, Chanel O, Pascal M, Forsberg B, Medina S, Goodman PG (2012) Air pollution interventions and their impact on public health. Int J Public Health 57: 757-768. <https://doi.org/10.1007/s00038-012-0369-6>
30. Henschel S, Querol X, Atkinson R, Pandolfi M, Zeka A, Le Tertre A, Analitis A, Katsouyanni K, Chanel O, Pascal M, Bouland C, Haluza D, Medina S, Goodman PG (2014) Ambient air SO₂ patterns in 6 European cities. Atmos Environ 79: 236-247. <https://doi.org/10.1016/j.atmosenv.2013.06.008>

31. Heyes A, Zhu M (2019) Air pollution as a cause of sleeplessness: social media evidence from a panel of Chinese cities. *J of Environ Economics and Management* 98: 102247.
32. Hoek G, Krishnan RM, Beelen R, Peters A, Ostro B, Brunekreef B, Kaufman JD (2013) Long-term air pollution exposure and cardio- respiratory mortality: a review. *Environ Health* 12: 43. <https://doi.org/10.1186/1476-069X-12-43>
33. IHME, World Bank (2016) The Cost of Air Pollution: Strengthening the Economic Case for Action (English), Washington, DC, World Bank Group, Report Number 108141, Volume No 1. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/781521473177013155/the-cost-of-air-pollution-strengthening-the-economic-case-for-action>. Accessed 20 June 2019
34. Im U, Brandt J, Geels C, Hansen KM, Christensen JH, Andersen MS, Solazzo E, Kioutsioukis I, Alyuz U, Balzarini A, Baro R, Bellasio R, Bianconi R, Bieser J, Colette A, Curci G, Farrow A, Flemming J, Fraser A, Jimenez-Guerrero P, Kitwiroon N, Liang CK, Nopmongcol U, Pirovano G, Pozzoli L, Prank M, Rose R, Sokhi R, Tuccella P, Unal A, Vivanco MG, West J, Yarwood G, Hogrefe C, Galmarini S (2018) Assessment and economic valuation of air pollution impacts on human health over Europe and the United States as calculated by a multimodel ensemble in the framework of AQMEII3. *Atmos Chem Phys* 18: 5967–5989. <https://doi.org/10.5194/acp-18-5967-2018>
35. INECC (2014) Valoración económica de los beneficios a la salud de la población que se alcanzarían por la reducción de las PM_{2.5} en tres zonas metropolitanas mexicanas. INECC, México. https://www.gob.mx/cms/uploads/attachment/file/195224/2014_CGCSA_Beneficios_economicos_al_reducir_PM2.5.pdf. Accessed 15 March 2020

36. INECC (2017) Estimación de impactos en la salud por contaminación atmosférica en la región centro del país y alternativas de gestión. INECC, México. http://cambioclimatico.gob.mx:8080/xmlui/bitstream/handle/publicaciones/52/738_2017_Estimacion_impactos_contaminacion_atmosferica_centropais.pdf?sequence=1&isAllowed=Accessed. Accessed 15 March 2020
37. INEGI (2015) Densidad de población. Instituto Nacional de Estadística y Geografía. <https://www.inegi.org.mx/app/buscador/default.html?q=densidad+de+poblacion#tabMCCollapse-Indicadores>. Accessed 17 January 2020
38. INEGI (2017) Anuario estadístico y geográfico de Sinaloa 2017. http://www.internet.contenidos.inegi.org.mx/contenidos/Productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/anuarios_2017/702825094898.pdf. Accessed 25 February 2020
39. INEGI (2017) Información sobre el volumen de las defunciones registradas en el país, así como algunas características por edad y sexo de los fallecidos y las principales causas que originan los decesos. <https://www.inegi.org.mx/temas/mortalidad/>. Accessed 8 March 2020
40. INEGI (2018) Anuario estadístico y geográfico por entidad federativa 2018. http://internet.contenidos.inegi.org.mx/contenidos/Productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/AEGPEF_2018/702825107017.pdf. Accessed 28 April 2020
41. INEGI (2018) Cuentas Económicas y Ecológicas de México. DGAdC, INEGI. <https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2019/StmaCntaNal/CtasEcmcasEcolgicas2018.pdf>. Accessed 22 May 2020

42. INEGI (2010) Censo de Población y Vivienda 2010. <https://www.inegi.org.mx/programas/ccpv/2010/>. Accessed 8 May 2020
43. Jerrett M, Burnett RT, Ma R, Pope CA, Krewski D, Newbold KB, Thurston G, Shi Y, Finkelstein N, Calle EE, Thun MJ (2005) Spatial analysis of air pollution and mortality in Los Angeles. *Epidemiol* 16: 727–736. <https://doi.org/10.1097/01.ede.0000181630.15826.7d>
44. Jin Y, Andersson H, Zhang S (2020) Do preferences to reduce health risks related to air pollution depend on illness type? Evidence from a choice experiment in Beijing, China. *Journal of Environmental Economics and Management* 103: 102355.
45. Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, Thun MJ (2009) Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality [No. 140]. Boston, MA: Health Effects Institute. <https://www.healtheffects.org/publication/extended-follow-and-spatial-analysis-american-cancer-society-study-linking-particulate>. Accessed 13 June 2020
46. Laden F, Schwartz J, Speizer FE, Dockery DW (2006) Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities study. *Am J Respir Crit Care Med* 173: 667-672. <https://doi.org/10.1164/rccm.200503-443OC>
47. Le Tertre A, Henschel S, Atkinson RW, Analitis A, Zeka A, Katsouyanni K, Goodman P, Medina S (2014) Impact of legislative changes to reduce the sulphur content in fuels in Europe on daily mortality in 20 European cities: an analysis of data from the Aphekom Project. *Air Qual Atmos Health* 7: 83-91. <https://doi.org/10.1007/s11869-013-0215-x>

48. Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A (2015) The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525: 367–371. <https://doi.org/10.1038/nature15371>
49. Montori VM, Kleinbart J, Newman TB, Keitz S, Wyer PC, Moyer V, Guyatt G, Evidence-Based Medicine Teaching Tips Working Group (2004) Tips for learners of evidence-based medicine: Measures of precision [confidence intervals]. *CMAJ [Canadian Medical Association Journal]* 171(6): 611–615. <https://doi.org/10.1503/cmaj.1031667>
50. NOM-025-SSA1-2014 [Norma Oficial Mexicana, salud ambiental] (2014) Valores límite permisibles para la concentración de partículas suspendidas PM₁₀ y PM_{2.5} en el aire ambiente y criterios para su evaluación. Secretaría de Salud, DOF. https://www.dof.gob.mx/nota_detalle.php?codigo=5357042&fecha=20/08/2014. Accessed 20 January 2020
51. Organization for Economic Co-operation and Development (2016) The economic consequences of outdoor air pollution. OECD Publishing, Paris. <https://www.oecd.org/environment/indicators-modelling-outlooks/Policy-Highlights-Economic-consequences-of-outdoor-air-pollution-web.pdf>. Accessed 27 March 2020
52. Páez-Osuna F, Flores-Campaña LM, Karam-Quñones C, Páez-Michel AL, Saucedo-Barrón JC, Zavala-Norzagaray A, Osuna-Martínez CC, Becerra-Pérez LA (2018) Alternatives for reducing the environmental impact of an ammonia production plant adjacent to a coastal lagoon in the southeastern Gulf of California. *J Cleaner Prod* 200: 960-970. <https://doi.org/10.1016/j.jclepro.2018.08.020>
53. Pascal M, Corso M, Chanel O, Declercq C, Badaloni C, Cesaroni G, Henschel S, Meister K, Haluza D, Martin-Olmedo P, Medina S (2013) Assessing the public health impacts of

- urban air pollution in 25 European cities: results of the Aphekom Project. *Sci Total Environ* 449: 390-400. <https://doi.org/10.1016/j.scitotenv.2013.01.077>
54. Peng F, Tsuji G, Zhang JZ, Chen Z, Furue M (2019) Potential role of PM_{2.5} in melanogenesis. *Environ Int* 132: 105063. <https://doi.org/10.1016/j.envint.2019.105063>
55. Perez L, Declercq C, Iñiguez C, Aguilera I, Badaloni Ch, Ballester F, Bouland C, Chanel O, Cirarda FB, Forastiere F, Forsberg B, Haluza D, Hedlund B, Koldo C, Lacasaña M, Moshhammer H, Omorep P, Rodríguez-Barranco M, Medina S, Künzli N (2013) Chronic burden of near-roadway traffic pollution in 10 European cities (APHEKOM network). *Eur Resp J* 42: 594-605. <https://doi.org/10.1183/09031936.00031112>
56. Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Kazuhiko I, Thurston GD (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* 287: 1132–1141. <https://doi.org/10.1001/jama.287.9.1132>
57. Pope CA, Burnett RT, Thurston GD, Thun MJ, Calle EE, Krewski D, Godleski JJ (2004) Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. *Cir* 109: 71–77. <https://doi.org/10.1161/01.CIR.0000108927.80044.7F>
58. Pope CA, Dockery DW (2006) Health effects of fine particulate air pollution: lines that connect. *J Air Waste Manage Assoc* 56: 709–742. <https://doi.org/10.1080/10473289.2006.10464485>
59. SEMARNAT (2018) Programas de Gestión para Mejorar la Calidad del Aire en Sin 2018-2028 https://www.gob.mx/cms/uploads/attachment/file/300694/21_ProAire_Sinaloa.pdf. Accessed 11 January 2020

60. Trejo-González AG, Riojas-Rodriguez H, Texcalac-Sangrador JL, Guerrero-López CM, Cervantes-Martínez K, Hurtado-Díaz M, Zuñiga-Bello PE (2019) Quantifying health impacts and economic costs of PM_{2.5} exposure in Mexican cities of the National Urban System. *Int J Public Health* 64: 561-572. <https://doi.org/10.1007/s00038-019-01216-1>
61. Tsai TL, Lin YT, Hwang BF, Nakayama SF, Tsai CH, Sun XL, Ma C, Jung CR (2019) Fine particulate matter is a potential determinant of Alzheimer's disease: A systemic review and meta-analysis. *Environ Res* 177:108638. <https://doi.org/10.1016/j.envres.2019.108638>
62. Tsoli S, Ploubidis GB, Kalantzi OI (2019) Particulate air pollution and birth weight: A systematic literature review. *Atmos Pollut Res* 10: 1084-1122. <https://doi.org/10.1016/j.apr.2019.01.016>
63. US Environmental Protection Agency (2011) The Benefits and Costs of the Clean Air Act: 1990 to 2020. Final report of US Environmental Protection Agency Office of Air and Radiation. <https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act-1990-2020-report-documents-and-graphics>. Accessed 12 January 2020
64. Whitley E, Ball J (2002) Statistics review 2: Samples and populations. *Critical Care* 7(1): 8. <https://doi.org/10.1186/cc1867>
65. World Bank (2017) World Development Report, New York. <https://www.worldbank.org/en/publication/wdr/wdr-archive>. Accessed 12 January 2020
66. World Health Organization (2006) Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. WHO/SDE/PHE/OEH/06.02. https://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/. Accessed 13 February 2020

67. World Health Organization (2013) Review of Evidence on Health Aspects of Air Pollution –REVIHAAP– First Results. WHO Regional Office for Europe. http://www.euro.who.int/_data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report.pdf. Accessed 9 April 2020
68. World Health Organization (2016) Ambient air pollution: A global assessment of exposure and burden of disease. WHO Geneva Switzerland. <https://www.who.int/phe/publications/air-pollution-global-assessment/en/>. Accessed 15 April 2020
69. Wu MY, Lo WC, Chao CT, Wu MS, Chiang CK (2020) Association between air pollutants and development of chronic kidney disease: A systematic review and meta-analysis. Sci Total Environ 706: 135522. <https://doi.org/10.1016/j.scitotenv.2019.135522>
70. Wu R, Dai H, Geng Y, Xie Y, Masui T, Liu Z, Qian Y (2017) Economic Impacts from PM_{2.5} Pollution-Related Health Effects: A Case Study in Shanghai. Environ Sci Technol 51: 5035-5042. <https://doi.org/10.1021/acs.est.7b00026>
71. Yang BY, Fan S, Thiering E, Seissler J, Nowak D, Dong GH, Heinrich J (2020) Ambient air pollution and diabetes: a systematic review and meta-analysis. Environ Res 180: 108817. <https://doi.org/10.1016/j.envres.2019.108817>
72. Yuan S, Wang J, Jiang Q, He Z, Huang Y, Li Z, Cai L, Cao S (2019) Long-term exposure to PM_{2.5} and stroke: A systematic review and meta-analysis of cohort studies. Environ Res 177: 108587. <https://doi.org/10.1016/j.envres.2019.108587>
73. Zhang Z, Yan W, Chen Q, Zhou N, Xu Y (2019) The relationship between exposure to particulate matter and breast cancer incidence and mortality: A meta-analysis. Med 98. <https://doi.org/10.1097/MD.00000000000018349>

74. Zuk M, Garibay V, Iniestra R, López MT, Rojas L, Laguna I (2006) Introducción a la
evaluación de los impactos de las termoeléctricas de México: Un estudio de caso en
Tuxpan, Veracruz. Instituto Nacional de Ecología.
[http://cambioclimatico.gob.mx:8080/xmlui/bitstream/handle/publicaciones/130/496_2006
Intr evaluacion impactos termoelectricas Mexico.pdf?sequence=1&isAllowed=y](http://cambioclimatico.gob.mx:8080/xmlui/bitstream/handle/publicaciones/130/496_2006_Intr_evaluacion_impactos_termoelectricas_Mexico.pdf?sequence=1&isAllowed=y).
Accessed 5 May 2020

Figures

Figure 1

Location of the three cities examined: Culiacán, Los Mochis and Mazatlán [38] Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

(c)

Figure 2

PM2.5 Daily average concentrations (µg/m3) in cities participating in the study (a) Culiacan, (b) Los Mochis, (c) Mazatlan during 2017

(a)

(b)

Figure 3

Avoidable total and cardiovascular mortality due to the reduction in PM_{2.5} concentration levels (a) (cases per 100,000 inhabitants) (b), for population older than 30 years in the three cities examined

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [AppendixA.docx](#)