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Towards a Sustainable Industrial City: Spatial Analysis of Gaseous Emissions and Their Developmental Impacts in Zliten City

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Abstract

Background: Industrial development plays an important role in employment creation, infrastructure expansion, construction activity, and economic development; however, the spatial concentration of industrial activities can generate environmental externalities that challenge the sustainability of surrounding urban areas. Zliten City represents an important Libyan case because industrial activities, particularly cement and construction-material production, coexist with rapid urban growth, intensive transportation, waste-disposal activities, and expanding residential land uses. The study therefore addresses a gap in the Libyan literature by integrating industrial management, atmospheric pollution, and spatial sustainability within a single analytical framework.

Objective: This study aimed to analyze the spatial distribution and temporal variability of gaseous atmospheric pollutants in Zliten City and assess their environmental and developmental implications in order to support the city's transition toward a sustainable industrial-development model.

Methods: A spatiotemporal descriptive-analytical approach was employed using Sentinel-5P/TROPOMI satellite observations integrated with Geographic Information System (GIS) techniques. Atmospheric data covering 2019–2024 were analyzed for sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3). Quality-controlled satellite observations were used to examine temporal variability, spatial distribution, and potential pollution hotspots and to interpret their spatial relationships with industrial activities, transportation corridors, populated areas, waste-related activities, and surrounding land uses.

Results: The analysis revealed considerable spatial and temporal heterogeneity in atmospheric pollution across the study area, indicating that environmental pressure is not uniformly distributed. SO_2 concentrations displayed pronounced monthly and interannual fluctuations, with elevated winter concentrations and substantial variation throughout 2019–2024. CO concentrations similarly exhibited persistent temporal variation; the annual mean declined to 29,283.11 ppb in 2022 before increasing to 32,207.52 ppb in 2024, indicating the absence of a sustained improvement trajectory. Spatial interpretation further suggested that areas of elevated pollution may correspond with combinations of industrial activity, transportation, urban concentration, waste disposal, and other combustion-related sources. However, spatial coincidence was treated as evidence of potential source influence rather than definitive causation because atmospheric transport and meteorological conditions can modify observed pollutant distributions.

Conclusion: The findings demonstrate that sustainable industrial development in Zliten requires a transition from conventional pollution monitoring toward spatially integrated environmental management. Industrial sustainability cannot be achieved solely through end-of-pipe emission controls; it requires cleaner production, technological modernization, improved energy and transportation efficiency, effective waste management, continuous air-quality monitoring, land-use compatibility, and stronger environmental governance. GIS and satellite remote sensing can therefore function as strategic decision-support instruments for identifying priority intervention areas, designing buffer zones, guiding industrial expansion, and integrating environmental considerations into urban-development decisions. The study concludes that Zliten's transition toward a sustainable industrial city depends on its ability to decouple industrial and developmental value creation from increasing environmental pressure, thereby transforming air-quality information into an operational component of industrial management and spatial planning.

Keywords: Sustainable Industrial City; Gaseous Emissions; Air Pollution; Spatial Analysis; GIS; Sentinel-5P; TROPOMI; Industrial Management; Sustainable Development; Zliten; Libya.

1 | Introduction

Industrial development remains one of the principal drivers of economic growth, employment creation, infrastructure expansion, and urban transformation. However, the contemporary evaluation of industrial performance has moved beyond conventional indicators such as production volume, capacity utilization, profitability, and employment generation. Increasingly, industrial systems are expected to demonstrate their ability to generate economic value while minimizing emissions, resource consumption, environmental degradation, and spatial conflicts with surrounding communities. From an industrial management perspective, this transition represents a shift from a production-centered model toward a sustainable industrial performance model, in which environmental efficiency becomes an integral component of operational and strategic performance. Accordingly, the sustainable industrial city should not be understood merely as a city containing environmentally compliant factories, but as an integrated production–urban system in which industrial location, technology, environmental performance, infrastructure, land use, and community development are coordinated within a common sustainability framework (Al-Asadi et al., 2024).

Within this framework, gaseous emissions represent a particularly important challenge because they reveal an inherent tension between industrial productivity and environmental carrying capacity. Industrial combustion, material processing, energy consumption, transportation, and high-temperature manufacturing processes can release pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter. The significance of these emissions extends beyond their atmospheric concentrations because their environmental and developmental impacts depend on the location of emission sources, prevailing winds, atmospheric stability, industrial concentration, population distribution, and the spatial configuration of urban and industrial land uses. Consequently, industrial-emission management requires a transition from simply asking “how much is emitted?” toward examining “where emissions originate, where they accumulate or disperse, which urban areas are exposed, and how these spatial relationships influence sustainable development.”

This transition is particularly relevant to the cement industry, which performs a strategically important economic function by supplying essential materials for housing, transportation infrastructure, industrial construction, and urban development, while simultaneously generating substantial environmental pressures. Cement production involves energy-intensive thermal processes and clinker manufacture, creating significant direct and indirect emissions. Habert et al. (2020) demonstrated that reducing the environmental footprint of cement and concrete cannot depend on a single technological intervention; rather, it requires an integrated portfolio of measures involving material efficiency, clinker substitution, alternative fuels, energy-efficiency improvements, carbon capture, and changes throughout the production and construction value chain. This observation is particularly relevant from an industrial-management perspective because it positions emissions reduction not as an end-of-pipe environmental obligation, but as an issue of process optimization, technological modernization, resource productivity, and long-term industrial competitiveness.

The spatial dimension adds another level of complexity to industrial-emission management. Air pollutants do not necessarily remain within factory boundaries or administrative zones, and therefore the environmental performance of an industrial facility cannot be evaluated solely within the physical perimeter of the plant. Chen et al. (2022) demonstrated significant spatial agglomeration and spillover effects in industrial SO_2 emissions, showing that industrial scale, industrial structure, technological innovation, and environmental regulation can influence pollution not only locally but also in neighboring areas. Their findings are particularly important for sustainable industrial planning because they demonstrate that environmental externalities generated by industrial activity possess a geographical dimension. In practical terms, this means that conventional industrial zoning becomes insufficient when it ignores atmospheric dispersion, adjacent residential development, prevailing wind direction, and the cumulative environmental effects of multiple industrial activities.

Industrial agglomeration itself illustrates this management dilemma. Concentrating industries geographically may improve supply-chain coordination, infrastructure utilization, knowledge transfer, labor-market efficiency, and economies of scale. Yet the same concentration can generate cumulative emissions and increase environmental pressure within specific urban zones. Research examining the relationship between industrial agglomeration and air pollution has consequently shown that economic concentration can produce both productivity benefits and environmental costs, with environmental regulation, technological progress, and industrial restructuring influencing the balance between them (Wang et al., 2022). This suggests that the fundamental challenge for industrial management is not necessarily to reduce industrial concentration, but to transform the quality of industrial agglomeration by improving technology, energy efficiency, emission control, environmental infrastructure, and spatial compatibility with surrounding land uses.

Accordingly, the concept of a sustainable industrial city requires the integration of industrial management with spatial planning. These disciplines are frequently treated separately: industrial management focuses on productivity, technology, operations, supply chains, and competitiveness, whereas urban and environmental planning focuses on land use, environmental quality, population distribution, and infrastructure. Sustainable industrial development requires these perspectives to converge. Al-Asadi et al. (2024) argue for stronger integration between sustainable industrial practices and urban environments, emphasizing that industrial development should function as part of a wider urban sustainability system. From this perspective, industrial facilities should be evaluated not only according to what occurs inside their production boundaries but also according to how their operations interact with transportation networks, residential areas, ecological systems, energy infrastructure, and future urban expansion.

Spatial analysis therefore becomes a strategic management instrument, rather than merely a cartographic technique. Mapping emission sources and their surrounding areas can help identify environmental hotspots, potential exposure zones, spatial incompatibilities between industrial and residential land uses, and areas requiring stronger monitoring or mitigation. It can also support decisions concerning industrial buffer zones, future facility expansion, environmental monitoring stations, green belts, transportation corridors, and the spatial allocation of new investments. More importantly, spatial analysis allows industrial managers and policymakers to recognize that environmental risk is rarely distributed uniformly across an urban area. Spatially differentiated pollution therefore requires spatially differentiated management responses. Evidence of strong spatial heterogeneity in air pollution reinforces the need to move beyond city-wide averages toward geographically explicit environmental assessment and decision-making.

The case of Zliten, Libya, provides a particularly relevant context for applying this integrated perspective. The city combines urban growth with important industrial activities, particularly cement production, making the relationship between industrial development and environmental quality increasingly relevant to its future development trajectory. The environmental implications of cement-related emissions in Zliten are not purely theoretical. Recent local evidence concerning the Arab Cement Factory in Zliten reported environmental and health concerns associated with cement dust exposure among workers and surrounding residents and emphasized the importance of improving filtration technologies and strengthening periodic environmental monitoring (Harhour et al., 2026). Although such evidence establishes the local relevance of industrial pollution, assessing Zliten's transition toward sustainability requires moving beyond documenting pollution effects toward examining how industrial emissions are distributed spatially and how their distribution intersects with the city's developmental structure.

This distinction is fundamental. From a sustainability perspective, the developmental impact of gaseous emissions cannot be reduced to environmental deterioration alone. Industrial emissions may generate broader externalities affecting the suitability of land for future development, residential expansion, environmental quality, infrastructure planning, investment attractiveness, and the long-term relationship between industrial facilities and surrounding communities. At the same time, industrial facilities provide employment, productive capacity, construction materials, fiscal activity, and economic linkages. The policy objective should therefore not be framed as a simplistic choice between industry and environment. Instead, the relevant management question is how industrial productivity can be maintained or enhanced while progressively reducing its environmental intensity and preventing the spatial transfer of industrial costs to surrounding communities. This is the essence of sustainable industrial management: increasing the economic value generated per unit of environmental burden.

Against this background, the present study, entitled "Towards a Sustainable Industrial City: Spatial Analysis of Gaseous Emissions and Their Developmental Impacts in Zliten City," seeks to develop an integrated understanding of industrial emissions through the combined lenses of industrial management, spatial sustainability, and environmental performance. Rather than treating gaseous emissions as isolated environmental measurements, the study examines their spatial distribution in relation to industrial locations, surrounding urban structures, land-use patterns, and potentially affected development zones. This approach is intended to identify areas of elevated environmental pressure and to assess their implications for sustainable spatial development. The study ultimately seeks to shift the discussion from pollution measurement to pollution-informed industrial decision-making, providing an evidence base for cleaner production, environmental monitoring, spatial zoning, industrial buffer management, technological upgrading, and environmentally responsible urban expansion. In this sense, Zliten is treated not merely as a location experiencing industrial emissions, but as a city facing a strategic transition: from conventional industrial growth toward a spatially integrated and environmentally sustainable industrial-development model.

2 | Problem Statement

Despite the significant contribution of industrial activities to economic growth, employment, infrastructure development, and urban expansion in Zliten City, the spatial concentration of industrial facilities, particularly cement-related activities, raises increasing concerns regarding gaseous emissions and their environmental and developmental implications. Existing local evidence has largely focused on documenting pollution and its environmental or health effects, while limited attention has been given to the spatial distribution of industrial emissions and their interaction with residential areas, land-use patterns, urban expansion, and sustainable development priorities. Therefore, the central research problem lies in the lack of an integrated spatial–industrial assessment capable of identifying emission hotspots and evaluating how their spatial distribution may affect the transition of Zliten from conventional industrial growth toward a sustainable industrial city. Accordingly, the study addresses the following research questions:

2.1 | Research Questions

1. What are the spatial distribution patterns of gaseous emissions generated by industrial activities in Zliten City?
2. Where are the major gaseous-emission hotspots, and how are they spatially related to industrial facilities and surrounding urban areas?
3. To what extent do gaseous emissions vary according to distance from industrial emission sources and the spatial characteristics of the surrounding areas?
4. What are the major environmental, spatial, and developmental implications of industrial gaseous emissions in Zliten City?
5. How can the findings of spatial emission analysis support industrial management and spatial planning toward the development of Zliten as a sustainable industrial city?

3 | Significance of the Study

The significance of this study lies in integrating industrial management, environmental performance, and spatial sustainability within a single analytical framework. Scientifically, the study contributes to addressing the limited spatially explicit evidence on industrial gaseous emissions in Libyan cities by moving beyond conventional pollution measurement toward identifying spatial patterns, hotspots, and potentially affected development zones. From an industrial-management perspective, the findings can support decisions concerning cleaner production, technological upgrading, emission-control systems, environmental monitoring, and the improvement of industrial environmental efficiency. Spatially, the study can provide evidence for evaluating compatibility between industrial locations, residential areas, future urban expansion, buffer zones, and land-use planning. From a policy perspective, it may assist local authorities and industrial decision-makers in developing geographically targeted interventions rather than applying uniform environmental measures across the entire city. This orientation is consistent with the study's broader objective of shifting from pollution measurement to pollution-informed industrial decision-making.

4 | Study Objectives

4.1|General Objective

The study aims to analyze the spatial distribution of industrial gaseous emissions and assess their environmental and developmental implications in Zliten City in order to support its transition toward a sustainable industrial city.

4.2 | Specific Objectives

1. To identify and analyze the spatial distribution patterns of gaseous emissions associated with industrial activities in Zliten City.
2. To identify major emission hotspots and examine their spatial relationship with industrial facilities, residential areas, and surrounding land uses.
3. To assess variations in gaseous emissions according to distance from industrial sources and the spatial characteristics of the investigated locations.
4. To evaluate the environmental, spatial, and developmental implications associated with the distribution of industrial gaseous emissions.
5. To propose an evidence-based industrial and spatial management framework for reducing emission-related pressures and supporting the transition of Zliten toward a sustainable industrial city.

5 | Scope and Delimitations of the Study

Spatial scope: The study is geographically limited to Zliten City, Libya, with particular emphasis on industrial emission sources and the surrounding urban and development areas potentially influenced by their spatial distribution.

- **Thematic scope**: The study focuses on industrial gaseous emissions, their spatial distribution and hotspots, their relationship with industrial locations and surrounding land uses, and their environmental and developmental implications. The analysis is framed through the perspectives of industrial management and spatial sustainability rather than treating air pollution as an isolated environmental phenomenon.
- **Analytical scope**: Spatial analysis constitutes the principal analytical dimension of the study and is used to examine the geographical distribution of emissions, differences according to proximity to industrial sources, and potential spatial relationships between emission concentrations and urban or developmental areas. This is consistent with the paper's conception of spatial analysis as a strategic management instrument for identifying hotspots, exposure zones, buffer requirements, and spatial incompatibilities.
- **Temporal scope**: The temporal boundary should correspond to the actual field-monitoring period during which gaseous-emission measurements are collected. The specific months and year should therefore be reported after confirming the field-sampling schedule rather than assigning an unsupported period.

- **Pollutant scope**: The final list of pollutants should likewise correspond strictly to the gases actually measured with the field instruments. Although the introduction discusses pollutants such as CO_2, SO_2, NO_x, CO, and particulate matter as common industrial emissions, only pollutants for which actual measurements are available should be presented as study variables.

6 | Literature Review

Recent literature has increasingly shifted from treating industrial air pollution as an isolated environmental problem toward examining it as a multidimensional challenge involving industrial efficiency, spatial planning, environmental governance, public health, and sustainable urban development. Within the Libyan context, Mahmoud et al. (2020) examined gaseous and particulate emissions from the El-Mergheb Cement Factory near Khoms in northwestern Libya. The study focused on estimating CO, CO_2, SO_2, NO_x, and particulate emissions and modelling their dispersion around the plant over an area extending approximately 20 km from the emission source. The results indicated that gaseous and particulate emissions exceeded selected reference limits, highlighting the importance of improved operational practices and emission-control measures. This study is particularly relevant because it demonstrates that industrial emissions in the Libyan coastal environment are not confined to the factory boundary but have a measurable spatial dimension.

From another Libyan perspective, Zaatout et al. (2022) investigated the effects of cement manufacturing on health, safety, and environmental conditions at the El-Fataih Cement Plant. The study focused on the interaction between industrial operations and HSE performance and revealed that inadequate pollution-control practices could generate environmental and occupational risks. It emphasized technical and engineering interventions, maintenance of air-pollution control systems, recycling systems, warning mechanisms, and comprehensive HSE management. The significance of this study lies in demonstrating that emission reduction is not simply an environmental requirement but is closely associated with industrial operations management and preventive maintenance.

More recently, Omar (2025) examined the relationship between cement-factory emissions and respiratory-health concerns in Benghazi, Libya, using a cross-sectional survey involving healthcare, environmental, and regulatory professionals. The study revealed that 74.2% of respondents associated factory emissions with increased respiratory conditions in nearby communities, while substantial proportions identified deficiencies in environmental communication and regulatory performance. The study therefore moved the Libyan debate beyond physical pollution toward environmental governance, community exposure, and institutional responsibility, although it did not spatially map pollution concentrations or relate them systematically to urban land-use patterns.

At the level of the Libyan cement sector as a whole, Inweer et al. (2025) conducted a life-cycle carbon-footprint assessment of cement production in Libya. The study assessed four Libyan cement factories and considered emissions associated with domestic production and imported cement. It estimated an emission factor of approximately 1083.6 kg CO_2 per ton of cement and proposed mitigation strategies for reducing the industry's carbon footprint. The importance of this work lies in shifting attention from localized pollution toward the carbon efficiency of the Libyan cement-production system, thereby establishing a useful basis for integrating production performance with environmental sustainability.

Nevertheless, the life-cycle approach does not directly identify intra-urban spatial hotspots or their relationships with surrounding residential and developmental areas.

Within the broader Arab context, Al-Kasser (2021) reviewed the sources and effects of air pollution across Iraq and showed that atmospheric pollution results from multiple sources, including fossil-fuel combustion, energy production, transportation, oil activities, brick and cement industries, generators, agricultural burning, and dust storms. The study identified CO, CO_2, NO_x, SO_x, O_3, suspended particles, hydrocarbons, and heavy metals among the major pollutants. Its findings are relevant to the present research because they demonstrate that urban industrial pollution must be interpreted within a multi-source atmospheric system, rather than attributing all observed concentrations automatically to a single industrial facility.

In Egypt, Sayad et al. (2023) aimed to evaluate the effect of different fuels used by the Alexandria Portland Cement Company on pollutant emissions and ambient air quality. The study focused on total suspended particles, NO_2, and SO_2 during 2014–2020 and applied the AERMOD atmospheric-dispersion model. The results demonstrated that fuel type strongly influences both emission rates and ambient pollutant concentrations and confirmed the value of dispersion modelling for identifying the geographical extent of industrial influence. This provides a particularly useful methodological precedent for the present study because it connects industrial operating inputs with emission behaviour and spatial air-quality outcomes.

In Saudi Arabia, Khan et al. (2023) investigated the dynamics of greenhouse-gas emissions from the cement industry and examined both the challenges and opportunities associated with sectoral decarbonization. The study analyzed relationships between cement-production emissions and their principal drivers and emphasized the need for short- and long-term strategies capable of reconciling industrial growth with national climate objectives. Its contribution lies in showing that sustainable cement management requires more than technological control at individual plants; it also requires an integrated strategy connecting production, energy, emissions, policy, and long-term industrial transformation.

Similarly, research focusing on the Saudi context examined how transformation of the cement and concrete industries could contribute to climate-change mitigation. The study demonstrated that increasing demand for cement generates substantial greenhouse-gas emissions and pressure on natural resources, but also identified pathways through which technological and managerial transformation can reconcile societal demand, ecological constraints, and technical capabilities (Miller et al., 2022). This perspective strengthens the argument that sustainable industrial management should not be framed as reducing industrial activity per se, but as changing the environmental intensity and technological structure of production.

In Algeria, Nabil et al. (2025) focused on the role of ecological taxation in controlling industrial air pollution associated with the Lafarge Holcim cement plant. The study examined environmental legislation governing dust and gaseous emissions and showed that ecological taxation can contribute to reducing pollution when combined with cleaner-production technologies and effective regulatory mechanisms. Unlike purely technical emission studies, this work introduces an important governance dimension: sustainable industrial performance depends not only on engineering controls but also on economic instruments, regulatory enforcement, and corporate environmental responsibility.

Moving to the international literature, Habert et al. (2020) provided one of the most influential contemporary assessments of environmental impacts and decarbonization strategies in cement and concrete industries. The study showed that cement-sector sustainability cannot be achieved through a single intervention and instead requires material efficiency, clinker substitution, alternative fuels, improvements in energy efficiency, carbon capture, and changes throughout the construction value chain. From an industrial-management perspective, the study is important because it redefines emissions as an issue of production-system design and resource productivity, rather than an external environmental problem treated only after pollutants have been generated.

At the technological and economic level, Poudyal and Adhikari (2021) focused on environmental sustainability in cement manufacturing and examined an integrated approach to green and economically viable cement production. They evaluated carbon capture and storage, supplementary cementitious materials, and emerging technologies as potential pathways for reducing CO_2 emissions. Their analysis showed that technological alternatives offer significant environmental opportunities but differ in cost, feasibility, and industrial scalability. The study consequently reinforces the need to evaluate cleaner-production options through both environmental effectiveness and operational-economic feasibility.

Using a life-cycle perspective, Beressa and Saradhi (2021) evaluated Ethiopian cement manufacturing, focusing on greenhouse-gas emissions, energy-use intensity, and resource exploitation at the Mugher Cement Factory. The study revealed the environmental burden associated with fossil-fuel dependence and proposed improvements in fuel use. Its importance for the current study lies in demonstrating that emissions observed outside an industrial facility originate from decisions made within the production system concerning fuel selection, energy efficiency, and process configuration.

From a broader emissions-control perspective, Elehinafe et al. (2022) reviewed pollutants associated with cement production and the environmental problems resulting from these emissions. The study highlighted the range of atmospheric pollutants generated by cement manufacturing and discussed technical measures for their control. It concluded that effective mitigation requires integrated control of process emissions rather than reliance on isolated interventions. This provides support for treating gaseous-emission management as a core component of sustainable industrial operations.

In a study particularly close to the spatial orientation of the present research, Ajayi et al. (2022) assessed the spatial distribution of CO_2 pollution emitted by a cement industry in Sagamu, Nigeria. The study explicitly examined how cement-related CO_2 concentrations vary geographically around the industrial source. Its spatial orientation demonstrates the analytical value of moving beyond factory-level emission inventories toward geographically explicit assessment capable of identifying differences in environmental pressure across surrounding areas. This approach closely supports the methodological premise of the present Zliten study, although a broader integration with urban land use and developmental impacts remains necessary.

At the city and regional scale, Han et al. (2022) investigated the effects of industrial agglomeration on NO_2 pollution using spatial panel Durbin and threshold models. Their findings demonstrated that industrial development generates ecological effects that cannot be adequately explained through non-spatial analysis because pollution relationships extend across geographical boundaries. The study is particularly significant for sustainable industrial planning because it confirms that the environmental consequences of industrial concentration may depend on the level and structure of agglomeration, making spatial econometric reasoning important for environmental policy.

Similarly, Qin et al. (2022) examined the spatial relationship between industrial agglomeration and pollution discharge in the Yellow River Basin. The study identified significant spatial correlations and regional heterogeneity, indicating that the relationship between industrial concentration and environmental pressure varies geographically. These results challenge uniform environmental-management approaches and support the adoption of place-based industrial environmental policies, in which regulatory intensity and mitigation measures reflect the environmental characteristics of individual locations.

Jia et al. (2022) further investigated the impacts of industrial agglomeration on industrial pollutant emissions in the Lanzhou–Xining urban agglomeration using spatial analysis and spatial econometric techniques. The study showed that industrial concentration can simultaneously contribute to economic and social prosperity while intensifying environmental pressures and associated public-health risks. This dual outcome is especially relevant to Zliten because it illustrates the central management dilemma underlying the concept of a sustainable industrial city: industrial activity generates developmental benefits, but those benefits must be evaluated against the spatial externalities generated by pollution.

Using data from 271 cities, Kong et al. (2022) investigated whether manufacturing agglomeration aggravates regional environmental pollution. The study identified a nonlinear, inverted U-shaped relationship between manufacturing concentration and environmental pollution, indicating that industrial agglomeration can initially increase environmental pressure but that its effects may change as industrial systems develop and become more efficient. This finding is theoretically important because it suggests that industrial sustainability depends not merely on the quantity of industrial activity but on its technological maturity, structural characteristics, and environmental-management capacity.

At the global mitigation level, Shah et al. (2022) examined the potential of substituting conventional cement with secondary materials and estimated that such substitution could reduce annual global CO_2 emissions by as much as 1.3 gigatons under appropriate scenarios. The study demonstrates that the transition toward sustainable industrial production can be achieved partly through changes in material flows and circular-economy strategies rather than relying exclusively on end-of-pipe emission controls. This has important managerial implications for cement-producing cities because cleaner industrial performance requires intervention at the level of inputs, processes, products, and waste-resource circulation.

Finally, Watari et al. (2022) investigated how more efficient use of cement and concrete could reduce dependence on supply-side technologies in achieving net-zero emissions. Their findings showed that demand-side material efficiency can substantially complement technological decarbonization. Rather than viewing carbon capture or fuel substitution as the only pathways, the study emphasized efficient material use and systemic changes throughout the cement–concrete value chain. This expands the concept of sustainable industrial management beyond factory emissions toward resource efficiency, demand management, circularity, and value-chain optimization.

6.1 | Critical Synthesis and Research Gap

Collectively, the reviewed literature establishes a strong scientific relationship between industrial activity, particularly cement production, and gaseous emissions, particulate pollution, environmental degradation, carbon intensity, and health risks. Libyan studies have provided important evidence from El-Mergheb, El-Fataih, Benghazi, and the wider national cement sector, while Arab studies from Egypt, Iraq, Saudi Arabia, and Algeria have expanded the discussion toward dispersion modelling, fuel choice, environmental regulation, and industrial decarbonization. International studies have advanced further by incorporating spatial econometrics, industrial-agglomeration effects, life-cycle assessment, material efficiency, and cleaner-production strategies. However, these research streams remain relatively fragmented: emission studies frequently measure pollutants without examining their developmental geography, spatial studies often analyse pollution without connecting it to facility-level industrial management, and sustainability studies emphasize decarbonization without explicitly assessing the compatibility between industrial locations, residential expansion, land use, and urban development.

This limitation is particularly evident in the Libyan context. Although available studies demonstrate the existence and environmental significance of cement-related emissions, there remains limited empirical research integrating measured gaseous emissions, spatial distribution, distance from industrial sources, emission hotspots, surrounding residential and land-use patterns, and sustainable spatial-development implications within one framework. This gap corresponds directly to the present study's research problem, which seeks to move beyond documenting pollution toward understanding how emissions intersect with Zliten's urban and developmental structure.

6.2 | Scientific Contribution of the Present Study

The scientific contribution of the present research therefore lies in developing an integrated industrial–spatial sustainability perspective for Zliten City. Rather than considering gaseous emissions as isolated atmospheric measurements, the study links their concentrations and spatial distribution to industrial locations, distance, surrounding urban areas, land-use patterns, and developmental implications. In managerial terms, this transforms spatial analysis from a descriptive mapping exercise into a decision-support instrument for sustainable industrial management, capable of informing emission-control priorities, cleaner-production investments, environmental monitoring, industrial buffer zones, land-use compatibility, and future urban expansion. This contribution is consistent with the study's broader objective of shifting from *pollution measurement* toward *pollution-informed industrial and spatial decision-making*.

7 | Materials and Methods

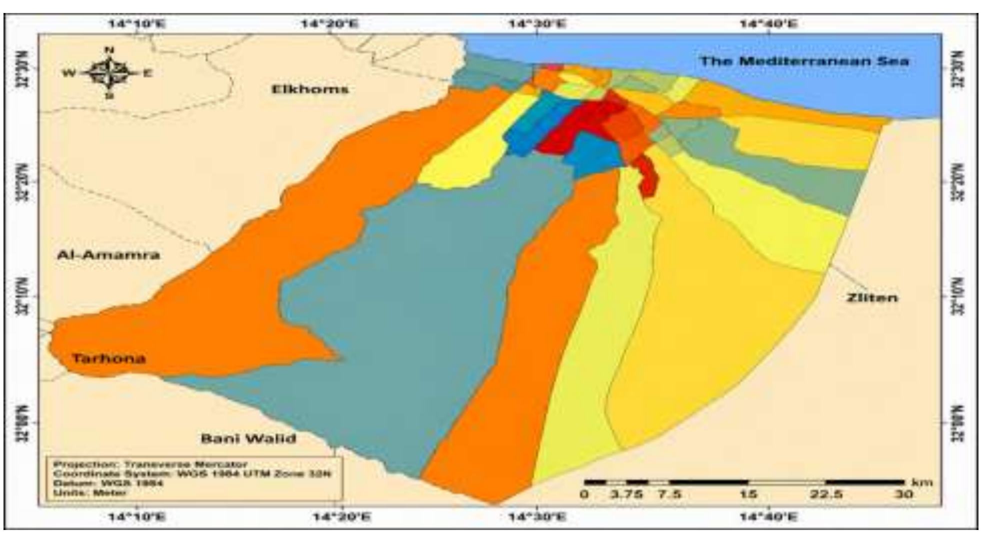
7.1 | Study Area Location

The study area is located in Zliten, along the Mediterranean coast in the central part of the Libyan coastline. The coastal zone extends for approximately 35 km and lies about 160 km east of Tripoli, the capital of Libya. Geographically, the area is situated between latitudes 32°31′37.09″ N and 32°05′18.19″ N, and longitudes 14°46′24.99″ E and 14°04′42.90″ E.

Zliten is characterized by the presence of several important industrial activities, particularly the cement and construction-material industries, with a number of factories operating within and around the area. The expansion of these industrial activities has been accompanied by increased fuel consumption to meet operational and production requirements, resulting in emissions of atmospheric pollutants. Such emissions may contribute to the deterioration of local air quality, particularly during peak production periods when industrial activity intensifies.

In addition, the study area has experienced rapid population and urban growth, which has contributed to increasing traffic density. Diesel-powered vehicles are particularly important in this context, as they are extensively used to transport cement and construction materials both within Zliten and to surrounding regions. Owing to its geographical location, Zliten also functions as an important commercial center and transportation link between central and western Libya. Consequently, the high volume of commercial traffic passing through the city may further increase emissions of air pollutants, as illustrated in Figure 1. Other environmental factors also contribute to pollution within the study area. These include fires occurring in agricultural areas, the local phenomenon known as "Al-Marduma", which contributes to the release of smoke and potentially harmful gases, as well as emissions associated with the presence of a municipal waste disposal site. Collectively, industrial activities, transportation, open burning, agricultural fires, and waste disposal represent interconnected sources of environmental pressure, posing potential environmental and public-health challenges that require effective monitoring and mitigation measures.

Map 1. Study Area Location (Zplten)



7.2 Research Design

This study employed a spatiotemporal descriptive-analytical approach to assess the spatial distribution and temporal trends of atmospheric pollutants across the Zliten area during the period 2019–2024. The methodological framework integrated satellite remote sensing with Geographic Information System (GIS)-based spatial analysis to identify pollution patterns, detect potential hotspots, examine temporal variations, and explore their possible relationships with industrial activities, transportation networks, population distribution, and surrounding land-use characteristics.

The methodological approach was designed to move beyond conventional pollution description toward a spatially explicit assessment capable of supporting industrial environmental management and sustainable spatial planning. Accordingly, the analysis was structured around three interconnected dimensions: temporal pollutant trends, spatial pollutant distribution, and the spatial relationship between pollution patterns and potential anthropogenic sources.

7.3 | Satellite Data Source

The study primarily relied on atmospheric observations obtained from the Sentinel-5 Precursor (Sentinel-5P) satellite of the European Union's Copernicus Earth Observation Programme. Sentinel-5P carries the Tropospheric Monitoring Instrument (TROPOMI), which provides systematic observations of atmospheric composition and is widely used for regional and global monitoring of air pollutants and trace gases.

Four atmospheric pollutants were investigated: sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3). These pollutants were selected because of their environmental significance and their potential associations with industrial combustion, energy consumption, transportation, fuel combustion, and other anthropogenic activities. Their inclusion also enables a multidimensional assessment of atmospheric pollution rather than relying on a single pollutant as an indicator of environmental pressure.

7.4 | Study Period and Data Acquisition

Satellite observations covering the period from 2019 to 2024 were collected for the geographical extent of the Zliten study area. The six-year period was selected to provide sufficient temporal coverage for identifying annual variability and longer-term tendencies in atmospheric pollutant levels.

Sentinel-5P/TROPOMI products for SO_2, CO, NO_2, and O_3 were obtained from available open-access satellite-data platforms. The geographical boundaries of the study area were defined before extracting the relevant satellite observations, thereby ensuring that subsequent processing and spatial analysis were restricted to Zliten and its surrounding areas included within the research boundary.

7.5 | Data Pre-processing and Quality Control

Before conducting the spatial and temporal analyses, the satellite data underwent a systematic pre-processing and quality-control procedure. Observations were geographically clipped to the study-area boundary and screened using the Quality Assurance (QA) information associated with the respective TROPOMI products to reduce the influence of low-quality retrievals, cloud contamination, unfavorable observation conditions, and potentially unreliable values.

After quality filtering, valid observations were organized according to pollutant, location, and observation period. Temporal aggregation was subsequently applied according to the analytical requirements of the study to generate comparable datasets for examining annual and temporal variations between 2019 and 2024.

Importantly, the analysis retained and documented the appropriate measurement characteristics and units of each TROPOMI product, because satellite products for NO_2, SO_2, CO, and O_3 do not necessarily represent identical atmospheric quantities. This distinction is essential for avoiding inappropriate direct comparisons between pollutants expressed using different retrieval products or units.

7.6 | Spatial Analysis of Atmospheric Pollutants

Geographic Information System (GIS) techniques were employed to analyze and visualize the spatial distribution of SO_2, CO, NO_2, and O_3 across the study area. Spatial maps were produced separately for each pollutant to examine geographical variations and identify locations characterized by persistently or comparatively elevated pollutant levels.

The spatial analysis focused particularly on detecting potential pollution hotspots, defined as areas exhibiting relatively elevated pollutant values or recurrent concentrations over the investigated period. The resulting pollution maps were subsequently compared with the geographical distribution of industrial facilities, major roads and traffic corridors, populated areas, and relevant land-use patterns.

This approach allowed the study to examine whether elevated pollutant levels exhibited spatial correspondence with major anthropogenic activities and to identify areas that may require priority environmental monitoring or management intervention.

7.7 | Temporal Trend Analysis

In addition to spatial analysis, temporal trends in SO_2, CO, NO_2, and O_3 were evaluated over the 2019–2024 period. Descriptive temporal indicators were used to examine changes in pollutant levels and determine whether individual pollutants exhibited increasing, decreasing, relatively stable, or fluctuating patterns during the study period.

Temporal variations were also interpreted alongside spatial patterns to determine whether pollution behavior was consistent across the study area or whether particular locations exhibited distinctive temporal trajectories. Integrating the spatial and temporal dimensions provides a more robust assessment than relying on observations from a single year or isolated monitoring period.

7.8| Identification of Potential Pollution Sources

Potential pollution sources were investigated through spatial overlay and proximity-based interpretation. Pollutant-distribution maps were compared with the locations of industrial activities, major transportation routes, populated areas, and surrounding land uses to examine potential spatial associations.

Areas where elevated pollutant levels repeatedly coincided with industrial zones or major traffic corridors were considered potential source-influence areas requiring further interpretation. Particular attention was given to industrial activities because of their relevance to the study's broader objective of evaluating the environmental sustainability of industrial development in Zliten.

However, spatial coincidence was not interpreted as definitive evidence of causation. Satellite-observed pollutant patterns may also be affected by meteorological conditions, wind speed and direction, atmospheric transport, boundary-layer characteristics, and pollution originating outside the immediate study area. Accordingly, the term "potential pollution source" was adopted rather than assigning elevated pollutant levels conclusively to a particular industrial facility or traffic source.

7.9 | Development of the Zliten Air-Quality Database

A structured spatial and temporal database was developed to organize atmospheric-pollution information for the Zliten area during 2019–2024. The database incorporated pollutant type, observation period, geographical location, satellite-observed values, and relevant spatial attributes.

The database was designed not only as a research dataset but also as a potential baseline for future environmental monitoring. It may therefore support periodic updating of air-quality information, comparison of future pollution trends with the 2019–2024 baseline, and evidence-based environmental and industrial decision-making.

From a sustainable industrial-management perspective, such a database can assist local authorities and industrial decision-makers in identifying priority monitoring areas, evaluating changes in environmental pressure, and developing geographically targeted pollution-control strategies.

Table 1. Information on the Satellite Used in the Study

Satellite	Sensor	Operating Agency	Launch Date	Orbit	Spatial Coverage
Sentinel-5 Precursor (Sentinel-5P)	TROPOMI (Tropospheric Monitoring Instrument)	European Space Agency	13 October 2023	Sun-synchronous orbit (SSO) at an altitude of 824 km	Daily global coverage

- (Tropospheric Monitoring Instrument.
- SO_2 (μmol/m²), vertical column 9-day mean.
- NO_2 (μmol/m²), vertical column 9-day mean.
- CO (μmol/m²), vertical column 9-day mean.

The data were extracted from Sentinel-5P, after defining the geographical boundaries of the study area and selecting the target atmospheric pollutants. The dataset was subsequently filtered temporally according to the study period and subjected to quality-control procedures to remove anomalous or unreliable observations potentially associated with cloud cover, unfavorable atmospheric conditions, or sensor retrieval errors. The satellite data were then spatially clipped to the boundaries of the study area.

Following the pre-processing stage, the data were temporally classified and monthly mean values were calculated for each target year to reduce short-term variability and noise and to improve the interpretation of temporal pollution patterns. After data processing, Geographic Information System (GIS) techniques were employed to conduct the spatial analysis. The processed satellite observations were used to generate spatial distribution and heat maps illustrating the relative levels of each atmospheric pollutant across the study area and to identify potential pollution hotspots.

The resulting dataset for the Zliten area was analyzed over the period from 1 January 2019 to 31 December 2024, focusing on the spatial and temporal patterns of the four target atmospheric pollutants**:** sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3)**.**

Map 2. Geographical Distribution of Waste Processing Plants And landfills in Zliten Municipality

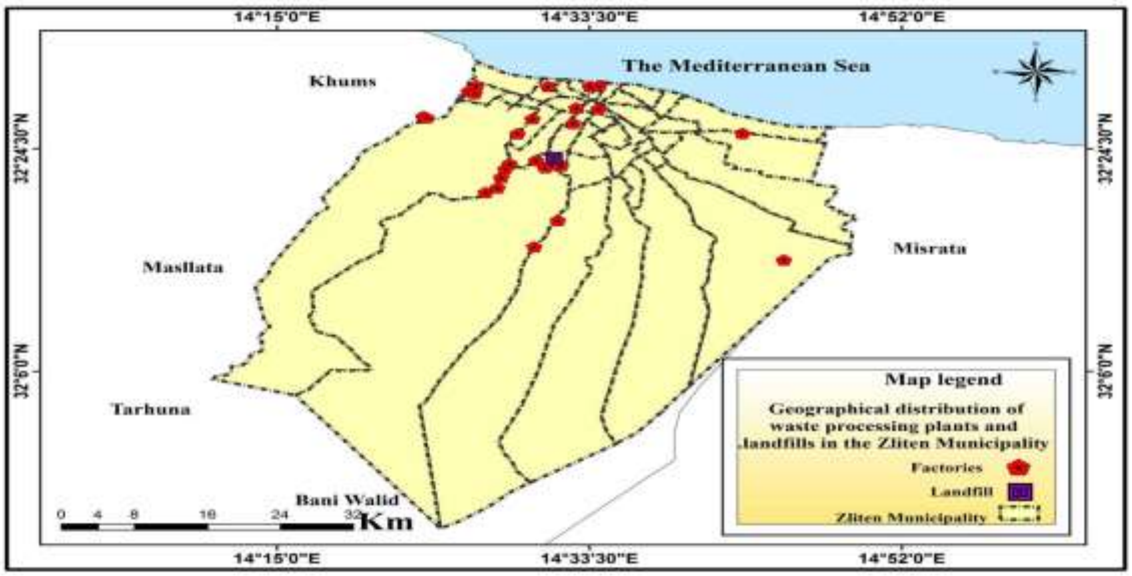


Table 2. Data used for measuring

Description	Upper Limit	Lower Limit	Measuring Unit	Pixel Size	Band Name	Pollutant Gas
Surface-Level Vertical Column Density of Sulfur Dioxide (SO_2), Calculated Using the DOAS Technique	0.2079* mol/m^2	-0.4051* mol/m^2	mol/m^2 to (µmol/m²),	1113.2 meters	SO2_column_number_density	Sulfur Dioxide SO_2
Vertically Integrated CO Column Density	5.71* mol/m^2	-34.43* mol/m^2	mol/m^2 to µmol/m²	1113.2 meters	CO_column_number_density	Carbon Monoxide (CO)

8 | Pollutant Gas Concentration Levels

8.1 | Sulfur Dioxide (SO_2) Emission

Sulfur dioxide (SO_2) is a chemical compound characterized as a colorless gas with a strong, pungent odor. It is classified as one of the major sulfur-containing gases and is considered among the most hazardous air pollutants affecting both human health and the environment. SO_2 is emitted from a variety of anthropogenic activities as well as natural sources.

Anthropogenic sources represent the largest contributors to SO_2 emissions. Significant quantities are released from industrial facilities, including fossil-fuel-based power plants, oil refineries, and smelting operations. Industrial activities, particularly cement manufacturing, are also considered major sources of SO_2 emissions due to the use of sulfur-containing raw materials and fuels. In addition, the transportation sector contributes to SO_2 emissions, particularly through diesel-powered vehicles, as diesel fuel may contain sulfur compounds. Heavy machinery used in construction and agricultural activities can further contribute to these emissions, thereby exacerbating local air pollution.

From a natural perspective, volcanic activity is considered a major source of sulfur dioxide (SO_2) emissions, as large quantities of the gas can be released during volcanic eruptions. However, natural emissions are generally lower than those originating from anthropogenic activities, accounting for less than one-third of global SO_2 emissions. Agricultural areas may also contribute to sulfur dioxide emissions, although their contribution is relatively limited.

Sulfur dioxide is highly soluble in water and forms sulfurous acid (H_2SO_3) when dissolved. In the atmosphere, sulfur-containing compounds can subsequently undergo oxidation processes that lead to the formation of sulfuric acid (H_2SO_4), which is a major contributor to acid rain. Acid deposition can have harmful effects on terrestrial and aquatic ecosystems and can accelerate the deterioration of buildings, infrastructure, and construction materials.

Sulfur dioxide can be detected by its characteristic odor at relatively low concentrations, with sensory effects becoming noticeable at concentrations of a few parts per million (ppm). At higher concentrations, its odor becomes increasingly sharp, pungent, and irritating.

The amount of sulfur dioxide emitted varies considerably depending on the type and sulfur content of the fuel used. Fossil fuels such as coal and petroleum may contain substantial quantities of sulfur and therefore represent important sources of SO_2 emissions during combustion. In contrast, natural gas, propane, and wood generally contain lower levels of sulfur and consequently tend to contribute less to sulfur dioxide emissions. Diesel fuel, in particular, can be an important contributor to sulfur-related air pollution, depending on its sulfur content, whereas gasoline generally contains lower sulfur levels but may still contribute to SO_2 emissions, particularly in areas characterized by high traffic density.

The risks associated with sulfur dioxide (SO_2) air pollution to humans, animals, and plants vary according to its concentration in the atmosphere. Sulfur dioxide pollution can cause substantial damage to vegetation, as it may be deposited in the form of sulfates within mesophyll tissues, thereby inhibiting the photosynthetic process. The gas can also react with atmospheric water vapor to form acidic sulfur-containing aerosols, which may cause severe damage to vegetation and to structures constructed from limestone and sandstone. In addition, sulfur dioxide pollution may contribute to the corrosion and deterioration of metals and rubber, as well as the weakening and degradation of various types of fibers. The globally permissible limit for sulfur dioxide air pollution has been reported as 0.03 ppm.

At the global level, sulfur dioxide is regarded as a hazardous air pollutant that requires sustained efforts to reduce its emissions. Emissions resulting from anthropogenic activities account for approximately one-third of the total atmospheric emissions of sulfur compounds, while natural sources make a comparatively limited contribution. SO_2 adversely affects air quality and contributes to the formation of acid rain, which may result in widespread environmental damage. Therefore, it is essential to analyze temporal and spatial trends in SO_2 concentrations, identify pollution hotspots, determine potential emission sources, and examine their relationships with industrial activities, traffic patterns, and population density within the study area.

In the present study, the concentrations of the major air pollutants were extracted and analyzed together with local meteorological conditions, including wind speed and direction, temperature, and relative humidity across the Zliten area.

A. Temporal Distribution of Sulfur Dioxide (SO_2) Concentrations

Table (3) shows that sulfur dioxide (SO_2) concentrations vary on a monthly basis, while exhibiting an overall fluctuating trend across the study years. Elevated SO_2 levels were observed during the winter months, with concentrations reaching a peak value of 410.16 µmol/m² in December 2020, representing the highest median concentration recorded during the study period. In contrast, the minimum concentration was 19.918 µmol/m² in 2021. A noticeable decline in the average SO_2 concentrations was also observed in 2019.

In 2024, SO_2 concentrations increased compared with 2023, which may indicate an increase in industrial activity or changes in environmental conditions influencing the accumulation and dispersion of the pollutant.

Overall, SO_2 concentrations during the 2019–2024 period did not follow a stable pattern; instead, they exhibited successive increases and decreases. This temporal variability suggests the possible influence of seasonal factors, changing emission sources, and variable environmental and meteorological conditions.

Higher recorded values indicate periods of elevated SO_2 pollution within the study area, which may have implications for local air quality and public health. These temporal fluctuations highlight the importance of examining SO_2 concentrations in relation to seasonal meteorological conditions and potential anthropogenic emission sources in the Zliten area.

Table 3. Monthly and Annual Sulfur Dioxide (SO_2) Concentrations (µmol/m²)

Month	2019	2020	2021	2022	2023	2024	2019-2024
Jan.	195.409	348.507	297.241	272.515	332.67	370.303	301.991
Feb.	83.855	209.029	174.654	244.094	200.721	283.205	201.193
Mar.	128.1	129.51	63.375	108.197	103.123	105.964	107.713
Apr.	134.442	138.718	62.058	62.075	66.409	147.924	100.884
May.	57.455	142.017	103.246	92.922	111.166	75.801	98.331
June.	90.069	100.47	204.802	241.482	91.294	118.028	142.062
July	66.478	123.754	145.984	143.792	66.903	115.744	110.757
Aug.	88.412	83.704	102.327	64.234	147.999	147.331	106.171
Sep.	65.532	38.19	19.918	60.8	95.567	55.196	56.096
Oct.	85.746	36.718	28.93	104.604	42.336	57.35	60.673
Nov.	178.052	147.916	124.792	137.758	278.13	161.83	175.097
Dec.	350.641	375.377	387.919	410.16	346.066	104.688	330.516
Average	**127.0159**	**156.1592**	**142.9372**	**161.8861**	**156.8653**	**145.2803**	**149.2903**
Min.	**350.641**	**375.377**	**387.919**	**410.16**	**346.066**	**370.303**	**330.516**
Max.	**57.455**	**36.718**	**19.918**	**60.8**	**42.336**	**55.196**	**56.096**

B. Carbon Monoxide (CO) Emission Concentration Levels for the Period 2019–2024

Air pollution is considered one of the most serious environmental and public health challenges facing contemporary societies, as it contributes to increased rates of respiratory diseases and premature mortality, in addition to its adverse impacts on climate and ecosystems. Among the most common air pollutants, carbon monoxide (CO) is particularly important as a toxic, colorless, and odorless gas produced primarily by the incomplete combustion of fuels in vehicles, generators, and industrial facilities.

The assessment of CO concentrations is of considerable importance because this pollutant can serve as an indicator of combustion efficiency, the effectiveness of implemented environmental policies, and the extent to which different sectors comply with regulatory air-emission standards. Monitoring temporal variations in CO concentrations can also provide valuable information for evaluating the effectiveness of governmental and municipal measures aimed at reducing air pollution, particularly in densely populated urban and industrial areas.

Within this context, the present study aims to analyze carbon monoxide (CO) emission concentrations during the period 2019–2024, based on available environmental data obtained from atmospheric monitoring stations or relevant local and international environmental reports. The analysis focuses on identifying temporal variations in CO concentrations, determining the major potential emission sources, evaluating the effectiveness of existing environmental policies and control measures, and interpreting the observed patterns in relation to the local environmental and demographic context.

The importance of this temporal monitoring is further emphasized by global efforts to reduce atmospheric emissions in accordance with the Paris Agreement on climate change and the Sustainable Development Goals (SDGs), particularly SDG 3: Good Health and Well-being and SDG 13: Climate Action. Accordingly, this study represents an important step toward understanding the current environmental conditions and providing evidence that can support the development of public policies aimed at achieving a cleaner, healthier, and more sustainable future.

Table 4. Analysis of Carbon Monoxide (CO) Emission Concentrations (2019–2024) and Comparison with World Health Organization (WHO) Guidelines

Month	2019	2020	2021	2022	2023	2024	2019-2024
Jan.	31715.93	32097.36	32668.82	31501.704	29573.361	32464.779	31607.567
Feb.	33432.88	33390.16	32708.16	32273.648	30852.491	32049.408	32423.979
Mar.	34126.84	33290.32	34357.03	33423.922	31724.44	33765.606	33404.891
Apr.	35154.66	36144.64	35351.1	32506.512	32891.7	34666.481	34517.665
May.	33232.87	34299.47	32039.44	30774.323	32176.191	33372.168	32666.383
June.	29269.5	30382.15	28837.05	28420.531	31064.247	30607.951	29736.317
July	28702.56	29079.36	30291.51	28964.147	31110.665	31071.65	29821.643
Aug.	29741.77	28121.71	34315.27	28110.962	32144.41	34380.461	31079.22
Sep.	27739.19	28923.77	31402.01	26320.528	31195.809	31797.152	29555.834
Oct.	**27522.85**	**30325.54**	**30246.28**	**25634.867**	**29993.638**	**29646.624**	**28850.522**
Nov.	**28041.24**	**30560.05**	**29406.01**	**26211.797**	**29634.539**	**30200.795**	**28991.975**
Dec.	**29808.76**	**31494.73**	**30569.58**	**27254.425**	**31304.777**	**32467.139**	**30501.774**
Average	30707.42	31509.11	31849.35	29283.11383	31138.85567	32207.51783	31096.48083
Min.	35154.66	36144.64	35351.1	33423.922	32891.7	34666.481	34517.665
Max.	27522.85	28121.71	28837.05	25634.867	29573.361	29646.624	28850.522

Table (4) presents a monthly analysis of carbon monoxide (CO) concentrations over the period from January 2019 to December 2024, including annual averages and a comparison of the observed values with the guidelines established by the World Health Organization (WHO). Concentrations are expressed in parts per billion (ppb) to illustrate detailed monthly variations, thereby providing the level of analytical precision required to assess pollution levels and their potential environmental and health implications.

The data indicate that monthly CO concentrations remained relatively high throughout the study period, with noticeable variations across certain months and years. Monthly values ranged from a minimum of 25,634.867 ppb in October 2022 to a maximum of 36,144.64 ppb in April 2021. These variations indicate the occurrence of seasonal peaks in CO concentrations, which may be associated with climatic conditions or intensified anthropogenic activities during particular periods of the year, such as increased fuel consumption or reduced atmospheric dispersion.

With regard to annual averages, 2022 recorded the lowest mean CO concentration at 29,283.11 ppb, whereas 2024 recorded the highest annual mean at 32,207.52 ppb, corresponding to an exceedance of more than 920% relative to the referenced WHO guideline. Despite the observed interannual variability, all annual mean concentrations substantially exceeded the referenced health-based threshold of 4 mg/m³ (approximately 3,500 ppb). These findings indicate the persistence of concerning environmental conditions and suggest that no substantial improvement in air quality occurred during the study period.

The data also reveal a recurring seasonal pattern during certain months. The early months of the year (January–April) tend to record the highest CO concentrations, whereas relatively lower levels are observed during the autumn months (September–November). This pattern may be associated with reduced industrial activity or changes in meteorological conditions, such as improved natural ventilation, atmospheric dispersion, and fluctuations in temperature.

From an environmental perspective, these findings suggest potential structural deficiencies in air-quality management, both in terms of environmental monitoring and the implementation of emission-reduction policies. They also highlight the need for more detailed investigations into the sources of CO emissions within the study area and the relative contributions of different sectors—including transportation, industrial activities, and household activities—to elevated pollution levels.

In conclusion, this monthly and annual analysis provides an essential scientific basis for guiding environmental policies toward more accurate and effective air-quality management and planning, particularly with regard to emission-control measures, environmental awareness programs, and the transition toward cleaner energy sources. The findings also emphasize the importance of strengthening coordination between research institutions and relevant executive authorities to achieve measurable improvements in air quality and protect public health.

Table 5. Annual Mean Carbon Monoxide (CO) Emissions (2019–2024) and Percentage E

Year	Annual Mean (ppb)	Conversion to mg/m³	Percentage Exceedance of the WHO 24-Hour Guideline
2019	30,707.42	35.31	883% Permissible Limit
2020	31,509.11	36.24	906%
2021	31,849.35	36.63	916%
2022	29,283.11	33.68	842%
2023	31,138.86	35.81	895%
2024	32,207.52	37.04	926%

Table (5) presents a detailed annual analysis of the mean carbon monoxide (CO) concentrations over the period from 2019 to 2024, with the values converted from ppb to mg/m³ and compared with the World Health Organization (WHO) 24-hour guideline value of 4 mg/m³.

The data clearly indicate that all annual mean concentrations recorded during the six-year study period exceeded the referenced WHO guideline by substantial margins. The exceedance rate was approximately 883% in 2019 and gradually increased to 926% in 2024, representing a concentration approximately 9.3 times higher than the recommended safe level. This persistent increase in annual concentrations represents a negative environmental indicator that warrants serious attention.

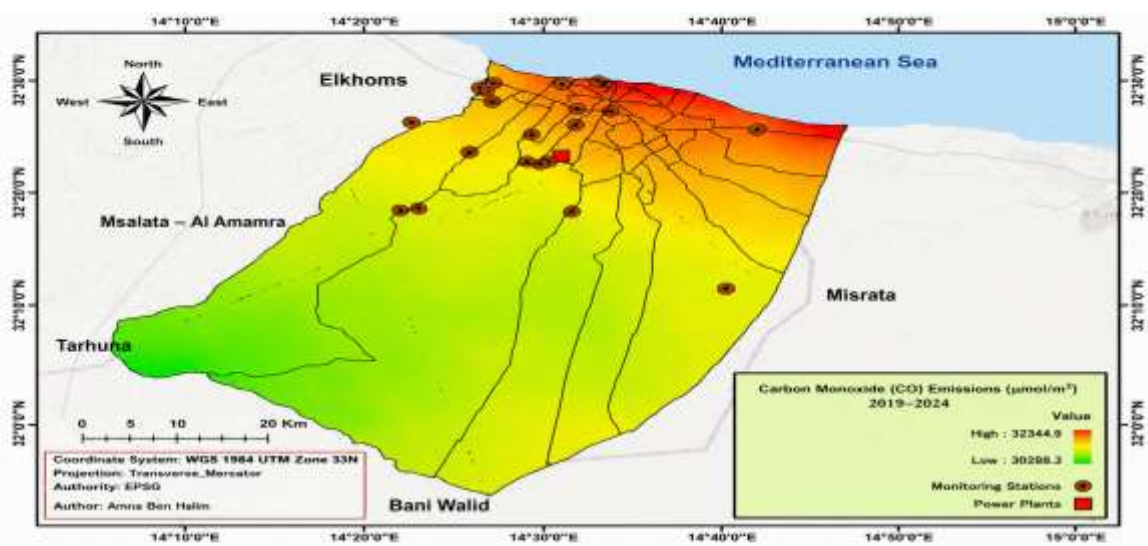
It is noteworthy that 2022 was the only year to show a relative decline in the annual mean concentration, recording 29,283.11 ppb, equivalent to 33.68 mg/m³, which represented the lowest level during the study period. Nevertheless, this concentration remained above the referenced safe limit. In contrast, 2024 recorded the highest annual mean concentration at 32,207.52 ppb, reinforcing the apparent upward trend in ambient CO pollution levels.

These findings indicate potential deficiencies in emission-control and air-quality management strategies, both in terms of environmental policies and the infrastructure associated with energy and transportation systems. They may also reflect limitations in the implementation of emission-reduction measures or the absence of sufficiently effective monitoring and response mechanisms.

Exceeding WHO guideline values by such substantial margins would indicate not only environmental deterioration but also potential concerns for public health, particularly among vulnerable groups such as children, older adults, and individuals with respiratory conditions. Accordingly, these indicators highlight the need for urgent national strategies to reduce CO emissions through the development of sustainable transportation, strengthened industrial emission controls, enhanced environmental awareness, and investment in continuous air-quality monitoring technologies.

Overall, the results presented in Table (5) highlight the importance of adopting an effective environmental governance framework capable of supporting environmental sustainability and establishing air-quality protection as both a public-health and sustainable-development priority

Map 3. Average Carbon Monoxide (CO) Concentration at the Zliten Waste Disposal Site, 2019–2024



9 | Conclusion

This study examined the spatial and temporal dynamics of gaseous air pollution in Zliten City within the broader conceptual framework of sustainable industrial development. Rather than treating atmospheric pollution as an isolated environmental outcome, the research approached it as an industrial-management and spatial-planning challenge arising from the interaction among industrial production, energy and fuel consumption, transportation activities, urban expansion, waste disposal, and surrounding land-use patterns. This orientation directly responds to the central research problem of the study: the limited integration, particularly in the Libyan context, between measured atmospheric pollution, its geographical distribution, industrial locations, surrounding urban areas, and sustainable development priorities.

Methodologically, the integration of Sentinel-5P/TROPOMI observations for the 2019–2024 period with GIS-based spatial analysis enabled the study to evaluate pollution through complementary temporal and geographical dimensions. Four major atmospheric pollutants—SO_2, CO, NO_2, and O_3—were incorporated into the analytical framework, while spatial overlays were used to interpret their possible relationships with industrial activities, transportation corridors, populated areas, and land-use characteristics. This approach is particularly important because environmental pressure is unlikely to be uniformly distributed across an industrializing city.

The findings provide a clear answer to the first research question concerning the spatial distribution of gaseous emissions: atmospheric pollution in Zliten should not be interpreted as spatially homogeneous. The analytical framework and pollution maps reveal differentiated geographical patterns, indicating that some areas experience comparatively greater atmospheric pressure than others. Such heterogeneity challenges the conventional practice of relying solely on city-wide averages and demonstrates the importance of geographically targeted environmental management. From a managerial perspective, therefore, the relevant question is no longer simply whether pollution exists, but where environmental pressure is concentrated, what activities potentially correspond spatially with those concentrations, and which locations should receive priority in monitoring and mitigation.

The temporal results reinforce this conclusion. SO_2 displayed substantial monthly and interannual fluctuations during 2019–2024 rather than a stable trajectory. Winter months were particularly important, with a peak value of 410.16 $\mu mol/m^2$ reported during the study period, while considerably lower values occurred during other periods. The increase observed in 2024 relative to 2023 further indicates that environmental performance cannot be assumed to improve automatically over time. Instead, pollutant concentrations appear to respond to a dynamic combination of seasonal conditions, changing anthropogenic activities, fuel consumption, industrial operations, and meteorological influences. This variability means that annual averages alone may conceal important episodes of environmental pressure and strengthens the case for continuous rather than intermittent monitoring.

The CO findings are even more critical from the perspective of long-term air-quality management. Monthly concentrations showed marked temporal variation, while the manuscript reports that the annual mean decreased to 29,283.11 ppb in 2022 before rising to 32,207.52 ppb in 2024. The study therefore provides no convincing evidence of a sustained downward trajectory in CO pollution. Instead, the temporary reduction in 2022 followed by renewed increases suggests that short-term improvements should not automatically be interpreted as structural progress in environmental performance. This distinction is crucial: a sustainable industrial city requires persistent reductions in environmental intensity, not isolated annual declines that may subsequently be reversed.

With respect to the second and third research questions—concerning emission hotspots and their relationships with industrial sources and surrounding spatial characteristics—the study supports the value of integrating pollution maps with the geography of factories, transportation corridors, waste-disposal activities, populated zones, and land uses. Zliten contains cement and construction-material industries, substantial diesel-based transportation associated with industrial logistics, commercial traffic, agricultural burning, open-burning practices, and municipal waste-disposal activities. These sources form an interconnected urban–industrial emissions system rather than a single-source pollution structure.

This observation also requires an important critical qualification. Spatial coincidence between elevated satellite-observed concentrations and industrial or transportation locations does not, by itself, establish causal attribution. The study appropriately recognizes that atmospheric concentrations can be influenced by wind speed and direction, atmospheric transport, boundary-layer conditions, meteorological variability, and pollutants transported from outside the immediate study area. Accordingly, the identified locations should be interpreted as potential source-influence areas rather than definitive proof that a particular facility caused the observed concentration. This methodological caution strengthens rather than weakens the study because it prevents spatial association from being overstated as causal evidence.

In relation to the fourth research question, the developmental implications extend beyond air-quality deterioration. Spatially concentrated pollution can potentially influence residential expansion, land-use compatibility, public-health exposure, infrastructure planning, investment attractiveness, environmental quality, and the future relationship between industrial facilities and surrounding communities. At the same time, industrial activities remain economically significant because they contribute to employment, productive capacity, construction-material supply, transportation activity, and urban development. The findings therefore do not justify framing Zliten's development challenge as a binary choice between industrialization and environmental protection. Instead, they point toward a more demanding objective: maintaining the developmental contribution of industry while progressively reducing the environmental intensity and spatial externalities associated with industrial production.

This distinction provides the answer to the fifth research question and constitutes the study's principal managerial contribution. Spatial analysis should become an operational component of industrial decision-making rather than merely a technique for producing pollution maps. The results can potentially inform decisions concerning cleaner production, industrial modernization, environmental monitoring locations, buffer zones, green infrastructure, transportation management, future industrial expansion, and land-use compatibility. This interpretation corresponds directly to the study's stated objective of transforming spatial analysis into a decision-support instrument for sustainable industrial management.

Critically, therefore, the transition of Zliten toward a sustainable industrial city cannot be achieved through emission control at factory stacks alone. The results point instead toward a systems-level transition involving industrial technology, fuel quality and energy efficiency, transportation and logistics, waste management, environmental monitoring, urban planning, institutional coordination, and environmental governance. The strategic objective should be to decouple industrial and economic development from increasing environmental pressure. In this sense, sustainability does not require eliminating Zliten's industrial function; it requires transforming the technological, managerial, and spatial conditions under which that industrial function operates.

The study nevertheless has limitations that should shape the interpretation of its conclusions. Satellite-derived atmospheric observations provide strong spatial and temporal coverage, but they should ideally be complemented by ground-based monitoring stations, facility-level emission inventories, detailed meteorological modelling, traffic-volume measurements, population-exposure data, and statistical source-apportionment techniques. Consequently, future research should progress from identifying spatial correspondence toward quantitatively estimating the contribution of individual industrial, transportation, waste, and other sources. Such integration would enable stronger causal inference and provide a more rigorous foundation for regulatory intervention.

Overall, the study demonstrates that the pathway toward a sustainable industrial Zliten lies neither in unrestricted industrial expansion nor in environmentally restrictive policies detached from economic realities. It lies in **spatially intelligent industrial management**: a model in which environmental data become part of production decisions, industrial investment, land-use planning, transportation policy, urban expansion, and environmental governance. The study therefore advances the discussion from *measuring pollution* to *managing development through pollution intelligence*, positioning air-quality information as a strategic resource for reconciling industrial competitiveness, environmental protection, public well-being, and long-term urban sustainability.

The study leads to the following principal conclusions:

1. Gaseous pollution in Zliten is both spatially and temporally differentiated, demonstrating that city-wide averages alone are insufficient for environmental decision-making.
2. The 2019–2024 period does not demonstrate a consistent improvement in atmospheric environmental performance. Instead, pollutant concentrations exhibit fluctuations, seasonal behavior, and renewed increases during particular years.
3. SO_2 exhibits pronounced seasonal variability, indicating that atmospheric conditions and changing emission activity should be incorporated into environmental monitoring and industrial-management decisions.
4. CO represents a particularly important environmental-management concern, as the decline observed in 2022 was followed by renewed increases, culminating in the highest annual mean reported for 2024.
5. Pollution patterns should be understood within a multi-source urban–industrial system involving industrial production, diesel transportation, commercial traffic, waste disposal, agricultural fires, and other combustion activities rather than being attributed automatically to one industrial facility.
6. Spatial proximity or coincidence between hotspots and anthropogenic activities provides important evidence for identifying priority investigation areas, but does not independently prove causation.

7. The environmental implications of industrial emissions are inseparable from developmental considerations because atmospheric pollution can influence public health, residential expansion, land-use compatibility, infrastructure planning, and the environmental attractiveness of future development areas.
8. The central sustainability challenge is therefore not whether Zliten should remain an industrial city, but how its industrial structure can generate greater economic and developmental value with progressively lower environmental intensity.
9. GIS and satellite remote sensing have demonstrated strategic value beyond environmental description; their integration can provide a spatial decision-support system for industrial management, monitoring, zoning, and urban planning.
10. The study consequently supports a transition from conventional industrial growth toward an integrated sustainable industrial-city model, in which cleaner production, spatial planning, environmental governance, and continuous air-quality monitoring operate as interconnected components.

11 | Recommendations

Based on these conclusions, the study recommends establishing an integrated Zliten Industrial Air-Quality Management System that combines Sentinel-5P/TROPOMI observations, GIS, permanent ground-monitoring stations, industrial emission inventories, meteorological data, traffic information, waste-disposal locations, population distribution, and land-use data within a continuously updated geospatial platform. The database already developed within the study provides an initial foundation for this direction and was specifically conceived as a baseline for future monitoring and geographically targeted pollution-control strategies.

At the industrial level, cement and other major facilities should progressively implement cleaner-production programmes based on energy efficiency, improved combustion control, low-emission fuels, modern filtration and gas-control technologies, preventive maintenance, resource efficiency, and periodic environmental auditing. Environmental performance indicators should become part of industrial performance evaluation alongside productivity, cost, quality, and profitability. Industrial licensing and future expansion should similarly incorporate spatial air-quality evidence rather than relying exclusively on conventional administrative zoning.

At the spatial-planning level, local authorities should use hotspot maps to establish or reassess environmental buffer zones between major emission sources and sensitive land uses, particularly residential areas, schools, healthcare facilities, and future urban-expansion zones. New industrial investments should undergo spatial environmental assessment before approval, while green belts and appropriate land-use transitions should be prioritized around areas experiencing recurrent atmospheric pressure.

Transportation should be treated as an integral component of industrial environmental management. Because diesel-powered vehicles play an important role in transporting cement and construction materials, policies should seek to optimize freight routes, prevent unnecessary heavy-vehicle movement through densely populated areas, strengthen vehicle-emission inspection, improve fuel quality, and gradually encourage lower-emission freight technologies.

Waste-management interventions are equally necessary. Open burning and uncontrolled disposal should be progressively eliminated, while waste collection, sorting, recycling, treatment, and controlled disposal infrastructure should be strengthened. Waste-related emission locations should be incorporated into the same GIS-based monitoring framework used for industrial and transportation sources.

Finally, environmental governance should shift from reactive pollution control toward preventive, data-driven management. This requires coordination among Zliten Municipality, environmental authorities, industrial companies, universities and research centers, public-health institutions, transportation authorities, and urban-planning agencies. Periodic public air-quality reports should be issued, environmental data should be transparently communicated, and measurable reduction targets should be established for priority pollutants. Future studies should combine satellite observations with ground measurements, meteorological modelling, industrial operating data, traffic counts, and health/exposure information to establish stronger causal relationships and evaluate whether implemented interventions produce measurable environmental improvements.

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