



Limitations of Project-Based Environmental Impact Assessment (EIA) and the Need for Cumulative Effects Assessment (CEA) in the Assaluyeh Coastal Industrial Zone, Iran [†]

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Abstract

The Assaluyeh coastal industrial zone, home to extensive oil, gas, and petrochemical facilities, is among Iran’s most environmentally stressed regions. Despite numerous project-specific Environmental Impact Assessments (EIAs), environmental degradation persists, revealing systemic gaps in the conventional EIA framework. This study reviews publicly available EIA and Environmental, Social, and Health Impact Assessment (ESHIA) reports, alongside scientific literature from 2015 to 2024, to assess whether cumulative impacts have been adequately considered. Analysis focused on the explicit mention of cumulative effects, methodological rigor, and transparency of documentation. Findings indicate that most EIAs overlook cumulative impacts, focusing primarily only on individual project boundaries. Field-based studies further confirm significant accumulation of heavy metals (Pb, Cd, Ni, V), polycyclic aromatic hydrocarbons (PAHs), BTEX compounds, and particulate matter, reflecting the cumulative influence of multiple pollution sources and synergistic interactions. Key quantitative findings include: heavy metal concentrations in the central industrial zone reaching Pb = 120 µg/g and Ni = 45 µg/g with PLI = 2.5; organic pollutant levels of ΣPAH = 72.5 µg/m³ and BTEX = 38.2 µg/m³, both exceeding the WHO guideline of 20 µg/m³; carcinogenic risk classified as High for Cd and Hg (exceeding EPA acceptable limits); and strong pollutant correlations (PAH–BTEX: *r* = 0.80). These results underscore the urgent need for the implementation of a regional Cumulative Effects Assessment (CEA) integrated within a Strategic Environmental Assessment (SEA) framework, which can improve environmental governance and promote long-term sustainability in Iran’s industrial coastal zones.

Keywords: Assaluyeh; cumulative effects assessment; strategic environmental assessment; industrial pollution; Persian Gulf



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1. Introduction

1.1. Regional Background and Significance

Assaluyeh, located in southern Iran along the Persian Gulf, has emerged as one of the country’s most significant industrial hubs. The region hosts major energy and petrochemical complexes—including South Pars, Jam, Pardis, and Marjan—located within the Pars Special Economic Energy Zone (PSEEZ) [1]. Over the past two decades, rapid

industrial expansion and the clustering of gas processing and petrochemical plants have exerted substantial pressure on local soil, water, and air resources.

Recent studies highlight that, in the absence of integrated management and comprehensive environmental assessments, intensive industrial development in Assaluyeh has led to cumulative releases of pollutants such as heavy metals, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and particulate matter. These pollutants pose increasing risks to coastal ecosystems and nearby communities [2]. This context underscores the urgent need for systematic review of existing conditions, identification of gaps in Environmental Impact Assessments (EIAs), and greater emphasis on Cumulative Effects Assessment (CEA) as a tool for strengthening regional environmental governance.

1.2. Environmental Challenges

Project-based Environmental Impact Assessments (EIAs) have often proven insufficient in mitigating pollution in industrial regions such as Assaluyeh. Field investigations reveal concerning accumulations of contaminants—including heavy metals (Pb, Cd, Ni, V), PAHs, and BTEX compounds—not only within industrial zones but also in adjacent residential areas [2].

These findings reflect the multi-source and cumulative nature of emissions. These pollutants originate from petrochemical and gas processing facilities, traffic, and supporting industrial activities. Traditional project-specific EIAs, which evaluate projects independently, fail to adequately capture the combined and long-term pressures on air, water, and soil [3].

Moreover, the persistence of these contaminants raises concerns about bioaccumulation and potential human health impacts. This situation highlights the necessity for integrated regional monitoring and assessment strategies. Adopting broader, regional-scale approaches—such as CEA within a Strategic Environmental Assessment (SEA) framework—can provide more effective tools to manage multi-source pollution, safeguard ecosystems, and support sustainable industrial development. The conceptual pathway linking industrial pollution sources, environmental media, and human and ecological impacts is illustrated in Figure 1.

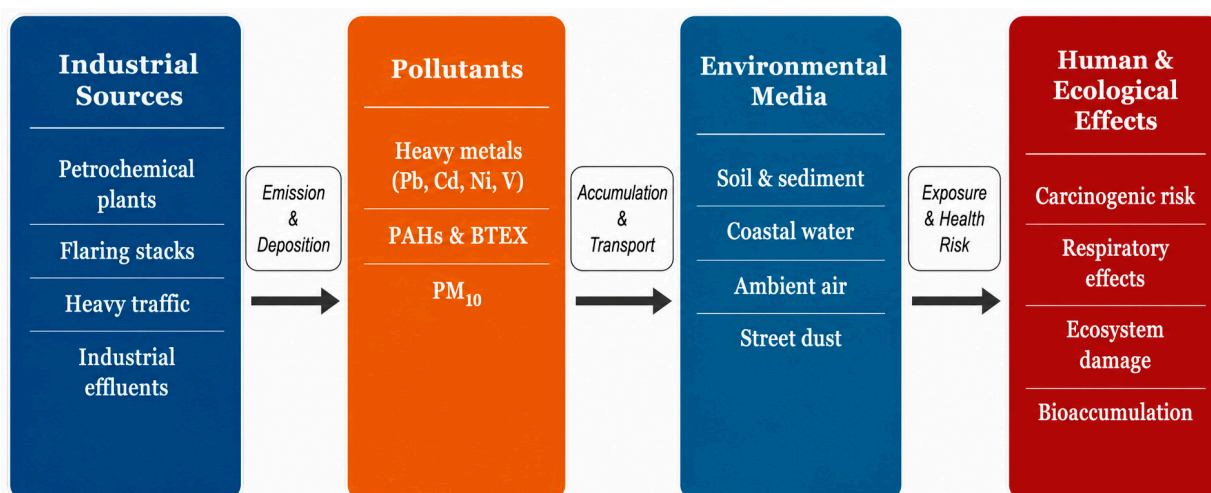


Figure 1. Pathway of industrial pollutants and their cumulative impacts in Assaluyeh. Pollutants released from petrochemical facilities, gas flaring, heavy traffic, and industrial effluents contaminate the air, soil, and water, resulting in human health risks (including carcinogenic and respiratory effects), ecosystem degradation, and bioaccumulation. The figure illustrates the cumulative and synergistic interactions among multiple pollution sources and pathways that are not adequately addressed by conventional project-based Environmental Impact Assessments (EIAs).

1.3. Limitations of Project-Based EIAs

The limitations of project-based EIAs and the value of broader assessment frameworks have attracted growing scholarly attention over the past two decades. Morgan [4] offered a wide-ranging global review of EIA practice and found that persistent weaknesses in addressing cumulative and long-term impacts were particularly pronounced in rapidly industrializing settings. Duinker and Greig [5] showed that CEA in Canada remained largely ineffective because clear regulatory requirements and methodological consistency were absent; their central recommendation was that CEA must be anchored within strategic-level planning rather than left to project-by-project discretion. Therivel and Ross [6] added an important nuance, demonstrating that the usefulness of cumulative assessment depends heavily on the scale at which it is applied, and that project-level assessments are structurally ill-suited to capturing region-wide pressures. Canter and Ross [7] reached a similar conclusion in their global review, finding that despite rising awareness of CEA's importance, actual implementation remained patchy and inconsistent. Writing specifically about developing countries, Alshuwaikhat [8] made a compelling case that SEA is indispensable in contexts where multiple industrial activities overlap, and a project-by-project approach inevitably misses the bigger picture. More recently, Gunn and Noble [9] and Bidstrup et al. [10] turned their attention to the practical difficulties of integrating CEA into SEA frameworks and proposed operational pathways to close the gap between aspiration and implementation. Wright et al. [11] took a more critical stance, tracing the persistent disconnect between EIA theory and on-the-ground practice to institutional inertia and chronic data shortages. Taken together, these studies point clearly toward the need for integrated, regional-scale assessment; yet, to the best of our knowledge, no study has systematically examined whether EIA and ESHIA practices in the Assaluyeh–PSEZ industrial corridor meet that standard, nor has any prior work brought together quantitative multi-pollutant field data and human health risk assessment within a unified CEA–SEA framework. The present study is designed to fill that gap.

The inadequacy of conventional project-based EIAs in heavily industrialized settings such as Assaluyeh is not simply a procedural shortcoming—it has real environmental consequences. By focusing narrowly on individual projects, these assessments routinely miss the ways in which multiple industrial activities interact and compound one another within a shared regional environment [8]. Field evidence demonstrates that heavy metals, polycyclic aromatic hydrocarbons (PAHs), and particulate matter do not behave as isolated contaminants; instead, they combine to produce additive or synergistic effects that erode air quality, degrade soil productivity, and damage coastal and marine ecosystems over time [3]. Cross-boundary pollution, multi-source emissions, and the slow temporal accumulation of contaminants fall largely outside the lens of conventional EIA, leaving environmental planners and regulators with an incomplete and potentially misleading picture [11]. Moving toward more integrated approaches—specifically, CEA embedded within an SEA framework—is therefore not merely desirable but necessary.

1.4. Need for CEA and SEA

The integration of CEA into SEA frameworks is increasingly recognized as a critical step in managing environmental pressures in regions characterized by intense and overlapping industrial activities. Unlike project-specific EIAs, which focus narrowly on individual projects, CEA evaluates how multiple projects collectively influence environmental conditions across time and space [9]. Incorporating CEA into SEA enables an integrated regional understanding, facilitates detection of cumulative and long-term impacts, and strengthens planning and decision-making processes [10,12,13].

1.5. Study Objectives

This study seeks to evaluate the effectiveness of current environmental assessment practices in capturing cumulative and regional-scale impacts of industrial development in Assaluyeh. The objectives of this study are threefold: (1) review existing EIA and ESHIA reports to identify methodological gaps in addressing cumulative impacts; (2) analyze field measurements of heavy metals, PAHs, and particulate matter to quantify multi-source pollution; and (3) propose integrated policy solutions combining CEA and SEA for regional environmental governance.

2. Materials and Methods

This chapter describes the research design adopted in this paper. The authors did not carry out any new field sampling. All environmental data were derived from previously released EIA/ESHIA reports and peer-reviewed literature from the Assaluyeh area. The present study focuses exclusively on data re-analysis, data integration, and cumulative impact assessment.

2.1. Data Extraction Protocol

To ensure reproducibility and transparency, a structured data extraction protocol was developed and applied consistently across all reviewed sources. The following elements were documented:

1. The literature search was conducted using Scopus, Web of Science, and Google Scholar. The search strategy included the following keywords: "Assaluyeh," "Pars Special Economic Energy Zone," "heavy metals," "PAHs," "BTEX," "particulate matter," "cumulative effects assessment," "EIA," "ESHIA," "Persian Gulf pollution," and related keyword combinations.
 2. Inclusion/exclusion criteria: Studies were included if they reported quantitative environmental measurements (soil, sediment, air, or water) from the Assaluyeh region, published between 2015 and 2024, in peer-reviewed journals or official institutional reports. Studies lacking primary quantitative data, located outside the study area, or with insufficient methodological description were excluded.
 3. Number of reports screened and included: A total of 23 peer-reviewed studies and 5 EIA/ESHIA reports were screened. Of these, 14 peer-reviewed studies and 2 reports [1,13] met the inclusion criteria and were included in the analysis.
 4. Data extraction: For each included study, pollutant concentrations, sampling locations, sampling periods, and analytical methods were recorded. Each table and figure in this paper explicitly identifies the source study (see Section 3).
 5. Raw data vs. digitized values: In most cases, data were extracted directly from published tables. Where values were presented only in figures, digitization was performed using Web Plot Digitizer (version 4.6).
 6. Units alignment: All soil and sediment concentrations were harmonized to $\mu\text{g/g}$ (dry weight), and air concentrations to $\mu\text{g/m}^3$. Unit conversions applied are documented in each table footnote.
 7. Studies containing incomplete datasets or lacking measurement units were excluded from quantitative analyses to avoid introducing uncertainty through data imputation.
 8. Statistical and software packages: Statistical analyses, including Pearson correlation and multivariate analyses, were conducted using IBM SPSS Statistics version 27.
- Spatial interpolation and mapping were performed using QGIS v.3.28 (see Section 2.4).

2.2. Examination of EIA and ESHIA Reports

All available EIA and ESHIA reports for significant industrial projects in Assaluyeh were systematically examined, focusing on sampling techniques, baseline data quality, cumulative effects Section, and analytical methods.

A total of 12 EIA/ESHIA reports were identified for major industrial projects in the Assaluyeh region based on publicly available registries and PSEEZ official records. Of these, only 3 were partially or fully accessible ([1,13]; one additional project-specific EIA). The remaining 9 were classified as restricted or inaccessible. Restricted and non-accessible reports were retained in Table 1 to document the transparency deficit; they were excluded from quantitative analysis but included in the qualitative governance discussion.

Table 1. Review of EIA/ESHIA reports and data quality.

Project	Report Accessibility	Cumulative Effects Section	Environmental Methodology	Data Transparency
JICA [1]	Public	Not included	Limited	Moderate
Total	Restricted	Not included	Low	Low
Jam	Restricted	Not included	Low	Low
Pardis	Not accessible	–	–	–
Marjan	Not accessible	–	–	–

Methodology and transparency ratings assigned using a structured scoring checklist (Supplementary Table S2). ‘Low’: absence of key methodological elements; ‘Limited’: partial coverage with significant gaps; ‘Moderate’: adequate description but lacking some standard elements.

A structured qualitative scoring checklist was developed to evaluate each accessible report across four dimensions: (a) Report Accessibility (Public/Restricted/Not accessible), (b) Cumulative Effects Section (Yes/No/Partial), (c) Environmental Methodology Quality (High/Moderate/Low/Not assessable), and (d) Data Transparency (High/Moderate/Low/Not assessable). Ratings were assigned independently by the two authors and cross-checked. “Low” indicates absence of key methodological details; “Limited” indicates partial coverage with significant gaps; “Moderate” indicates adequate description but lacking some standard elements. The full scoring rubric is provided in Supplementary Table S2.

2.3. Field Sampling Strategy (As Reported in Original Studies)

No new field sampling was conducted. Sampling designs described here reflect those in the original source studies. Environmental samples were gathered in industrial soils near petrochemical units and flaring stacks, along the Persian Gulf shoreline, street/atmospheric dust in industrial and residential zones, and PM10 in air. Sampling locations were typically organized in gradients from industrial complexes outward to residential and background areas [2].

2.4. Spatial Analysis

As stated above, no new field sampling or GIS interpolation was performed by the authors. The spatial maps included in this study were adapted and reproduced from the original source studies [2,14] with appropriate attribution. Full methodological details of the GIS software, interpolation methods, cell resolution, and semi variogram parameters are provided in the original publications.

Approximate coordinates of the sampling locations used in the source studies are compiled in Supplementary Table S1, based on published maps and textual descriptions from the original papers. Spatial uncertainty is higher in peripheral zones with lower sampling density, as acknowledged in the source studies. Readers are directed to the original publications for the complete spatial interpolation methodology, including the GIS software and software version, as well as cross-validation statistics.

2.5. Laboratory Procedures (From Original Studies)

Analytical methods used in the reviewed literature included Atomic Absorption Spectroscopy (AAS) for heavy metals and Gas Chromatography–Mass Spectrometry (GC-MS) for PAHs and BTEX. QA/QC measures, including certified reference materials, replicates, blanks, and multi-point calibration, were applied as per the original protocols.

2.6. Pollution Indices

Three indices were calculated independently using extracted datasets: Contamination Factor ($CF = C_{\text{measured}}/C_{\text{background}}$), Pollution Load Index $PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n}$ and Composite Pollution Index (CPI). Background reference values used for CF calculation are listed in Supplementary Table S4.

3. Results and Discussion

3.1. Review of EIA/ESHIA Reports

The systematic review revealed that the vast majority of EIA and ESHIA reports did not contain a dedicated cumulative effects assessment section and generally exhibited low methodological quality. The JICA [1] report was the only publicly available document, but even it did not address cumulative impacts (Table 1). These weaknesses reflect the inefficiency of project-based EIA frameworks in highly industrialized regions like Assaluyeh, which is consistent with previous studies [4–7].

3.2. Heavy Metal Concentrations and PLI

Field measurements showed that heavy metal levels, particularly Pb and Ni, were significantly higher in the central industrial zone than in residential areas. Table 2 shows Pb concentrations of 120 µg/g and Ni = 45 µg/g in the industrial core, compared to Pb = 45 µg/g and Ni = 12 µg/g in residential zones. The Pollution Load Index (PLI) in the central industrial zone (2.5) was significantly higher than in residential zones (PLI = 0.9), confirming the presence of cumulative multi-source contamination.

Table 2. Heavy metal concentrations and PLI in different areas of Assaluyeh.

Area	Pb (µg/g)	Cd (µg/g)	Ni (µg/g)	V (µg/g)	PLI
Central Industrial Zone	120	5.2	45	32	2.5
Near Jam Complex	95	4.8	38	28	2.1
Near Pardis Complex	88	3.9	35	25	1.9
Residential Areas	45	1.2	12	10	0.9

Concentration data derived from Tashakor et al. [2], and Naderizadeh et al. [14]. PLI values calculated by the authors using $CF = C_{\text{measured}}/C_{\text{background}}$. Background values from Supplementary Table S4.

3.3. Organic Pollutants (ΣPAH and BTEX)

ΣPAH and BTEX levels in industrial areas of Assaluyeh were well above the WHO guideline value of 20 µg/m³. Table 3 shows ΣPAH = 72.5 µg/m³ and BTEX = 38.2 µg/m³ in the central industrial zone, whereas residential areas recorded substantially lower values (ΣPAH = 18.6 µg/m³; BTEX = 10.2 µg/m³), below the acceptable limit (Figure 2).

Table 3. Correlation coefficients between pollutant groups.

Pollutants	Pb	Cd	Ni	V
ΣPAH	0.65 **	0.50 *	0.70 **	0.40 ns
BTEX	0.55 *	0.45 *	0.60 **	0.35 ns

Correlations calculated by the authors using IBM SPSS Statistics v.27 from datasets extracted from Tashakor et al. [2], Ghaemi et al. [15], and Bayatzadeh et al. [16]. ** $p < 0.01$; * $p < 0.05$; ns: not significant.

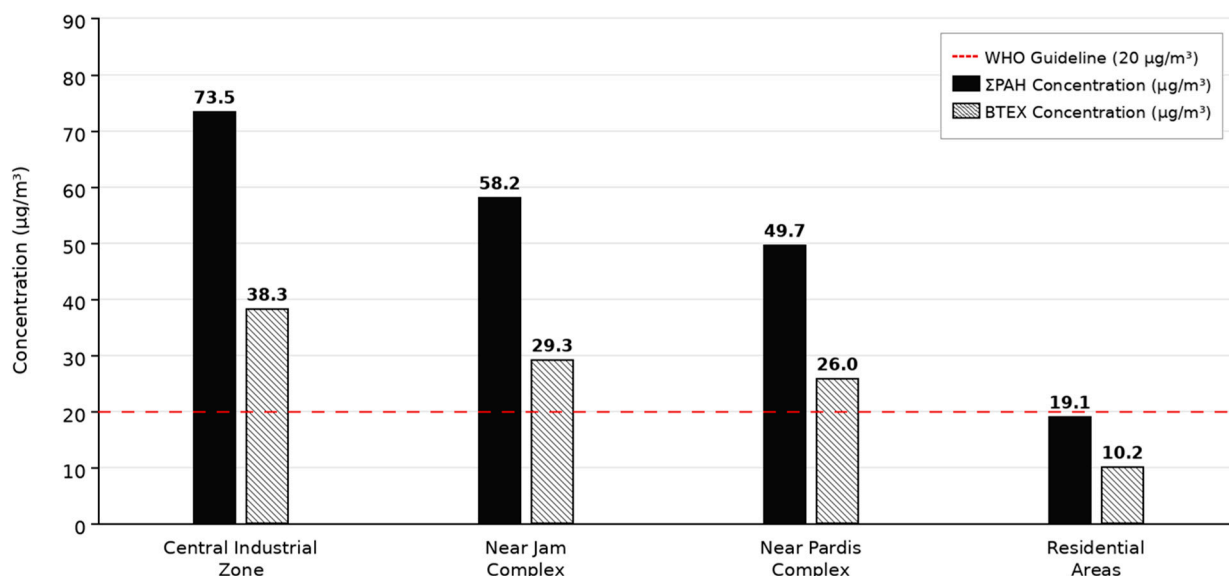


Figure 2. Comparative concentrations of ΣPAH and BTEX ($\mu\text{g}/\text{m}^3$) across different zones of Assaluyeh. Values in the central industrial zone ($\Sigma\text{PAH} = 73.5$; $\text{BTEX} = 38.2 \mu\text{g}/\text{m}^3$) and near the Jam and Pardis complexes substantially exceed the WHO guideline of $20 \mu\text{g}/\text{m}^3$ (dashed red line), while residential area levels remain below this threshold. Data derived from Tashakor et al. [2] and Ghaemi et al. [15]; figure produced by the authors.

3.4. Correlation and Source Apportionment

Correlation analysis indicated that PAHs and BTEX were strongly associated, suggesting a common combustion-related origin. Heavy metals exhibited more variable relationships because they are influenced by multiple emission pathways, including industrial effluents and sedimentation processes. The relative contributions of the major pollution sources are summarized in Table 4.

Table 4. Relative contributions of pollution sources to soil, coastal water, and air in Assaluyeh.

Medium	Flaring	Olefin Units	Truck Traffic	Industrial Effluents
Soil	20%	30%	10%	40%
Coastal Water	15%	25%	10%	50%
Air	40%	25%	25%	10%

Source apportionment estimates derived from multivariate analysis conducted by the authors on datasets from Tashakor et al. [2] and Mirza et al. [17].

3.5. Human Health Risk Assessment (HHRA)

The HHRA was conducted following U.S. EPA [18] guidelines, considering ingestion, inhalation, and dermal contact exposure pathways.

Risk equations applied: Non-carcinogenic hazard quotient: $\text{HQ} = \text{CDI}/\text{RfD}$. Carcinogenic risk: $\text{CR} = \text{CDI} \times \text{CSF}$. Daily intake (CDI) was calculated separately for ingestion, inhalation, and dermal contact pathways.

Exposure parameters (Table 5): Exposure frequency (EF) = 350 days/year; Exposure duration (ED) = 30 years (adults), 6 years (children); Soil ingestion rate (IR) = 50 mg/day (adults), 100 mg/day (children); Body weight (BW) = 70 kg (adults), 15 kg (children); Averaging time for carcinogenic risk (AT) = 70×365 days.

Cancer slope factors (CSFs) and oral reference doses (RfDs) for Pb, Cd, As, Hg, and Ni were taken from the U.S. EPA Integrated Risk Information System (IRIS) database.

Based on the calculated cancer slope factors (CSFs) and exposure parameters, the carcinogenic risk levels of heavy metals in Assaluyeh soils were evaluated for adult and child receptors. The results are presented in Table 6.

Table 5. Exposure parameters used for human health risk assessment (HHRA).

Parameter	Symbol	Unit	Adults	Children
Exposure frequency	EF	days/year	350	350
Exposure duration	ED	years	30	6
Soil ingestion rate	IR	mg/day	50	100
Body weight	BW	kg	70	15
Averaging time for carcinogenic risk	AT	days	25,550 (70 × 365)	25,550 (70 × 365)
Exposure pathways	—	—	Ingestion, inhalation, dermal contact	Ingestion, inhalation, dermal contact

Note: HHRA calculations followed U.S. EPA (2011) guidelines. HQ and CR were estimated using CDI-based exposure calculations.

Table 6. Carcinogenic risk levels of heavy metals in Assaluyeh soils for adults and children.

Metal	Concentration (µg/g)	CF	Risk Level—Adults	Risk Level—Children	Significance
Pb	120	3.0	Low–Medium	Medium	*
As	15	2.5	Medium	Medium	*
Cd	5.2	5.2	High	High	**
Hg	2.8	4.5	High	High	**
Ni	45	4.5	Medium	Medium–High	**

Calculated by the authors following U.S. EPA [18] guidelines. Risk categories: CR < 1×10^{-6} : Negligible; 1×10^{-6} – 1×10^{-4} : Acceptable (Low–Medium); $>1 \times 10^{-4}$: Unacceptable (High). Concentration data from Tashakor et al. [2] and Naderizadeh et al. [14]. ** exceeds EPA acceptable limits; * within acceptable range.

“Low–Medium” corresponds to carcinogenic risk values within the U.S. EPA acceptable range (CR: 1×10^{-6} to 1×10^{-4}). “High” indicates CR $> 1 \times 10^{-4}$, exceeding EPA acceptable limits. “Medium–High” refers to CR values approaching or reaching the upper boundary of the acceptable range, with potential to exceed it under realistic worst-case exposure scenarios.

A one-at-a-time sensitivity analysis was performed by varying key exposure parameters, including body weight (BW $\pm 20\%$) and exposure duration (ED $\pm 30\%$). Results showed that CR estimates for Cd and Hg remained in the “High” category across all tested scenarios, indicating the robustness of the findings. Uncertainty is higher for children due to greater variability in exposure parameters. In addition, the use of generalized U.S. EPA default values may not fully reflect local demographic or behavioral conditions. These limitations are further discussed in the Section 7.

3.6. Spatial Analysis and Pollution Hotspots

The heatmap (Figure 3) indicates pollution hotspots in the northern and central areas of Assaluyeh, corresponding to the locations of petrochemical complexes, flaring stacks, and major transportation routes. The integrated composite pollution index map (Figure 4) confirms the highest cumulative index values in the central industrial zone, with a gradual radial decrease toward peripheral and residential areas. These spatial patterns are consistent with the measured pollutant concentrations and confirm the multi-source and synergistic nature of contamination.

As explicitly stated in the Section 2, no new GIS interpolation was performed by the authors. The spatial maps were adapted from the original source studies [2,14]. Full methodological details, including the interpolation methods, cross-validation (RMSE), semi variogram parameters, and GIS settings, are available in the original publications. Spatial uncertainty is higher in peripheral low-density sampling zones, as reported in the source studies. The approximate geographic coordinates compiled from the published studies are provided in Supplementary Table S1.

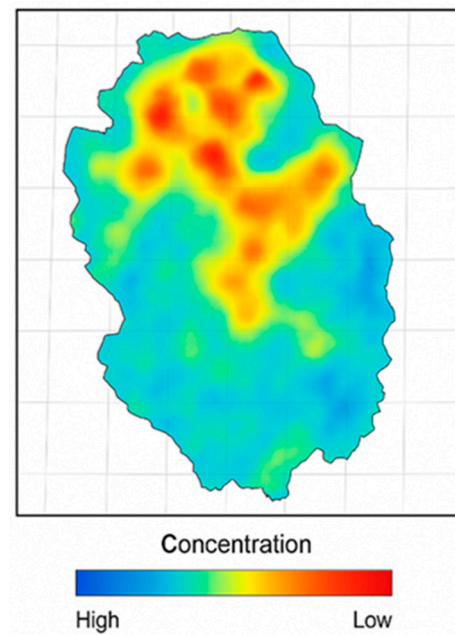


Figure 3. Spatial hotspots of environmental pollution in Assaluyeh based on heatmap analysis. Red/orange zones indicate high pollutant concentrations in the central industrial area; blue/green zones indicate lower concentrations in peripheral and residential areas. Adapted from Tashakor et al. [2].

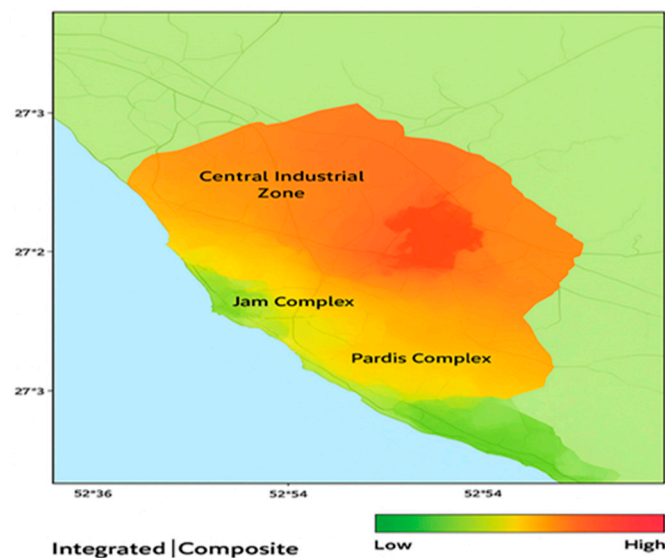


Figure 4. Integrated Composite Index Map showing hotspot areas of cumulative environmental impact in Assaluyeh. The central industrial zone (red) shows the highest cumulative index values; contamination decreases radially toward the Jam and Pardis complexes (orange/green). Adapted from Naderizadeh et al. [14] and Tashakor et al. [2].

4. Limitations of Project-Based EIA and the Need for CEA

The findings clearly demonstrate that project-based EIAs are inadequate in highly industrialized zones such as Assaluyeh. The review revealed the absence of dedicated cumulative effects sections, methodological weaknesses, and limited or inaccessible data. Field-based evidence—including elevated concentrations of heavy metals (Pb, Cd, Ni, V), organic pollutants (Σ PAH and BTEX), high PLI and CPI values, and HHRA outcomes—confirms the cumulative and synergistic nature of pollution. Strong correlations among pollutants (PAHs–BTEX: $r = 0.80$) highlight the role of shared sources in undermining environmental quality and public health.

Only through the implementation of Cumulative Effects Assessment (CEA) within a Strategic Environmental Assessment (SEA) framework can long-term and combined impacts be systematically identified, quantified, and managed.

5. Conclusions

This study demonstrates that the Assaluyeh industrial region is subject to cumulative and multi-source pollution pressures affecting soil, water, and air. Elevated concentrations of heavy metals ($\text{Pb} = 120 \mu\text{g/g}$, $\text{Ni} = 45 \mu\text{g/g}$, $\text{PLI} = 2.5$ in the central industrial zone), organic pollutants ($\Sigma\text{PAH} = 72.5 \mu\text{g/m}^3$ and $\text{BTEX} = 38.2 \mu\text{g/m}^3$, both exceeding the WHO guideline value of $20 \mu\text{g/m}^3$), and carcinogenic risks classified as high for Cd and Hg (exceeding EPA acceptable limits) were documented. Strong correlations between PAHs and BTEX ($r = 0.80$) confirm common combustion-related sources. The review of existing EIA and ESHIA reports highlighted critical methodological gaps, particularly the absence of cumulative effects assessment, underscoring the inadequacy of project-based EIAs in capturing synergistic and long-term environmental impacts. Integrating CEA within SEA frameworks is therefore essential to address overlapping industrial pressures, anticipate ecological and health risks, and guide sustainable development in heavily industrialized coastal regions.

By combining systematic review, spatial visualization, and human health risk assessment, this study provides a comprehensive evidence base for regional-scale environmental governance. The findings underscore the urgent need for long-term monitoring, early warning systems, and targeted interventions in high-risk zones.

6. Future Research

Although this study offers a comprehensive assessment, several areas require further investigation. Establishing long-term monitoring programs for heavy metals, PAHs, BTEX, and particulate matter across soil, water, and air is essential. Future research should employ receptor modeling (receptor modeling, isotopic fingerprinting), expand human health risk assessment (HHRA) with probabilistic approaches and population-based exposure scenarios, and integrate remote sensing and GIS-based analyses. Policy-oriented studies should evaluate current environmental regulations and develop adaptive management frameworks incorporating Cumulative Effects Assessment (CEA) within Strategic Environmental Assessment (SEA) processes. Comparative analyses with other industrial coastal regions, as well as investigations into the interactions between pollution and climate change, will also be crucial.

7. Limitations

All environmental data were obtained from previously published EIA/ESHIA reports and peer-reviewed studies. The accuracy of the findings depends on the methodological rigor and data quality of original sources, which varied considerably. Access to many industrial reports was restricted. Datasets represent snapshots of environmental conditions and may not capture temporal variability or seasonal fluctuations. While statistical and spatial analyses provided valuable insights, the absence of advanced receptor modeling limited source identification precision.

The HHRA relied on generalized EPA default exposure parameters, which may not fully reflect local demographic, behavioral, or socio-economic conditions. Sensitivity analysis showed that conclusions regarding Cd and Hg risk remain robust, but uncertainty for children's exposure estimates is acknowledged. Future research should incorporate long-term monitoring, improved data transparency, and advanced analytical techniques to strengthen CEA and provide more robust evidence for environmental governance.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/eesp2026042021/s1>, Supplementary Table S1. Coordinates of Sampling Locations; Supplementary Table S2. EIA/ESHIA Quality Scoring Checklist; Supplementary Note. Spatial Analysis (replacing former Table S3); Supplementary Table S4. Background Reference Values for CF Calculation; Supplementary Table S5. Exposure Parameters and Toxicity Factors (HHRA) [19–21].

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