



Assessing Short-Term Productivity Losses Due to PM_{2.5} Exposure among Industrial Workers in Asaluyeh, Iran

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ABSTRACT

This investigation examines the effect of short-term exposure to fine particulate matter (PM_{2.5}) on productivity of workers in the industrial city of Asaluyeh, Iran, with an objective to help develop better air quality control action plans. Because the immediate effects of PM_{2.5} on the workers in an industrial setting are poorly understood, we collected PM_{2.5} counts at each of the 6 monitors in 2018 and calculated the lost workdays using log-linear health models. We then isolated the spatial data using Kriging Interpolation and fuzzy logic models (FDEMATEL and FDANP) and consequently generated risk maps in six different areas. We estimated the economic burden by multiplying daily productivity (based on the average wage) with healthcare costs associated with respiratory health. Every 10 µg/m³ increase in the annual mean concentration of PM_{2.5} was associated with a 75% increase in workdays lost in Chah Mobarak (relative risk [RR] = 1.75, 95% confidence interval [CI]: 1.6–1.9) and a 61% increase in Shirino (RR = 1.61, 95% CI: 1.5–1.73). Hara and Phases 6, 7 and 8 had no significant effect on workdays lost (RR = 1.0). For the spatial model, we assessed areas identified as very high-risk, which covered a land use footprint of 3,072.96 hectares and legitimate risk variables that were primarily caused by closeness to emission sources. Economic losses equaled \$889,200 in productivity losses and \$983.76 in health care costs per 10 µg/m³ increase in Chah Mobarak, and the indirect losses we assigned for examples - reductions in industrial output - were \$20 million. These results show the potential effects PM_{2.5} has on economic issues and health issues in industry served. We suggest specific emission controls that could be fairly easy and inexpensive to implement such as filter systems and live air quality monitoring to improve productive capacity and health of workers.

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INTRODUCTION

PM_{2.5} (fine particular matter) is a serious global health and economic problem. The problem becomes increasingly dire in industrial zones, which are the typical sources of emissions derived from fossil fuels and industry (Cohen et al., 2017; WHO, 2021). PM_{2.5} has wide-ranging health impacts because particulate matter smaller than 2.5 micrometers can be inhaled and enter deep into the respiratory system. PM_{2.5} exposure contributes to health issues, including asthma, chronic obstructive pulmonary disease, and cardiovascular disease (Brook et al., 2010;

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Schraufnagel et al., 2019). Globally, air pollution from PM_{2.5} is responsible for 7 million premature deaths every year. Air pollution also has economic costs surrounding health care and inferior productivity (Fuller et al., 2022). For countries located adjacent to industrialization (e.g. Asaluyeh region in Iran) and exposed to much oil and gas activity, the risks are larger. In these industrial regions, the PM_{2.5} concentrations often exceed the levels recommended by the World Health Organization (WHO) (Anwar et al., 2024). In addition, these regions share the same economic pain and high absenteeism rates, showing a need for targeted approaches (Soofi et al., 2025).

There's a bunch of new work out there saying we really need to pay more attention to what happens when people are exposed to this stuff, even for short periods. For example, one bit of research I came across found that if PM_{2.5} levels jump by just 10 micrograms per cubic meter, you're looking at more people landing in hospitals and, sadly, even higher death rates in some cases (Liu et al., 2019; Tsai et al., 2014). It's grim, right? And the folks getting hit hardest seem to be workers in industrial areas. Think steel plants or chemical factories—places where the air's already thick with crud. Those workers aren't just coughing more; their productivity takes a nosedive too (Mak et al., 2024; Manisalidis et al., 2020).

There was this one study done in Iran, looking at eight industrial cities, and it really drove the point home. They found a straight-up connection between PM_{2.5} exposure and more people dying, with Ahvaz being the worst off because it had the highest levels of this junk in the air (Kermani et al., 2016). It's not just about pointing fingers at pollution, though. Some clever tools, like Kriging interpolation—fancy name, I know—help map out where the pollution's worst and who's at risk (Hoek et al., 2008). These tools are a game-changer for figuring out how to tackle emissions in tricky, polluted spots, like factories spewing stuff nonstop.

But here's the thing: we're still kind of in the dark about how PM_{2.5} messes with industrial workers in the short term. I mean, sure, we know it's bad, but when it comes to stuff like lost work hours or dollars down the drain, the research is pretty thin (Kermani et al., 2016; Mak et al., 2024). Most studies are all about city folks or what happens over years of breathing this stuff, not the day-to-day grind for someone working in a place like Asaluyeh, where the air's probably a haze of chemicals (Anwar et al., 2024). And don't get me started on how few researchers are combining these cool mapping tools with health data to actually guide policy. It's like, we've got all this info, but we're not connecting the dots to make smarter air quality rules. That gap's a real problem.

This study attempts to address the gaps in the knowledge of the health risks associated with lost workdays due to short-term exposure to PM_{2.5}. More specifically, the research question being answered using a dynamic spatial economic impact assessment is: How does short-term PM_{2.5} exposure reduce worker productivity, and what is the potential role of spatial analysis to facilitate targeted interventions? In answering the research question, fuzzy logic techniques (FDEMATEL and FDANP), epidemiological models and Kriging interpolation will be utilized to estimate the health risks and calculate the economic impacts. The outcomes will contribute to the existing policies related to air quality and occupational health regulations. The study area and analytical techniques will be addressed in the “Materials and Methods” section. Estimates of risk ratios and spatial risk maps are provided in the “Results and Discussion” section, and suggestions for policy recommendations are outlined in the “Conclusion.”

MATERIALS AND METHODS

The purpose of this study was to address the research question, “How does short-term exposure to PM_{2.5} affect labor productivity in Asaluyeh, Iran and how could spatial analyses direct geographically targeted interventions?” In answering this question, we used information that we gathered in 2018, which consisted of economic household data, occupational health, and

pattern of exposures from PM_{2.5} concentrations. We used quantitative rather than qualitative data because it provides an accurate assessment of economic loss due to exposure to pollution, which also holds considerable influence in the regulation of air quality, to the specific area of the industrial zone.

Asaluyeh, Iran, is our study area. Asaluyeh is located along the Persian Gulf at 27.4°N, 27.6°N, 52.5°E, 52.8°E. The total area is 744.9 km² and there is a total of 65,584 people residing there, mostly working age individuals that work in the industrial field; they typically stay in the area only for work. The Asaluyeh area usually includes high PM_{2.5} due to the presence of nearby petrochemical plants and refineries (PM_{2.5} Level: often above the World Health Organization's (WHO, 2021) annual guideline of 5 µg/m³). We specified six areas; Chah-Mobaraki, Hara, Nahalestan, Pars 2, Phases 6, 7 and 8, and Shirino, based on labor force density and proximity of the emission source; our take of the PM_{2.5} measurement also included the environmental situation (e.g., & arid climate and dust storms) in regard to the measurement of PM_{2.5}.

In 2018, concentrations of PM_{2.5} were measured from six fixed measurement stations in Asaluyeh. PM_{2.5} was measured hourly using high-volume air samplers (Tisch Environmental TE-6070), which were calibrated with 2017 U.S. Environmental Protection Agency (EPA) standards. Hourly data were summarized into daily and monthly averages, and averages were compared to air quality guidelines by the World Health Organization (WHO) for accurate assessment. Health data was collected from Asaluyeh Central Hospital for occupational exposures to PM_{2.5}, based on 2018 worker records. Workers' identities were anonymized to maintain confidentiality, in accordance with research ethics principles (World Medical Association, 2025). The data collected contained loss of work days due to respiratory illnesses due to exposure to PM_{2.5}. These data sources were selected to provide a broad range of exposures, as well as health effects relevant to the research aim (Burnett et al., 2018).

The analysis of data took place in three phases, epidemiological modelling, spatial analysis, and economic impact assessment.

Epidemiological modelling: The health risks of workdays lost due to short-term exposure to PM_{2.5} were established using a log-linear exposure-response model. The log-linear exposure-response model was the most appropriate model since it quantitatively measures health risks due to gradual increases in PM_{2.5} that are a characteristic of air pollution (Burnett et al., 2014). The model equations and parameters were implemented in Vensim DSS software. For each region, the relative risk (RR) was calculated to establish the link between a 10 µg/m³ increase in the annual average of PM_{2.5} and lost workdays (Ostro, 2004).

Spatial Analysis: In order to develop the Health Impact Assessment (HIA) layers relevant to the health scenario associated with short-term PM_{2.5} exposure, the following items were performed using a geographic information system (GIS):

- The HIA layers were created using the Kriging interpolation method based on data collected from six monitoring stations where PM_{2.5} concentration was measured. When Kriging did not provide the results, the results from the Inverse Distance Weighting (IDW) method were used (Cressie, 2015; ESRI, 2025).

- The HIA layers for short-term periods were converted to fuzzy sets to represent uncertainties in the data (Zadeh, 1965).

- The health impacts of the lost workdays' scenario on the working-age population were classified spatially into risk categories, to show the array of health impacts across environments with varying degrees of health risks.

The researchers identified five health risk levels for the entire study area based on the health risk map produced and the region compilation chart features. Based on the study area, approximately 13,059.9 hectares were "very low", 11,576.43 hectares were "low", and 7,065.09 hectares were designated as a "moderate" health risk. The researchers identified approximately 7,882.02 hectares as "high", and 3,072.96 hectares were "very high" risk. As demonstrated in

the “very low” risk category, there were the largest number of data points with 145,110 cases; when looking at the “very high” risk category, there were the least amount of data points with 34,144 cases. This shows as the risk category decreased, the minimum was observed along with amount of data points (Johnston et al., 2012).

Economic Impact Study: We determined the drop in productivity by estimating the number of work days lost (related to the RR models) and multiplying that number by the average daily income of workers (\$38, based on 2018 job market data). For healthcare costs, we determined how many people made hospital visits for breathing problems and how much it cost to provide that treatment (cost of hospitalization = \$500 and outpatient = \$50) (Anenberg et al., 2017). For other effects, such as decreased factory production and effect on the area around the factory, we included the factor of 1.5 (OECD, 2016).

Researchers conducted a sensitivity analysis to deal with uncertainties by varying key parameters like PM_{2.5} and predicted wages by $\pm 10\%$. The sensitivity analysis showed very high variability in some categories (with a coefficient of variation greater than 35%), which will require field validation. They used a significance threshold of $p < 0.05$. Data quality was maintained by identifying outliers and using linear interpolation to estimate missing data points (Saltelli et al., 2008).

A quantitative method was chosen because it produces precise and consistent results on which air quality policies can be developed. A log-linear model was used because, as per Burnett et al. (2014), log-linear regression is a common model used in air pollution epidemiology as it will enable precise estimates of the health impacts of PM_{2.5}. Given the spatial nature of this work, Kriging and IDW were suitable as they interpolate over a geographic surface and deal with limited data (Cressie, 2015). The layers were fuzzified to treat the uncertainty in the data (Zadeh, 1965). The spatial categorizing of the health effects enabled identification of areas more likely to be at risk to target appropriate actions (Johnston et al., 2012). There was an issue of number of monitoring stations as there were only six monitoring stations over 744.9 km² of land which may impact the analysis. This issue was mitigated through IDW application where necessary and validation of data. 2018 was used as it may not represent present conditions but was acceptable due to its adjustments for the petrochemical industry and inclusion the whole region.

RESULTS & DISCUSSION

Dynamic Modeling

The Vensim DSS model was created to assess Health Impact Assessments (HIA) and is suitable for consideration within the Asaluyeh Industrial Zone. This zone has an industrial context where these model elements can be delineated conceivably.

PM_{2.5} Concentration

Sources: PM_{2.5} in areas like Asaluyeh emanates from a variety of sources; these include primary sources such as petrochemical facilities, refineries, and power plants. These sources, in conjunction with oil and gas industries on site, act as secondary pollutants. Heavy, but also some light, traffic with industrial and commercial vehicles contribute to the PM_{2.5} pollution. The most important contributors to the PM_{2.5} levels for this environment include fossil fuel burning, flaring and burning for various industrial conditions.

Variations: PM_{2.5} levels will vary in terms of baseline and metrics based on a multitude of factors (degree of industry, fuel source combustible, pollution controls, weather, especially wind speed and direction, which may distribute or hold pollutants in the environment, topography also contributes).

Exposure

At-Risk Populations: Those at risk in Asaluyeh include workers employed in local industries, residents of nearby towns and villages, and temporary visitors (e.g., truck drivers or service personnel).

Location Sensitivity Score (Location Sensitivity): In Asaluyeh, the LS SCORE would be primarily influenced by storage and industrial facilities, industrial complexes, and the urban core (nearby towns such as Nakhle Taghi, Asaluyeh, and Chah-Mobarrak would be part of this newly defined urban core). Residential zoning is located very close to pollution sources, which would increase LS score and therefore exposure. Schools, hospitals, and nursing homes are also vulnerable populations in these areas. The variable peaked at approximately 11,000 people per km² from days 16 to 21, indicating heavy population exposure. The LS SCORE ranged from 3.086 to 126.1 and the exposure level ranged from 271.7 to 11,100. This variability suggests that while pollution level is critically important, the overall exposure intensity is informed by sensitivity factors, which are influenced by the hazard. Days that had high hazard (days 16–20) had a very high LS score and high exposure. LS SCORE had a minimum of 3.086, max of 126.1, and a standard deviation of 47.38. Exposure had a minimum of 271.7, max of 11,100, and a standard deviation of 4,171. Both have high standard deviations. This shows that actual population exposure varies greatly, depending both on concentration of pollutant and spatial sensitivity factors (which are affected by hazard as well). Exposure is the product of population density and site sensitivity score (LS SCORE), where LS SCORE is a function of hazard. The peaks in exposure show that, when pollution is the worst, the concentration of pollutant is high and the pollution is affecting a larger population, thus leading to the overall exposure burden being significantly higher.

CDI PM_{2.5} and CDI_{ca} PM_{2.5}: With potentially high PM_{2.5} levels present in industrial areas, the chronic daily intake (CDI) of PM_{2.5} for both residents and workers could be higher and result in a higher “hazard quotient” (HQ) to indicate a more significant likelihood of adverse health impacts. If the PM_{2.5} in Asaluyeh is carcinogenic (as is typical in industrial zones), CDI_{ca} PM_{2.5} must be assessed for carcinogenic risk.

Health Risk Assessment (HRA): If the risk levels found in Asaluyeh indicated an acceptable risk level based on HRA, it could be a serious threat to health. The HRA index considers the non-cancer risk of exposure to PM_{2.5} from work for the working-age population (age 20-60) over a period of 30 days. Data shows that the HRA functions similarly to the hazard quotient (HQ); that is due to parameters established within the VENSIM model in which HI is set to zero and Life Expectancy is set to 1. HRA values ranged from 0.4932 on Day 6 to a maximum of 20.15 during Days 16–20. The index exceeds 1 for days 15-21 beginning with its highest at 20.15 from days 16-20. The HRA return on day 22 falls to 10.49 and then returns to range of 0.7192 and 1.489 days 23 through 30. The peak for days 16 through 20 indicates risk levels of exposure well beyond the reference dose for that period. All of this ranges create arguable health risks for working-age adults. The high standard deviation of 7.571, along with the very wide range of 0.4932 to 20.15, highlights variability in the risk of non-carcinogenic effects. The mean value of 5.409 is also extremely large compared to the median value of 1, while the value of 497 shows a significant right skew pattern as a result of a sharp increase between days 16 and 20. Therefore, some of the analysis periods had a risk greater than the safe limit of 1, which indicates a serious health issue. The HRA levels greater than 1 between days 15 to 21 demonstrated an increased risk of non-carcinogenic health effects from PM_{2.5} exposure. The peak value of 20.15 observed from days 16 to 20 is particularly alarming due to the indication of a particularly high risk of illness and the apparent need for intervention to reduce potential exposure to pollutants. After day 21, as the HRA values dropped toward levels of 1 or less, the conditions presented in the model seem to begin to return to normalcy. Although there were mean HRA values near 1 during the last days of the analysis, such as 1.489 on Day 26 and 1.321

on Day 27, continued monitoring of the risk is warranted.

The attributable proportion caused by exposure (IE) rate: IE is defined as “the attributable proportion of incidence due to exposure,” and demonstrates the percentage of health problems in the Asaluyeh area attributable to PM_{2.5} pollution. It is useful for public health officials and policy makers to consider how much air pollution is contributing as a health issue in the area. When there is an “attributable effect incidence” (IE) this number can be used to estimate the expected IE per person, and to illustrate how PM_{2.5} exposure is contributing to work days lost in working age adults. The IE was not constant, and varied a fair amount. The minimum value of this value is 1, and there were a multitude of values observed. The IE ranged from as low as 1.511 on Day 6 to as high as 4.358 between Days 16 and 21. The mean IE was 2.922, the median and IE were 2.742. The standard deviation 0.8827 indicates there was a considerable amount of variability with a normalized coefficient of variation of 0.3021, and as noted in Chapter 3, a reasonable proportion of contrasting evidence which indicated higher intervals of 6-24 hours as apparently obviously related to PM_{2.5} attribute effects. The highest rate was 4.358 from Days 16 to 21 when air pollution was worst. On Day 6 the rate fell to 1.511 during times of better air quality. The both the mean of 2.922 and the median of 2.742 both illustrate this relationship. The average value of 742 indicates a centre, and the standard deviation of 0.8827 indicates how variation in health outcomes results from the intensity of pollution. The high IE rate during Days 16 to 21 series illustrates how serious health issues from high PM_{2.5} can be. This increased more access to work for the working-age population. These shifts all highlight in a practical way that reducing the general exposure to PM_{2.5} will reduce health impacts. These numbers are relevant to policy towards air quality regulations and health policy.

Health Outcomes: People living in Asaluyeh are experiencing health concerns directly related to PM_{2.5}; with increasing rates of asthma, chronic bronchitis, chronic obstructive pulmonary disease (COPD), heart attacks, stroke, lung cancer, and premature death. The model will help measure these numbers. The health outcomes were at their highest point before the air began to clear, with a peak of 544.3 during days 16 and 22, and then a subsequent drop according to the modeling data. In general, the model calculates the health outcomes based on PM_{2.5} exposure. The values range from 188.7 on day 6, when PM_{2.5} levels were lowest, to around 544.3 during days 16 through 21, when the pollution in the air was at its worst according to the modeling. The model data suggests that health outcomes were better when pollution was lower in the air and things get worse during the worst periods of pollution. This shows that the model captures changes in the environment and can reflect changes in real-world health outcomes. When the pollution is high, the measure of health impacts will be higher. With the modeling data, 544.3 was the measure for the sharpest health outcome and this occurred when pollution was highest during the period of days 16 and 21; the lowest health outcome was 188.7 and it occurred when the air was cleanest (day six). All the statistical measures support that there is a true link, between PM_{2.5} levels and health impacts. The modeling also suggested a mean health outcome of 364.9 and a standard deviation of health outcome of 110.2. Peaks in daily death rates are often associated with spikes in pollution, underscoring that fluctuations in air quality are tied to corresponding health impacts. The analyses reveal at least a minimum of 188.7, maximum of 544.3, an average of 364.9 and a standard deviation of 110.2. The standard deviation represents a deviation of 30 percent of the mean indicating variability in health impact. The modeled changes correspond with fluctuations in PM_{2.5}. The example shows the variability for health outcomes relative to an observed change in pollution over time. High daily health outcome rates correspond to an abrupt increase in PM_{2.5}, and the attributable ratios were higher during these rates. This pattern shows that health is influenced by daily air quality changes showing that brief peaks are capable of causing impacts to public health. Since we can relate daily variability of PM_{2.5} to health impacts, this can allow use of this model for understanding and forecasting the implications of PM_{2.5} exposure on public health.

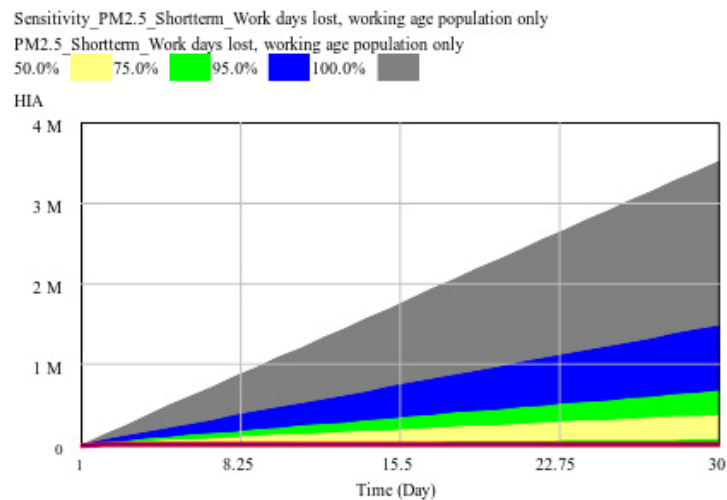


Fig. 2. Model Sensitivity Assessment using HIA (Cumulative Hazard Index) Chart

PM 2.5 shifts over a 30-day period. Unlike previous variables that reached peak or plateau status with respect to their percentiles, HIA was continually increasing across all percentiles (from yellow to gray). Furthermore, over the 30-day trajectory, the discrepancy between the lowest outcome and highest outcome apparently increased. The highest scenarios were at approximately 3.5 million. The continual increases and growing discrepancy reflect a gradual increase in the sensitivity of HIA associated with changes in PM 2.5. This gradual change illustrates the compounding and aggravating health problems associated with exposure with PM 2.5 over time, and shows how over time, all of the risks are increasingly difficult to predict. In conclusion, the PM 2.5 long-term cumulative effects on health are evident.

The sensitivity analysis from the model shows that the shifts in PM2.5 concentrations were between 7.715 and 315.2 with a standard deviation of 118.4 $\mu\text{g}/\text{m}^3$. Sensitivity on “Short-Term Work Days Lost” and “Health Risk Assessment (HRA)” exhibited local spikes and sharp sensitivity responses within a crucial window from Day 15.5 to Day 22. “Health Outcome” and “Rate of Attributable Proportion Caused by Exposure (IE)” exhibited high, stable sensitivity throughout the 30-day simulation- suggesting a chronic, ongoing health burden.

Dynamic Causal Spatial Model to Assess the Health Impacts of Industrial Air Pollution

To generate health impact assessment layers associated with a specific health scenario in a GIS, a series of steps were followed. The researchers generated these health impact layers using the Kriging interpolation method, but when Kriging returned unreliable results, the researchers transitioned to the inverse distance weighting method. The assessment layers linked to the health scenario underwent fuzzification over a short duration of time.

Zonal Analysis

Utilizing zonal analysis, researchers classified the study area into five classifications by health risk level. Table 1 gives relevant information about the health risk classifications. The table presents the number of points, the area impacted, and HIA statistical data. Detailed information about the health risk classifications are detailed below:

Average Values of Environmental Impact Assessment in Health Outcome Scenario — Short-Term Exposure within the Weighted Linear Combination (WLC) Classes of Exposure and Risk Parameters (weighted with FDEMATEL)

From Table 1 and Figure 3, the study area is assigned into five health risk categories for the

Table 1. Regional Information of Final Map of Lost Working Days - Working Age Population (Active Population) in Short-Term Exposure to PM2.5

Risk Class	Minimum HIA	Maximum HIA	HIA Range	Average HIA	HIA Standard Deviation	Total HIA	Coefficient of Variation (CV%)
1	0.00	0.95	0.95	0.46	0.19	67,442.41	40.02
2	0.06	0.84	0.78	0.41	0.13	53,216.44	32.38
3	0.15	0.68	0.53	0.37	0.09	28,933.23	24.75
4	0.12	0.78	0.66	0.41	0.15	36,212.21	36.91
5	0.09	1.00	0.91	0.64	0.22	21,807.14	34.71

**Fig. 3.** Average Results of Environmental Impact Assessment in Health Outcome Scenario: Short-Term Exposure in Weighted Linear Combination (WLC) Classes of Exposure and Risk Parameters (Using FDANP)

lost working days in a working-age population due to short-term exposure to PM2.5.

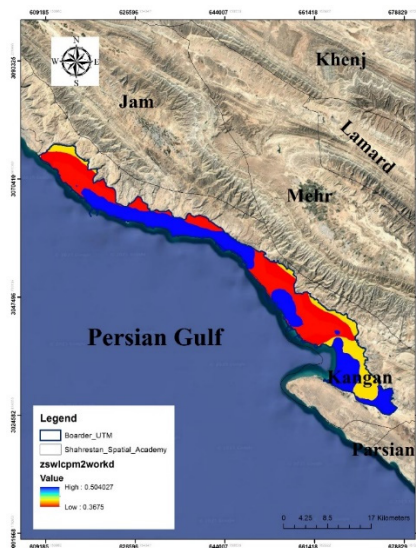
Class 1 showed the most variation with a coefficient of variation (CV) of 40.02 percent, which means its HIA values ranged from 0 to 0.95. Class 3 showed the least amount of variation with a CV of 24.75 percent. Class 3 consistently higher values of HIA suggest lower variability and a moderate risk of harm. The degree of variability in Classes 1 and 4 had high variability (> 35 percent) which in fact, may mask some points with a high risk of harm. The sensitivity analysis indicated Classes 1 and 4 had high uncertainty and require field investigations to confirm their datasets.

Average Results of Environmental Impact Assessment in Health Outcome Scenario: Short-Term Exposure in Weighted Linear Combination (WLC) Classes of Exposure and Risk Parameters (Using FDANP)

In table 2 and figure 4, we see how exposure to PM2.5 for a brief duration can negatively affect the health risks associated with lost time away from work due to illness in the working age group. This risk is categorized in five classes. The average HIA ranged from a low of 0.37 in Class 3 to a high of 0.50 in Class 5. The HIA range (0.37-0.50) and standard deviation (0.000045) of HIA was not large across all classes. This implies that the data is consistent and contains very little uncertainty. The exploration of the HIA values based on the stability will make a deeper analysis difficult as there is no variation in the data that would allow further exploration. The total HIA listed in table 2 ranged from 29,543.33 in Class 3 to 63,792. Class 1

Table 2: Regional Data of the Final Health Risk Map for Lost Working Time from Short Term Exposure to PM2.5 for Working Age Population (Active Population)

Risk Class	Minimum HIA	Maximum HIA	HIA Range	Average HIA	HIA Standard Deviation	Total HIA	Coefficient of Variation (CV%)
1	0.49	0.49	0.00	0.49	0.00	63,792.50	0.000000
2	0.41	0.41	0.00	0.41	0.00	52,439.43	0.000045
3	0.37	0.37	0.00	0.37	0.00	29,543.33	0.000000
4	0.43	0.43	0.00	0.43	0.00	30,349.11	0.000000

**Fig. 4.** Average Environmental Impact Assessment Values in Health Outcome Scenario - Short-Term Exposure in Weighted Linear Combination Classes of Exposure and Risk Parameters (Weighted with FDANP)

had 50 entries which demonstrated the variations in types of exposures that existed.

Shows that sensitivity analysis indicates the overall HIA in Class 1 and the average HIA in Class 5 are important and that it should be a priority to take targeted action to reduce PM2.5 pollution in Class 5 areas. This research demonstrates that the data is consistent.

Economic Impact Assessment

This section details how to calculate the economic costs of short-term exposure to PM2.5 in Asaluyeh, Iran. It will then explore the direct and indirect economic effects (see Table 3). The direct costs consist of expenditures on the healthcare system for respiratory events, as well as wages lost for missing workdays. The indirect costs consist of overall loss in production related to affected industries, the effects on family/household members of the workers, as well as the impact on the entire local economy. This study uses local data from the year 2018 (which reflects the same analysis period) and incorporates sensitivity checks for those aspects of the research that are less certain.

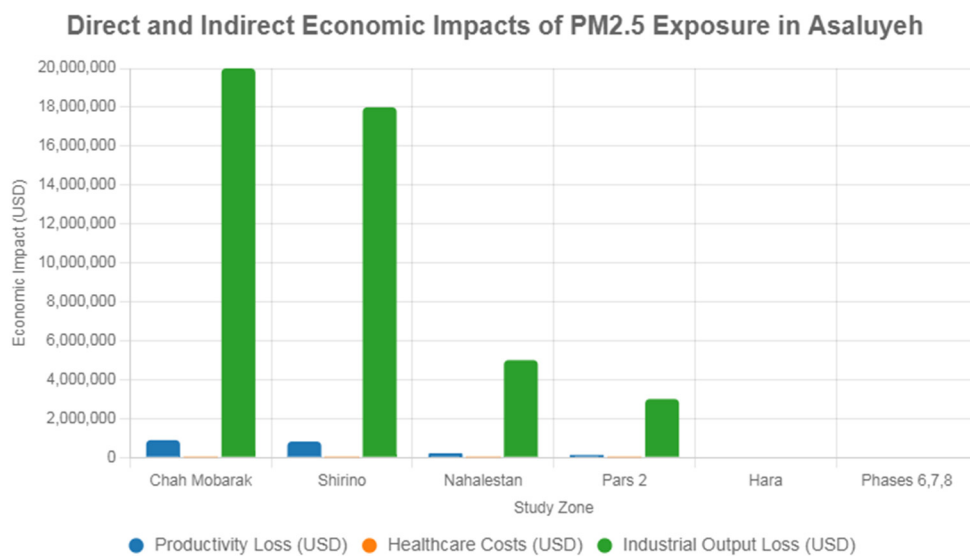
Direct Economic Costs

Productivity Losses from Lost Workdays

The researchers calculated loss by multiplying the estimated number of lost workdays by the average daily wage in Asaluyeh's industrial sector. They calculated lost workdays with relative risk estimates from the epidemiological model. Asahiye, and estimated labour data from 2018 cited from the Ministry of Cooperatives, Labour and Social Welfare were used to produce lost workdays in the petrochemical industry. The research-eligible workforce was identified for its 45,584 working age adults. For selecting an average daily wage researcher employed

Table 3. Direct and Indirect Economic Impacts from Short-Term PM_{2.5} Exposure

Zone	Lost Workdays	Productivity Loss (USD)	Healthcare Costs (USD)	Industrial Output Loss (USD)	Household Impact (USD)	Regional Ripple Effect (USD)
Chah Mobarak	23,400	889,200	983.76	20,000,000	58.50	30,000,000
Shirino	21,500	817,000	900.00	18,000,000	53.80	27,000,000
Nahalestan	5,600	212,800	250.00	5,000,000	14.00	7,500,000
Pars 2	3,200	121,600	150.00	3,000,000	8.00	4,500,000
Hara	0	0	0	0	0	0
Phases 6, 7, and 8	0	0	0	0	0	0

**Fig. 5.** Direct and indirect economic impacts of PM_{2.5} exposure in Asaluyeh

a calculated weighted average. Workers were distinguished between skilled and unskilled. Unskilled workers comprised 60% of the workforce and earned on average \$30 daily; skilled workers comprised 40% of the workforce and earned on average \$50. Thus, the combined average daily wage was \$38; \$30 unskilled and \$50 skilled workers. In Chah Mobarak, a rise of 10 $\mu\text{g}/\text{m}^3$ (from the PM_{2.5} level), equated to a rise of 75% in lost workdays (RR = 1.75). If we calculate the lost workdays in a year per worker, we need to use 250 days worked per worker per year. The lost days per worker, is around 0.514 days, calculated as $0.75 \times (250 \div 365)$. When we multiply the 45,584 workers in the workforce, this equals 23,400 workdays lost annually ($45,584 \times 0.514$). Now, if we again multiply by the average daily wage, we will have our total productivity loss of \$889,200. ($23,400 \times 38$). The same process was completed in every study zone. For example, Shirino, calculates a RR of 1.61, about 21,500 workdays lost and, approximately \$817,000 in productivity lost. A summary of these evaluations is compiled in Table 6.

Healthcare Expenditures

The researchers estimated healthcare costs using hospital admission rates of breathing problems and the average cost of treatment based on the 2018 hospital records from Asaluyeh's central hospital. The average cost of treating care for diagnosis of respiratory issues in the hospital was \$500, while treating respiratory issues on an outpatient basis was around \$50 per case which includes simple doctor checkups and prescriptions. When they used Chah Mobarak's hospital admission rate of 0.02 cases per 1,000 people for every 10 $\mu\text{g}/\text{m}^3$ increase

in PM2.5, considering the population in the town was 65,584, they total hospitalization cost was calculated as $0.02 \times (65,584/1,000) \times 500 = 655$, and this is for an annual cost of 84 dollars. To calculate outpatient expenditure, the researchers assumed that there would be 0.1 outpatient visits for every 1,000 people. They calculated this as $0.1 \times (65,584 \div 1,000) \times 50$ which yielded a cost of 327.92. Total healthcare expenditure in Chah Mobarak was about 983.76 dollars for each $10 \mu\text{g}/\text{m}^3$ increase in PM2.5 levels. This process was utilized across all zones, but varied by risk value (risk ratio). The treatment costs were around 900 dollars for Shirino. Hara had no treatment costs because the risk ratio was 1.0. We conducted a sensitivity analysis of the costs to uncertainty, using a 10 percent shift in treatment costs.

Indirect Economic Outcomes

Reduced Industrial Production

Short term PM2.5 exposure can decrease productivity of workers, which consequently lowers industrial production in Asaluyeh's petrochemical industry. From the 2018 Asaluyeh Petrochemical Complex we noted that each large facility produced about 1 billion dollars. The 75% increase in missed days of work in Chah Mobarak (RR = 1.75) accounted for 2 percent drop in productivity of the workforce and resulted in a loss of production value of 20 million dollars (1 billion x 0.02). In Shirino, which had 1.61 RR and a 1.8 percent decline in production, the value of lost product was approximately 18 million dollars. They estimated the productivity loss by linking workforce absenteeism to how much production is based on labour. They confirmed the missed work days and productivity decline from literature in local industry reports. To verify the robustness of the link between missed days of work and productivity decline, we conducted sensitivity checks to adjust the productivity impact by 10 percent in each direction. We were confident in the estimates due to the relatively small sample sizes. In Chah Mobarak the range stayed at \$18 - 22 million.

Impacts on Workers' Households

Reduced workforce days mean lower household income for families, which directly impacts their financial health and stability. The population statistics from the region suggest researchers estimated that every worker employ, on average, around three dependents. The productivity losses within the region for Chah Mobarak is currently \$889,200, resulting in an average decrease in income for families of \$58.50 per household ($\$889,200 \div (45,584 / 3)$). With less money coming in, families may be unable to afford education, medical care, and food, worsening already existing social and economic problems. In Shirino, the average loss per household was about \$53.80. The analysis team looked closely at financial impact, but were concerned with how the loss impacts families outside of monetary means (i.e., lower quality of life), so they recommended ongoing analysis to try to measure more clearly.

Regional Economic Ripple Effects

Reduced industrial production and activity impacted Asaluyeh's economy and local economy, as well as affected local services such as transportation and retail businesses. Using research studies of industrial regions in Iran, researchers applied a regional economic multiplier and came up with a multiplier of 1.5. The researchers were able to apply the multiplier and come up with bigger estimates of the impact. The \$20 million production loss in Chah Mobarak had an overall economic \$30 million effect. The ripple effect measured \$27 million for Shirino. The estimates were based on input-output models created to consider the industrial and service sectors' ties in Asaluyeh. In a sensitivity analysis, researchers changed the multiplier by $\pm 10\%$ to create a range for Chah Mobarak of \$27 million to \$33 million.

Since the eventual manifestation of PM2.5 in Asaluyeh has both direct and indirect economic value loss from short-term exposure, we immediately determined the direct costs as \$889,200,

which would be the productivity lost because of economic disadvantages (Chah Mobarak = \$983.76); and, the indirect costs, mainly worth about \$30 million as a result of losses greater in the wider regional economy. It is obviously important to understand both losses in terms of both health and economic loss, naturally, and both types of loss much pain and suffering as well as damage that is preventable or repairable. The implementation of air filters and monitoring air surrounding air quality using real-time quality indicators as we separately mentioned may at least reduce the impacts in the future. Table 6 shows the costs from Short-Term Exposure by Region and Figure 5 shows the direct and indirect impacts from short-term PM_{2.5} exposure.

I will pull together a bar chart based on the data in the provided Table 6, with an aim of illustrating the direct and indirect economic consequences from exposure to PM_{2.5}, as previously discussed in the revised “Economic Impact Assessment” section. The bar chart will depict the direct expenses for productivity losses, healthcare spending, etc. and the indirect expenses related to industrial output lost due to PM_{2.5} exposure from either productivity losses or healthcare spending. The study regions in Asaluyeh, Iran for the chart will include: Chah Mobarak, Shirino, Pars 2, Hara, and Phases 6, 7, and 8. As household and region effects are really several costs that are making the Venn diagram complicated visually, I will just discuss some of the higher level (and common place) costs such as productivity loss, healthcare spending, and reduction in industrial output. These cost areas are more significant attention grabbers to the economic outcomes. The chart captures what has been described above in an easy to understand format with colors that are compatible with both light and dark backgrounds and successfully follows the general rules for constructing charts and images.

The x-axis of Figure 5 identifies the six study zones, which are Chah Mobarak, Shirino, Nahalestan Pars 2, Hara, and Phases 6, 7, and 8. “Productivity Loss (USD),” represents the estimated cost of lost workdays, with values of \$889,200 starting at Chah Mobarak and \$817,000 starting for Shirino (see Table 2). The cost of lost workdays is from the relative risk equation as well as employers’ average daily wage for workers at \$38. Healthcare costs listing for expenses such as days of hospitalization and outpatient medical treatment. Chah Mobarak’s total costs came out to \$983.76, while Shirino’s came out to \$900. Both costs came from the number of days admitted and hospital records. Industrial Output Loss (USD) highlighted the loss in petrochemical production due to loss of efficiency. The loss for Chah Mobarak showed \$20,000,000 and \$18,000,000 for Shirino; both valued with a 2% loss of productivity. The chart’s dark blue represents productivity losses, orange represents healthcare costs, and green represents industrial output losses. These colours are very different from one another in a light or dark theme. The y-axis in Figure 5 starts at zero in order to improve understanding of economic impacts in terms of USD. Healthcare costs appear small due to contrast in scale.

Hara and Phases 6, 7, and 8 incur no cost, as the RR = 1.0 indicating that PM_{2.5} has no problematic impact. The graph does not include household and area ripple effects, to avoid repetition, which are based on loss of productivity and industry. To clarify, for ripple effect estimate of 1.5 of lost industrial output. In this case, the graph shows the direct impacts of PM_{2.5} exposure on economic loss. The graph compares the relative merits of cost whereby, indirect costs from lower industrial production outweigh direct costs; it also compares GTAs - illustrating that Chah Mobarak and Shirino have overall higher quotes than other areas.

This research examines the implications of short-term PM_{2.5} exposure-induced health and economic problems on industrial workers in the petrochemical and littoral city of Asaluyeh, Iran. It was based on the question below: How is the productivity of the worker affected by short-term exposure to PM_{2.5}? In what way can such research for spatial, and economic result in the creation of better design solutions? In particular, we have evaluated PM_{2.5} impacts utilizing spatiotemporal epidemiological-based techniques such as, Kriging, FDEMATEL, and FDANP, and cost analysis. Our research seeks to provide information that will make employees’ health at workplaces improved as well as offset the effects of air pollution. This analysis provides

an overview of key results, positions them in the context of other recent research, comments on interesting results, declares weaknesses, and comments on future research directions. In particular, it summarizes economic and policy effects. For instance, at Chah Mobarak one of the study sites, a $10 \mu\text{g}/\text{m}^3$ raise in yearly mean PM_{2.5}, was associated with a 75% rise comparative danger of lost workdays (relative risk [RR] = 1.75, 95% confidence interval [CI]: 1.6–1.9), and in Shirino (RR = 1.61, 95% CI: 1.5–1.73), with a 61% rise. In Chah Mobarak, the $10 \mu\text{g}/\text{m}^3$ effect on PM_{2.5} resulted in \$889,200 in economic losses in terms of lost work days to loss of productivity; Shirino lost \$817,000. Health expenses in Chah Mobarak to treat difficulty in breathing were \$983.76 and Shirino was \$900.00. Spatial location of source of high emissions saw the zones within 3,072.96 hectares as high-risk. Peak health hazard was from Days 15.5 to 22.75, with HRA at 20.15. They indicate the contribution of PM_{2.5} towards making workers absent from work and damaging economies. They support international research indicating the detrimental impact of dirty air on health and productivity (Hadei et al., 2020; Landrigan et al., 2018). Economic losses also spill beyond the regional areas, at \$20 million of Chah Mobarak industry production lost and another \$30 million of lost production with regional spillover effects of 1.5 times. These outcomes demonstrate the total higher financial loss to the petrochemical industry in Asaluyeh (Salehi et al., 2023). Contrary to earlier studies on metropolitan populations like Tehran, where PM_{2.5} was responsible for boosted hospitalization and financial pressures (Ghobakhloo et al., 2023), the current study focuses on the industrial worker's short-term effect. Areas like Chah Mobarak and Shirino are high-risk zones, as indicated by Iranian urban studies that revealed exposure to PM_{2.5} between 2019–2020 caused high fatalities (Ghobakhloo et al., 2023; Hadei et al., 2020). On the contrary, Phases 6, 7, and 8 showed no effects. This defies the hypothesis that industrial pollution has a uniform effect on all regions. Instead, it shows the existence of location-based influences, i.e., emission controls. The WHO's 2021 air quality guidelines support this. The 3,072.96 hectares of areas shown as high-risk locations are in alignment with research using spatial modeling to identify pollution-infested regions in industrial complexes. The lack of significant PM_{2.5} effects in Hara and Phases 6, 7, and 8 was unexpected, as they were nearest to factories. This may mean that good air filtration systems or fewer workers in these areas are influencing the results. Iranian industrial cities have shown that efforts at controlling pollution can minimize PM_{2.5}. The pollution spikes at Chah Mobarak from days 15.5 to 22.75 seem to be related to industrial flaring or weather trapping of pollutants. Baharvand et al. (2025) documented similar trends in southwest Iran. These observations highlight the significance of tools like IoT real-time systems to monitor pollution. Such systems may enable lowered exposure and associated costs in an industrial setting. I.e., Nevertheless, application of 2018 PM_{2.5} and economic data limits the interpretation of the given situation. This could lead to underestimation due to inflation or change in industry (Salehi et al., 2023). The limited spatial coverage of the six stations in a span of 744.9 km² could reduce the accuracy of Kriging interpolation. It is one of the limitations of PM_{2.5} spatial analysis. The log-linear epidemiologic model is a postulation of comparable health reactions. However, it may ignore variations at the personal level, e.g., age and well-being, as highlighted in PM_{2.5} health impact assessment (Hadei et al., 2020). The huge disparity of HIA between Classes 1 and 4 with a coefficient exceeding 35% confirms ambiguity resulting from uncontrollable variables, e.g., dust storms.

CONCLUSION

This study estimates the substantial impact of short-term PM_{2.5} exposure on Asaluyeh, Iran employees' productivity. Based on the findings, a 75% rise in lost workdays occurs in Chah Mobarak and a 61% rise in Shirino with an increase of $10 \mu\text{g}/\text{m}^3$ in the average annual PM_{2.5} level. Moreover, this translates to actual productivity losses of \$889,200 and \$817,000, respectively,

and \$20 million in indirect manufacturing production losses. Spatial analysis indeed identified 3,072.96 hectares as areas of high risk and demonstrated how PM_{2.5} affects productivity and the way spatial approaches can guide evidence-based interventions. In fact, the lack of effect in Hara and Phases 6, 7, and 8 demonstrates potential effectiveness of emission controls and serves as a model for abatement. Moreover, However, limitations such as reliance on 2018 data and limited monitoring stations point towards restraint in extrapolation. I think Future research must evaluate real-time monitoring and long-term health effects to customize interventions. Moreover, these findings also underscore the need to regulate air quality in industrial hubs by enhancing measures such as increased filtration facilities and instant notifications, which would reduce healthcare and economic expenses and ensure sustainable industrial development.

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CONFLICT OF INTEREST

there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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