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Integrated Assessment of Air Pollution Sources, Public Health Impacts, and Data Gaps in Adana Province: Evidence-Based Policy Interventions

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Abstract

This study provides an integrated assessment of air pollution in Adana Province based on air-quality monitoring data. Adana is one of Türkiye's major industrial, urban, and transportation centers, where multiple emission sources may contribute to deteriorating air quality. The analysis relies primarily on validated air-quality monitoring datasets for 2020–2021, while more recent observations are used only to illustrate continuing seasonal behaviour and are not included in statistical calculations. Concentrations of major pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) were evaluated against guideline values from the World Health Organization, the European Union, and Türkiye's national regulations. Particulate matter limits ($PM_{2.5}$ and PM_{10}) were exceeded at several stations, and data capture rates below 60% at some locations indicate monitoring continuity limitations that may affect long-term policy evaluation. Regionally reported emission pressures include coal-based energy use, residential fuel combustion, agricultural residue burning, and traffic emissions. These pressures may be amplified by local geographic and meteorological conditions, including winter inversions and weak dispersion, which favour pollutant accumulation. Monitoring data show seasonal winter increases in sulfur dioxide and particulate matter consistent with heating-related emissions. In line with established epidemiological evidence, such pollutant patterns are widely associated with elevated respiratory risk; however, this study does not quantify direct local clinical relationships. Based on observed monitoring patterns, the study outlines mitigation priorities, including reducing coal dependence, expanding cleaner residential energy access, promoting sustainable transport, limiting agricultural burning, and strengthening monitoring data transparency. The results emphasize the importance of sustained monitoring for environmental management in rapidly urbanizing industrial regions.

Keywords
Air Pollution, Emission Sources, Human Health Impacts, Strategic Policy Interventions

Adana İli Hava Kirliliğinin Bütüncül Değerlendirmesi ve Stratejik Politika Önerileri

Özet

Bu çalışma, Türkiye'nin önde gelen sanayi, kentleşme ve ulaşım merkezlerinden biri olan Adana ilindeki hava kirliliğini, izleme verilerine dayalı bütünleşik bir değerlendirme yaklaşımıyla incelemektedir. Analizler esas olarak 2020–2021 dönemine ait doğrulanmış hava kalitesi izleme verilerine dayandırılmış; daha sonraki dönemlere ait gözlemler yalnızca mevsimsel davranışın sürekliliğini bağlamsal olarak göstermek amacıyla kullanılmış ve istatistiksel hesaplamalara dâhil edilmemiştir. Başlıca kirleticilerin ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO ve O_3) konsantrasyonları, Dünya Sağlık Örgütü, Avrupa Birliği ve Türkiye ulusal hava kalitesi mevzuatında tanımlanan kılavuz ve sınır değerler çerçevesinde değerlendirilmiştir. Bulgular, partikül madde sınır değerlerinin ($PM_{2.5}$ ve PM_{10}) bazı izleme istasyonlarında aşıldığını ortaya koymakta; bazı istasyonlarda veri yakalama oranlarının %60'ın altında kalması ise izleme sürekliliğine ilişkin yapısal sınırlılıklara işaret ederek uzun dönemli politika değerlendirmeleri açısından belirsizlik oluşturabilmektedir. Bölgesel çevresel değerlendirmelerde sıklıkla belirtilen emisyon baskıları arasında kömüre dayalı enerji kullanımı, konutlarda yakıt tüketimi, tarımsal artıkların yakılması ve trafik kaynaklı emisyonlar yer almaktadır. Bu baskılar, özellikle kış döneminde görülen inversiyon koşulları ve sınırlı atmosferik dağılım gibi yerel coğrafi ve meteorolojik özellikler nedeniyle daha da şiddetlenebilmekte ve kirletici birikimini kolaylaştırabilmektedir. İzleme verileri, ısınma kaynaklı emisyonlarla uyumlu biçimde, kış aylarında kükürt dioksit ve partikül madde düzeylerinde belirgin mevsimsel artışlara işaret etmektedir. Yerleşik epidemiyolojik literatürle uyumlu olarak, bu tür kirletici desenlerinin solunum sağlığı açısından artmış risk ile ilişkili olduğu bilinmekle birlikte, bu çalışma kapsamında yerel klinik veriler üzerinden doğrudan nedensel veya istatistiksel bir ilişki nicel olarak ortaya konulmamıştır. Elde edilen izleme bulgularına dayanarak; kömür bağımlılığının azaltılması, daha temiz konut enerjisine erişimin genişletilmesi, sürdürülebilir ulaşım politikalarının teşvik edilmesi, tarımsal artık yakma uygulamalarının sınırlandırılması ve izleme verilerinde şeffaflığın güçlendirilmesi başlıca politika öncelikleri olarak tartışılmaktadır. Sonuçlar, hızla kentleşen ve sanayileşen bölgelerde çevresel yönetişim açısından sürekli ve güvenilir hava kalitesi izlemesinin kritik önemini vurgulamaktadır.

Anahtar Sözcükler
Hava Kirliliği, Kirletici Kaynakları, İnsan Sağlığı, Stratejik Politika Önerileri

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1. Introduction

Air pollution remains a major environmental management challenge in Türkiye, particularly in rapidly urbanizing and industrialized provinces where emissions from industry, residential heating, traffic, and energy production interact with local meteorological conditions. In this context, Adana Province represents a critical case because of its industrial activity, dense transportation network, agricultural production, fossil-fuel use, and seasonal meteorological conditions that may limit pollutant dispersion.

In Türkiye, air pollution continues to present a major public health and environmental concern. National monitoring reports reveal that a substantial portion of the population is chronically exposed to pollutant concentrations exceeding international safety guidelines. In 2021, Türkiye ranked among the countries with the highest annual $PM_{2.5}$ levels globally, and major urban centers like Istanbul recorded some of the highest NO_2 exposures in Europe (IQAir, 2021; Health Effects Institute, 2022). Data from the Right to Clean Air Platform indicate that air pollution-related mortality in Türkiye significantly exceeds fatalities from road traffic accidents (Right to Clean Air Platform, 2020).

A comparative analysis of emissions from heating, industry, and traffic reveals that industrial activities are the predominant source of SO_2 emissions. The public health projections associated with coal-fired power plants in Adana—namely Sugözü İsken and Tufanbeyli—underscore severe long-term consequences, including premature mortality, bronchitis, preterm births, and significant losses in workforce productivity (Table 1). Furthermore, PM_{10} measurements from 2019 indicate a persistent exceedance of World Health Organization (WHO) annual limits, reflecting the chronic nature of pollution in the region (Table 1). An evaluation of fuel consumption patterns reveals that the use of solid fuels remains widespread, particularly in both industrial and residential sectors (Table 1).

Table 1: Estimated cumulative health impacts and economic costs associated with coal-fired power plants in Türkiye and Adana (HEAL, 2022a; 2022b).

The cumulative health impact and cost of coal pollution caused by 30 plants in Turkey between 1965 and 2020				
		Terminate Coal Consumption Health Benefits(Türkiye)*[1]	**Adana Sugözü İsken Thermal Power Plant 2003*[2]**	**Adana Tufanbeyli Thermal Power Plant 2016*[2]**
Premature deaths	**196,091**	**102,601**	**3,839**	**108**
Preterm births	117,661	30,975	2,132	45
Bronchitis cases in children	1,247,334	419,835	26,473	556
Bronchitis cases in adults	118,542	67,108	2,934	76
Hospital admissions	221,026	114,683	5,033	144
Symptom days in children with chronic asthma and bronchitis	11,163,625	3,772,502	234,735	4,991
Lost working days	62 million	27,606,746	1,180,047	26,999
Restricted activity days	452 million	231,333,351	9,887,440	284,541
Health cost, upper estimate, billion Euros	320 billion Euro	194 billion Euro	7,31 billion Euro	0.24 billion Euro
Health cost, upper estimate, billion Turkish Liras	4.8 trillion Turkish Liras	3.1 trillion Turkish Liras	109.65 billion Turkish Liras	3.59 billion Turkish Liras

**1 Health effects and costs could be avoided if Turkey drops coal by 2030.*
**2 The year of operation*

The national estimates represent the cumulative health impacts and economic costs attributed to coal-fired power plants in Türkiye for the period 1965–2020. The Adana-specific columns present estimated impacts associated with the Sugözü İsken and Tufanbeyli coal-fired power plants from their respective commissioning years to 2020. Monetary values are reported in Turkish Liras and Euros. Data were adapted from HEAL (2022a, 2022b).

As shown in Table 1, the national-level estimates refer to the cumulative health burden associated with coal-fired power plants in Türkiye between 1965 and 2020. In contrast, the Adana-specific estimates represent the health impacts attributed to the Sugözü İsken and Tufanbeyli coal-fired power plants from their commissioning years to 2020. This distinction was clarified in the revised table title and explanatory note to improve readability and prevent misinterpretation.

The Cumulative Health Effects of Chronic Coal Pollution Special Report underscores the substantial human and economic burden imposed by coal-fired thermal power plants across Türkiye. According to the report, coal-based electricity generation in 16 Turkish cities resulted in approximately 200,000 premature deaths between 1965 and 2020, with associated healthcare expenditures reaching NT$4.8 trillion (HEAL, 2022a) (Table 1).

In Adana, following the commissioning of the Sugözü Thermal Power Plant in 2003 and the Tufanbeyli Thermal Power Plant in 2016, an estimated 3,947 premature deaths had occurred by 2020. The cumulative health-related economic burden of these two plants was calculated at NT$113.24 billion (EUR 7.55 billion) (Table 1). More recent projections suggest that decommissioning the coal-fired plants in Adana (Sugözü, Tufanbeyli, and Hunutlu) and the nearby Atlas plant in Hatay could prevent 86% of the estimated 100 future premature deaths and reduce healthcare costs by 82%, from EUR 34 billion to EUR 6 billion. Moreover, the HEAL estimates that if Türkiye phases out coal entirely by 2030, up to 102,601 premature deaths could be prevented—a figure more than twentyfold the annual number of traffic-related fatalities in the country.

In 2020, Türkiye’s total health expenditure amounted to NT$250 billion (EUR 15.5 billion) (Turkish Statistical Institute [TÜİK], 2021). Estimates indicate that a nationwide coal phase-out could reduce air pollution-related healthcare costs by as much as NT$3.1 trillion (EUR 194 billion)—equivalent to nearly 12.5 years of the country’s total health budget (Table 1).

Regarding ambient air quality, 97.7% of Türkiye’s 175 air quality monitoring stations reported annual average PM_{10} concentrations exceeding the WHO’s guideline limits in 2020. National thresholds were surpassed in 45 cities, with only Bitlis and Hakkari remaining below WHO limits. The WHO's Health and Climate Change: Turkey Country Profile, released at COP27, further revealed that in Türkiye’s ten most populous cities—including Adana—the annual $PM_{2.5}$ concentration exceeded the recommended limit of 5 μg/m³. In Adana specifically, $PM_{2.5}$ concentrations reached approximately 30 μg/m³ (Figure 1). On average, air pollution causes 37,000 premature deaths per year in Türkiye, translating to an estimated 6% loss in the country’s potential GDP growth (World Health Organization [WHO], 2022).

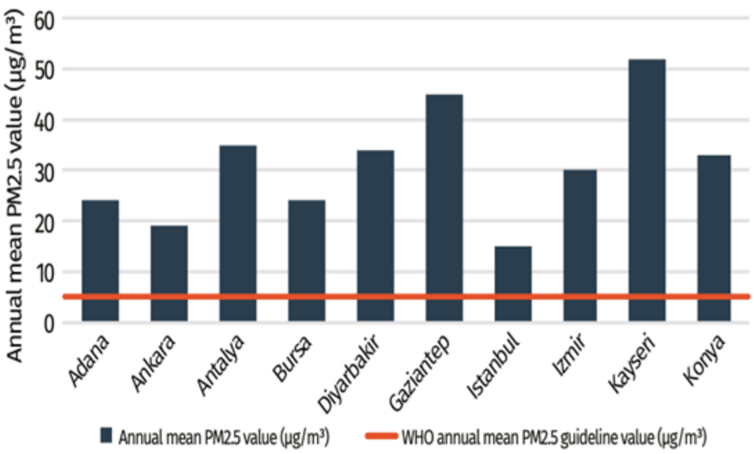

Figure 1: Compared with an average annual rate of PM2.5 for the ten most populous cities in Turkey to 5 µg/m3 PM2.5 for WHO guidance (Vohra et al., 2021; World Health Organization [WHO] and United Nations [UN] 2022).

According to the Turkish Air Pollution Perception Report, 87.4% of parents express concern that air pollution may adversely affect their children's health. One in four individuals reported personally knowing someone whose illness was directly attributed to air pollution. Respondents identified the primary sources of pollution as industry, energy production, mining, construction, and transportation. Between 2012 and 2022, 60.4% of the population observed a marked decline in air quality. Furthermore, 58.6% supported the closure of coal-fired power plants, and 73.8% acknowledged the potential lethality of air pollution. Notably, 86% of participants reported actively monitoring the air quality in their place of residence. However, a significant 97.3% indicated that “access to air quality data is difficult,” underscoring a major informational gap that this study also seeks to address (Right to Clean Air Platform & Yaşama Dair Vakıf [YADA], 2022).

Based on this background, the present study aims to evaluate air pollution in Adana Province using monitoring-based air-quality data. Specifically, the study examines pollutant concentrations, exceedance status relative to national and international standards, data completeness indicators, and major source-related pressures. Although the study is supported by a focused literature review, its main contribution lies in the evaluation of monitoring-based air-quality data and policy-relevant implications for Adana Province. Therefore, the manuscript is structured as a data-based research article rather than a conventional review paper.

1.1. Contextual Background and Research Gap

The accelerated pace of urbanization in Türkiye has made air pollution a pressing concern, not only from an environmental standpoint but also in terms of public health. In major metropolitan areas, the leading contributors to deteriorating air quality include traffic congestion, residential heating—particularly the use of solid fuels—industrial activities, energy production, and meteorological conditions. Urban expansion under these pressures has led to notable declines in air quality, especially in city centers. Air quality monitoring initiatives by the Ministry of Environment, Urbanization and Climate Change have primarily focused on major pollutants such as PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3. Numerous studies report frequent exceedances of regulatory thresholds for PM_{10} and NO_2, exhibiting clear seasonal and spatial variability (Aykaç & Yasin ,2021; Koşan et al., 2018). Data from cities like İstanbul, İzmir, and Konya show that pollutant levels peak during winter months, influenced by both local emissions and meteorological factors (Tayanç et al., 2022; Yücebaş & Şahin, 2024).

Longitudinal studies, such as those conducted in Erzurum, demonstrate that PM_{10} concentrations increase markedly during winter due to residential fossil fuel use (Koşan et al., 2018). Similarly, research in Konya identified heating and industrial processes as primary contributors to PM_{10} pollution (Tayanç et al., 2022).

A spatial assessment involving eight Turkish cities confirmed elevated PM_{10} and NO_2 concentrations during winter, strongly correlated with residential heating and vehicular emissions (Buğdaycı et al., 2023). These findings align with World Bank data indicating widespread exceedance of air quality limits across Türkiye, particularly in urban environments (World Bank, 2019). The health impacts of air pollution are extensive, encompassing respiratory diseases, cardiovascular conditions, asthma, and reduced pulmonary function. These effects are especially severe among vulnerable groups, including the elderly, children, and individuals with chronic illnesses (TÜBİTAK Marmara Research Center [TÜBİTAK MAM], 2020; Söğütlü et al., 2024). Epidemiological studies in Türkiye reveal a direct association between elevated $PM_{2.5}$ and NO_2 levels and increases in emergency hospital admissions. During the COVID-19 pandemic, fluctuations in air quality were also found to significantly influence infection rates (Ulutaş et al., 2023; Aladağ, 2024).

A 2019 study estimated that air pollution accounted for approximately 8% of annual deaths in Türkiye (Health Effects Institute, 2020), underscoring its severe public health burden. Particularly high rates of respiratory illness have been documented in communities near coal-fired power plants such as Afşin-Elbistan and Kemerköy (Greenpeace, 2020). Beyond human health, air pollution poses serious risks to ecosystems, water bodies, and built environments. Ground-level ozone in agricultural regions can reduce crop yields, while the accumulation of pollutants on buildings contributes to both aesthetic degradation and structural deterioration. In response, Türkiye has introduced Clean Air Action Plans and various urban-scale interventions. However, numerous challenges impede their effectiveness, including data gaps, insufficient monitoring capacity, and fragmented institutional coordination. The lack of emphasis on $PM_{2.5}$ in regulatory frameworks and limited city-level monitoring remain major barriers to fully evaluating health impacts (Temiz Hava Hakkı Platformu, 2023).

International research further contextualizes the link between urbanization and air pollution in Türkiye. For instance, a study by George Washington University found that over 90% of the global urban population is exposed to pollution levels exceeding WHO guidelines, contributing to roughly two million childhood asthma cases annually. Türkiye's urbanization trajectory reflects these global patterns.

Effective air quality management increasingly requires integrated approaches that combine technical interventions with social policy tools. Strategies such as improving access to clean energy for low-income households, promoting public transportation, and expanding urban green infrastructure are essential for comprehensive pollution control (United Nations Environment Programme [UNEP], 2020). Moreover, enhancing public awareness and encouraging citizen engagement are vital for improving environmental governance.

In light of the escalating challenges posed by urban air pollution, Türkiye urgently needs region-specific, multi-stakeholder, integrated, and sustainable policy solutions. Key priorities include strengthening monitoring infrastructure, ensuring transparent data dissemination, and enhancing the institutional capacity of local governments to enforce air quality standards.

Despite the growing number of studies on urban air pollution in Türkiye, province-specific assessments that jointly examine pollutant exceedances, monitoring-data completeness, seasonal patterns, and policy relevance remain limited. In particular, Adana requires closer examination because of its combined industrial, transport, residential heating, and agricultural emission pressures. This study addresses this gap by integrating monitoring data evaluation with a critical discussion of source-related and policy-relevant implications.

1.2. Potential Public Health Impacts of Environmental Air Pollution

Air pollution remains one of the most critical environmental and public health challenges of the modern era. According to the WHO, exposure to major air pollutants—including fine particulate matter $PM_{2.5}$ and PM_{10}, O_3, NO_2, SO_2, and CO—is strongly associated with increased incidence of respiratory and cardiovascular diseases, as well as premature mortality (WHO, 2018; 2021). Ambient air pollution is estimated to cause approximately 6.7 million premature deaths worldwide each year.

In Türkiye, particularly in industrialized urban centers such as Adana, emissions from transportation, residential heating, and industrial activities significantly amplify these health risks. The widespread presence of harmful pollutants in such regions highlights the urgent need to incorporate health-focused assessments into air quality monitoring systems and policy development processes (Pope & Dockery, 2006). Particulate matter, especially $PM_{2.5}$ and PM_{10}, poses a substantial threat to human health due to its ability to penetrate deep into the respiratory system and enter the bloodstream. Seminal studies, such as the Harvard Six Cities Study, have established strong links between long-term PM exposure and increased mortality and morbidity from chronic respiratory and cardiovascular conditions (Dockery et al., 1993; Pope & Dockery, 2006). $PM_{2.5}$ is particularly detrimental to vulnerable populations—especially children and the elderly—exacerbating illnesses such as asthma and bronchitis. Similarly, PM_{10} has been linked to inflammation of the respiratory tract and chronic pulmonary diseases (WHO, 2021; Brook et al., 2010).

NO_2, primarily emitted by motor vehicles, has been shown to aggravate asthma, impair lung function, and increase vulnerability to respiratory infections. Long-term exposure has also been associated with the development of chronic respiratory and cardiovascular diseases, particularly among older adults and individuals with underlying health conditions (Lee et al., 2014; WHO, 2021).

Ground-level O_3, a major component of smog, acts as a potent respiratory irritant. It has been linked to decreased lung function, airway inflammation, and increased hospital admissions related to asthma. While short-term exposure may cause coughing, throat irritation, and chest discomfort, prolonged exposure contributes to lasting respiratory damage (American Lung Association, 2023; WHO, 2021). SO_2, predominantly released from the combustion of fossil fuels, exacerbates respiratory symptoms and compromises lung function. Asthmatic individuals are particularly sensitive to SO_2, with even short-term exposure capable of triggering severe respiratory distress (U.S. Environmental Protection Agency [EPA], 2017; WHO, 2021).

CO poses a distinct hazard due to its interference with the blood's oxygen-carrying capacity. By binding to hemoglobin, CO can induce hypoxia, with low-level exposure causing symptoms such as headaches and dizziness, and high concentrations leading to severe neurological and cardiovascular complications, including death (Agency for Toxic Substances and Disease Registry [ATSDR], 2012; EPA, 2016). In Adana, intensive industrial activity, extensive agricultural practices, and high traffic volumes contribute to persistently elevated levels of air pollution. Epidemiological research has reported increased rates of respiratory illness during periods of high pollutant concentrations, particularly among sensitive groups such as children and the elderly. Despite these risks, public awareness remains limited. A regional study revealed that many residents lack adequate knowledge about the health consequences of air pollution, underscoring the need for targeted educational initiatives and community-based engagement strategies. Addressing the adverse health impacts of air pollution in Adana necessitates an integrated and coordinated policy response. Key strategies include the enforcement of stricter emission controls for industrial facilities, investment in sustainable public transportation infrastructure, the expansion of urban green spaces, and the implementation of comprehensive public health education campaigns. These measures have the potential to substantially improve air quality and reduce the prevalence of pollution-related diseases.

1.3.Strategic Policy Recommendations for Air Quality Management in Adana Province

The rapid expansion of urbanization, industrial activity, and motor vehicle usage has intensified air pollution across Türkiye. In industrial centers such as Adana, this issue has evolved into a significant public health concern. As such, there is an urgent need to develop integrated, sustainable, and scientifically grounded strategies for air quality management (Environment and Climate Health Initiative Platform, 2022).

Despite ongoing national monitoring efforts, the scope and reliability of air quality data remain inadequate—particularly regarding $PM_{2.5}$ concentrations, which are poorly monitored in many provinces. This data deficiency hinders accurate risk assessment and limits the formulation of evidence-based environmental and public health policies (TÜBİTAK MAM, 2022; WHO, 2021). In Adana, several monitoring stations report data capture rates below 60%, severely constraining the ability to evaluate pollution trends over time (HEAL, 2022a).

Coal-fired power plants such as Sugözü and Tufanbeyli are among the leading contributors to air pollution in Adana, with associated health-related costs estimated in the billions of Turkish lira (HEAL, 2022b). Given the global momentum toward coal phase-out—particularly among OECD countries—Türkiye's delay in establishing a clear coal exit strategy, especially in high-risk regions like Adana, has drawn increasing criticism (Global Energy Monitor, 2022).

A resilient air quality management system requires a reliable and comprehensive monitoring infrastructure. Weaknesses such as the low data acquisition rate at the Adana Seyhan station compromise policy effectiveness (Ministry of Environment and Urbanization [MoEU], 2020). Addressing these gaps necessitates the expansion of Türkiye's $PM_{2.5}$ monitoring network, calibration of equipment to meet national standards, and the implementation of open-data policies to ensure public access to environmental information (WHO & UN, 2022).

In addition to industrial emissions, seasonal agricultural practices—particularly stubble burning—contribute significantly to PM_{10} spikes in Adana. Tackling this issue requires stronger regulatory enforcement, the promotion of sustainable agricultural practices, and financial incentives for adopting non-combustion alternatives (MoEUCC, 2022a).

Adana's high traffic volume, with over 741,000 registered vehicles, represents another major source of air pollution (TurkStat, 2022a). Deficiencies in public transportation—such as limited light rail capacity and the central location of the city's main bus terminal—further exacerbate emissions. Policy responses should focus on expanding mass transit systems, developing pedestrian and bicycle infrastructure, promoting the use of electric vehicles, and establishing a comprehensive emissions inventory for the transportation sector (Perez et al., 2015).

During winter, SO_2 levels surge due to widespread use of low-quality solid fuels for domestic heating. Mitigation strategies should include the expansion of natural gas networks, a gradual transition away from coal, and targeted subsidies for low-income households to facilitate access to cleaner heating options. Industrial emissions remain a persistent issue, as many facilities continue to rely on high-sulfur fuels and lag in adopting pollution control technologies (MoEU, 2020). Reducing these emissions requires strengthening environmental inspections, mandating flue gas filtration systems, and introducing market-based instruments such as emissions trading schemes (Çapraz, 2021).

Urban planning shortcomings—including unregulated development and a lack of green space—further aggravate air pollution. High-density construction restricts air circulation, leading to pollutant accumulation. Environmentally conscious urban planning should prioritize green corridors, increase urban vegetation, and integrate air quality considerations into spatial development processes. Although public concern about air pollution is relatively high, access to real-time air quality data remains limited. A 2022 survey found that 97.3% of respondents reported difficulties accessing such information (THHP & YADA, 2022). Bridging this gap requires the development of open-access digital platforms, public education campaigns, and greater involvement of civil society in environmental governance. Furthermore, aligning with the European Green Deal and Türkiye's 2053 net-zero target will require coordinated planning across the energy, transportation, and environmental sectors (Intergovernmental Panel on Climate Change [IPCC], 2022).

The case of Adana exemplifies the need for participatory, multi-stakeholder approaches to air quality management. Long-term success will depend on integrating scientific evidence, community engagement, and environmental justice into a coherent and adaptive policy framework.

2. Method

This study evaluates the current state of air pollution in Adana and proposes evidence-based recommendations to mitigate adverse impacts on human and environmental health. As an initial step, a comprehensive literature review was conducted to contextualize the region's air quality challenges and to synthesize existing knowledge regarding the health and ecological effects of air pollution in the area. The empirical focus of the study was air quality monitoring data from Adana for the years 2020 and 2021, with the objective of identifying major pollutants and assessing their potential health risks. To maintain temporal consistency, tables and figures used for quantitative interpretation were restricted to the 2020–2021 monitoring period. Later contextual data were either removed from the main analysis or clearly identified as background information.

To determine the extent of pollution and to identify exceedances of regulatory thresholds, the study analyzed concentrations of seven key air pollutants known to be associated with severe health outcomes, including cancer, respiratory infections, asthma, allergic reactions, psychological stress, and depression. These pollutants included fine $PM_{2.5}$, PM_{10}, SO_2, NO_2, NO_x, CO, and O_3. All data were obtained from the National Air Quality Monitoring Network managed by the Ministry of Environment, Urbanization and Climate Change of the Republic of Türkiye.

Raw data from local air quality monitoring stations were processed using Microsoft Excel. Incomplete, inconsistent, or erroneous entries were systematically identified and excluded from the analysis. For each pollutant, annual average concentrations were calculated and compared with the air quality standards established by the WHO, EU, and Türkiye's national regulatory framework.

Because the definitive causes of station-level data gaps observed in the national monitoring network (e.g., missing days and/or low data-capture rates)—such as instrument malfunction, calibration and maintenance activities, power or communication outages, temporary deactivation of measurement channels, or measurement interruptions driven by meteorological conditions—cannot be verified through publicly accessible station event logs in the data portal, the present study could not attribute these gaps to station-specific causes. Accordingly, data integrity was monitored quantitatively using performance indicators including the annual percentage of valid data and the number of missing days, and the potential influence of low data-capture rates on the study findings is discussed in the "Limitations" section.

The analysis also accounted for data completeness, including the number of non-recorded days, the measurement frequency at each station, and the percentage of valid data collected annually. Findings were presented using tables and graphical visualizations to facilitate interpretation and highlight temporal and spatial trends. To improve clarity and comparability, the revised tables were organized by pollutant, source category, year, and regulatory benchmark, while the figures were revised to include clearer captions, parameter labels, units, data periods, and source information. This methodological approach enabled a robust and comprehensive assessment of both the state of air quality in Adana and the reliability of the monitoring infrastructure.

This study draws on measurement data from the air quality monitoring stations in Adana Province, including pollutant concentrations, exceedance status relative to regulatory limit values, and quantitative indicators of data completeness. The monitoring network comprises eight stations affiliated with the Mediterranean Clean Air Center: Doğankent, Meteoroloji, Valilik, Çatalan, Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova. As of 2020, four stations (Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova) were reported to produce data on a regular basis, and $PM_{2.5}$ measurements were not available at the Doğankent and Meteoroloji stations. Data completeness was therefore monitored and reported quantitatively by station and pollutant. To ensure analytical robustness and prevent statistical bias from incomplete series, annual means and trend estimates were calculated only for station–pollutant combinations with an annual valid-data capture rate of at least 60%. Series below this threshold were retained solely for descriptive reporting and were excluded from inferential interpretation. Because the public monitoring data portal does not provide station-level maintenance logs, calibration records, sensor malfunction reports, or transmission interruption histories, the precise causes of missing observations could not be independently verified for individual stations. This limitation was therefore considered during data completeness evaluation and interpretation.

3. Results

Air quality data were scientifically evaluated in accordance with the standards established by the WHO, the EU, and Türkiye's national regulatory framework. The assessment also included performance metrics for air quality monitoring stations, specifically focusing on annual data acquisition rates and measurement completeness.

Overall, pollutant concentrations in the eastern regions of Türkiye have consistently fallen within the "moderate" to "unhealthy" range over extended time periods. In particular, annual average concentrations of particulate matter (PM_{10}) have exceeded regulatory limits in numerous provinces.

Air quality monitoring data from various stations across Adana indicate significantly degraded air quality in several parts of the city. In particular, $PM_{2.5}$ and PM_{10} concentrations recorded in the Adana-Seyhan, Adana-Yakapınar, and Adana-Çukurova districts substantially exceed the WHO's recommended annual guideline values. Of additional concern are the pronounced increases in SO_2 levels during winter months, primarily due to residential heating. Elevated concentrations of NO_x and PM_{10} are also frequently observed in industrial zones. The principal sources of air pollution in Adana include emissions from thermal power plants, the combustion of low-quality coal, agricultural stubble burning, and vehicular traffic. Compounding this problem is the fact that many air quality monitoring stations in the region report annual data acquisition rates below 60%, thereby limiting the reliability and comprehensiveness of the dataset.

Adana's climatic and topographical conditions—such as frequent temperature inversions and low wind speeds—further exacerbate pollution levels by inhibiting the dispersion of airborne contaminants. These factors intensify the health risks associated with long-term pollutant exposure.

The city's air quality is influenced by a complex interplay of anthropogenic and environmental factors, including the use of solid fuels in public facilities (e.g., low-grade coal and No. 10 fuel oil), fossil fuel combustion, industrial gas emissions, unfiltered or poorly regulated chimney discharges, emissions from thermal power plants, transboundary dust transport from desert regions, and rapid population growth.

According to 2021 data from the TÜİK, Adana—with a population exceeding 2.2 million—accounts for approximately 3% of Türkiye's total population, ranking as the country's seventh most populous province (TÜİK, 2022b). Between 1970 and 1990, Adana underwent rapid industrialization marked by the establishment of large-scale manufacturing facilities. The province's diversified economic base—including agriculture, industry, seaports, highways, railways, and pipelines—has positioned it as a strategic hub for domestic and international trade. However, this logistical advantage has also contributed to increased levels of ambient air pollution.

Nationwide assessments of air quality monitoring data rank Adana first in Türkiye for SO_2 and NO_x-related pollution. This ranking is based on data from 213 monitoring stations in 81 provinces for SO_2 (hourly and daily measurements) and 173 stations in 49 provinces for annual NO_x data. PM_{10} concentrations in Adana also remain consistently at or near the upper regulatory limits.

The province is home to eight air quality monitoring stations affiliated with the Mediterranean Clean Air Center, located in Doğankent, Meteorology, Governorship, Çatalan, Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova. As of 2020, only four of these—Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova—were actively recording data. Notably, the Doğankent and Meteorology stations do not measure $PM_{2.5}$ concentrations (Continuous Monitoring Center, 2023).

Comparative tables generated from the National Air Quality Monitoring Network cover the period from January 1 to December 31, 2021, and provide station-specific data on key pollutants ($PM_{2.5}$, PM_{10}, NO_x, SO_2, CO, O_3) across Adana. These values were benchmarked against the annual limit thresholds established by the EU. Among the monitored stations, one had no data acquisition for a specific pollutant, and three others recorded only minimal data. Despite insufficient data acquisition from the Adana-Yakapınar and Adana-Governorate stations, daily PM_{10} concentrations at Yakapınar exceeded the WHO guideline value (WHO, 2021). Moreover, both EU and national daily limits were surpassed at this location. To provide a recent contextual illustration of the seasonal behaviour of air pollutants in Adana, the temporal variations in PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO concentrations during January–February of 2023, 2024, and 2025 are presented in Figures 2–4. These figures were not included in the statistical calculations of the study but were used to assess whether the wintertime fluctuation pattern observed in the principal 2020–2021 monitoring period continued in subsequent years. As shown in Figure 2, pollutant concentrations exhibited repeated short-term peaks during January and February 2023, indicating considerable temporal variability among monitoring stations.

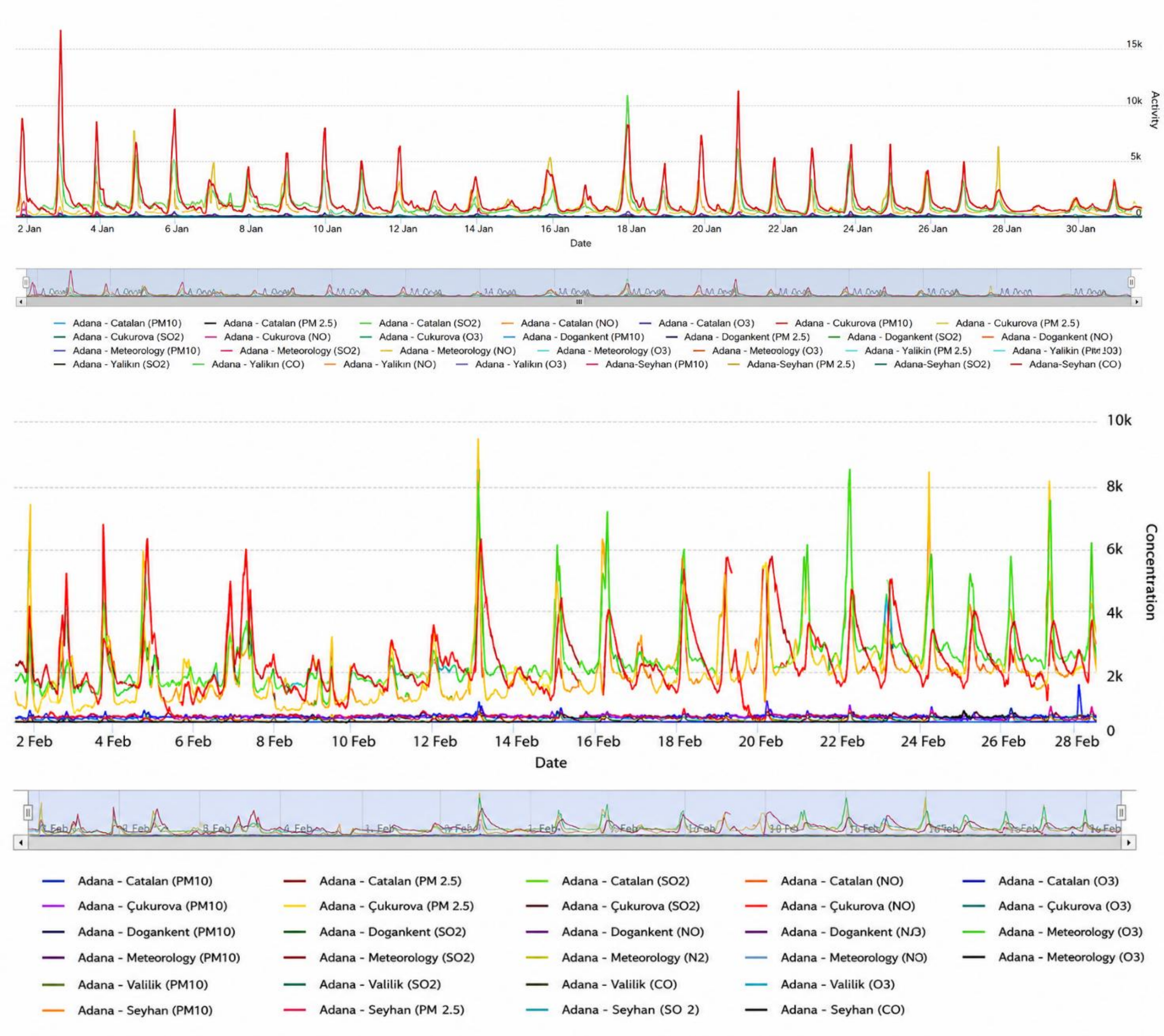

Figure 2: Temporal variation of selected air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO) in Adana during January–February 2023 (Continuous Monitoring Center [CMC], n.d.)

A comparable pattern of recurrent concentration peaks was also observed during January–February 2024, although the magnitude and timing of the fluctuations differed among pollutants and monitoring stations (Figure 3).

Figure 3: Temporal variation of selected air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO) in Adana during January–February 2024 (CMC, n.d.)

The January–February 2025 observations similarly showed pronounced short-term variations, particularly for particulate matter, suggesting that wintertime pollutant accumulation remained evident in the most recent contextual monitoring period (Figure 4).

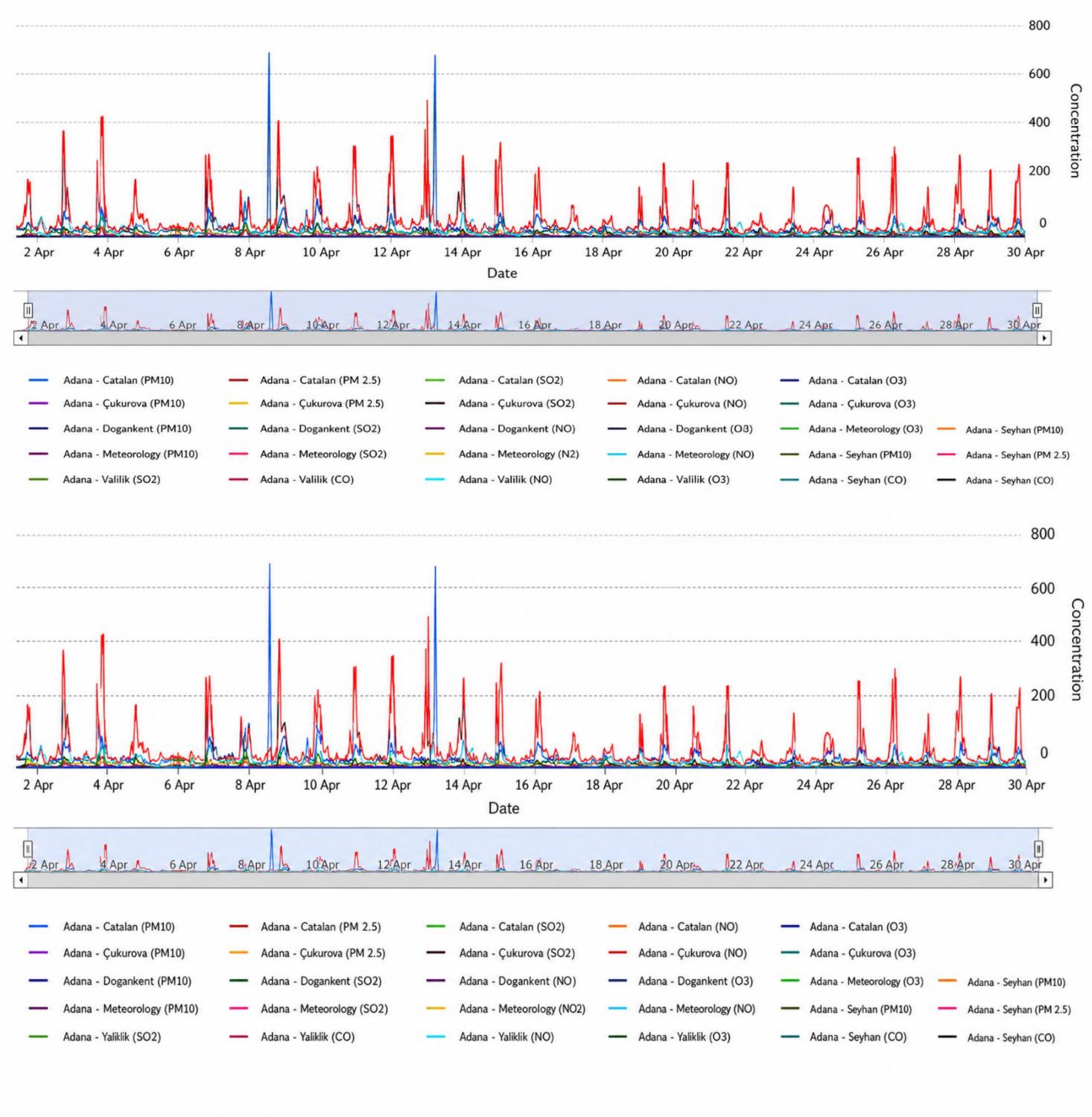

Figure-4: Temporal variation of selected air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, and CO) in Adana during January–February 2025 (CMC, n.d.)

Taken together, Figures 2–4 indicate that short-duration increases in particulate matter and gaseous pollutant concentrations recurred during the winter periods of 2023–2025. These patterns are consistent with the possible combined influence of residential heating emissions and unfavourable atmospheric dispersion conditions. However, because these figures represent contextual observations outside the principal 2020–2021 analytical period, they were not used to calculate annual means, exceedance frequencies, or temporal trends.

PM_{10} concentrations measured at the Meteorological Air Quality Monitoring Station in central Adana exceeded both the 2019 national and EU's limit values by a factor of two and surpassed the WHO guideline by a factor of four (Table 2) (HEAL, 2020b). According to the HEAL Hunutlu Thermal Power Plant and Adana Air Pollution Technical Assessment Note, residents of central Adana were exposed to polluted air on 236 days in 2019—equivalent to approximately 65% of the year (HEAL, 2020b). In the same year, Adana recorded a total of 2,072 non-accidental deaths, 21.9% of which were attributed to ambient air pollution. If air quality levels had remained within the WHO guidelines, one in every five of these deaths could have been avoided (HEAL, 2020b).

Table 2: Annual NOx, SO_2, and PM_{10} emissions from heating, traffic, and industrial sources in Adana *(MoEU, 2020)*

Emission source	**NO_X emission, tonnes/year**	**SO_2 emission, tonnes/year**	**PM_{10} emission, tonnes/year**
Industrial Emissions	3,185.48	**16,210.98**	1,683.79
Emission From Homewarmth	512.99	2,297.77	**2,585.48**
Traffic Emissions	**1,136.08**	14.25	64,00
Sum of Emissions	**4,834.55**	**18,523.00**	**4,333.27**

In Adana, exceedances of air quality standards have become increasingly common due to rapid, unregulated urbanization, a growing vehicle fleet, and the widespread use of low-quality fuels. The primary sources of emissions detected at the Meteorology and Governorate air quality monitoring stations have been identified as traffic-related and residential heating-related pollution (Table 2) (MoEUCC, 2021).

Industrial activity in Adana is spatially concentrated around major manufacturing zones. As a result, emissions from both industrial operations and domestic heating within these areas have become significant contributors to local air pollution. Several factors exacerbate industrial emissions in the region, including the continued use of outdated technologies, reliance on high-sulfur fuels for energy production, rising natural gas prices, and the simultaneous use of domestic coal alongside natural gas for heating purposes (MoEUCC, 2021).

Currently, Adana hosts two operational coal-fired thermal power plants: Enerjisa Tufanbeyli and İSKEN Sugözü (HEAL, 2022a). Recent findings have identified the İSKEN Sugözü plant as the tenth highest emitter of SO_2 among thermal power plants in Türkiye (Health and Environment Alliance [HEAL], 2020a). Despite widespread public opposition and mounting environmental concerns, construction is underway for a new coal-fired facility—the Hunutlu Thermal Power Plant (HEAL, 2022a). Although Türkiye ratified the Paris Agreement in 2021 and announced a 2053 net-zero target, the absence of a clearly defined coal phase-out timetable remains relevant for air-quality and energy-transition policy discussions (IPCC, 2022; Global Energy Monitor, 2022).

Notably, following the commissioning of the Sugözü plant in 2003—near the proposed site for the Hunutlu facility—the surrounding region experienced an elevenfold increase in cancer cases between 2009 and 2014, alongside a 275% rise in the diversity of cancer types diagnosed (HEAL, 2020a). These alarming patterns highlight the urgent need for comprehensive health impact assessments (HIAs) for all major energy infrastructure projects, especially those with direct implications for public health and air quality. Conducting such assessments is not only a scientific necessity but also a moral obligation grounded in the fundamental right to life (HEAL, 2020b).

In 2023, the total coal consumption—both domestic and imported—by the two operational coal-fired thermal power plants in Adana reached 13,137,754 tons (MoEUCC, 2024), increasing to 9,083,112 tons in 2023 (Table 3) (MoEUCC, 2024). The city relies on electricity, natural gas, and coal for residential heating. Although natural gas usage varies by district, the transition to this cleaner energy source has been gradual and uneven across the province. Locally mined coal continues to be widely used, particularly in the districts of Seyhan (10,786.50 tons), Yüreğir (10,000 tons), Çukurova (2,000 tons), and Sarıçam (1,300 tons). In terms of household fuel preferences, 152,720 households use solid fuels, 48,192 use imported coal, 100,000 burn wood, and 142,254 rely on natural gas for heating (MoEU, 2020).

Table 3. Fuel types and consumption quantities by sector in Adana in 2023 *(MoEUCC, 2024)*

	Solid Fuel			**Natural Gas**		**Fuel Oil**	
	Place of use	Types	Consumption rate (ton)	Place of use	Consumption rate (sm^3)	Place of Use	Consumption rate (kg)
Industry		Petroleum coke	207.683		376.113.142		
	Thermal power plant	Domestic coal	6.384.784				
	Thermal power plant	Imported coal	6.752.970				
		Biomass	321.035				
		Imported coal	159.057				
		Domestic coal	26.597				
	Consumption Rate (ton)			Consumption Rate (sm^3)		Consumption Rate (m^3)	
Home	157.939			106.613.114			

Adana receives an average of approximately 7.5 hours of sunlight per day (Turkish State Meteorological Service [TSMS], 2023), offering significant potential for solar energy production. However, the city's current energy mix remains dominated by hydroelectric power (47.2%) and fossil fuels—primarily coal and natural gas—at 50.8%, with solar energy accounting for just 0.4%, alongside biogas (0.5%) and other renewables (0.4%) (Energy Atlas, n.d.). Despite its high solar potential, the actual contribution of solar energy to Adana's overall energy production remains marginal.

Air pollution in Adana, particularly in the Seyhan district during winter months, severely reduces visibility and poses substantial health risks. Contributing factors include ongoing urban renewal projects, continuous construction activity, poor road conditions, and increasing traffic volumes throughout the year. In 2021, 248,708 vehicles in Adana underwent exhaust emissions testing (MoEUCC, 2022b).

Agricultural practices further exacerbate air quality issues. Following harvest, farmers frequently burn residual plant material in the fields to facilitate soil preparation. Though perceived as a time- and labor-saving method, this practice leads to seasonal wildfires typically occurring between June and September. These fires, combined with windborne pollutants from neighboring provinces, produce dense smoke and ashfall over Adana, posing acute respiratory hazards. The resulting increase in PM_{10} concentrations is one of the primary drivers of regional air pollution. In 2021, 112 such fire incidents were reported, resulting in fines totaling NT$373,017 (MoEUCC, 2022a).

Beyond human health impacts, these wildfires disrupt local ecosystems and significantly reduce soil fertility. Additional key drivers of air pollution in Adana include dense and unplanned urban development, an expanding vehicle fleet, unregulated industrial activity, widespread use of low-quality fuels, and unfavorable meteorological and topographical conditions. According to national statistics, the number of registered motor vehicles in Türkiye reached 26,349,156 in 2021—a 38.4% increase compared to the previous year. While Istanbul ranks first with 4,920,539 vehicles, Adana ranks seventh, with 741,335 registered vehicles (TÜİK, 2022a). This growing fleet, coupled with the increasing reliance on private cars, limited capacity of the light rail system, congestion during peak hours, and the central location of bus and airport terminals, has contributed significantly to traffic-related emissions in the city (MoEU, 2020).

Efforts to improve air quality in Adana should prioritize expanding the use of cleaner fuels and natural gas, enhancing public awareness, investing in infrastructure upgrades, and accelerating the shift toward sustainable transportation. Moreover, effective urban planning and robust emission control strategies will be essential for mitigating pollution from heating and traffic-related sources.

The air-quality monitoring data from Adana Province provide important insights into both air-quality management performance and the interpretation of potential public-health relevance. Annual mean concentrations of major pollutants, particularly $PM_{2.5}$ and PM_{10}, indicate exceedances of the WHO 2021 guideline values. However, substantial gaps in data collection and data-capture rates below acceptable levels at some stations limit the robustness of long-term exposure assessment and trend interpretation. These monitoring limitations point to structural weaknesses in the air-quality surveillance system and should be considered when using the findings for policy evaluation. In addition, seasonal increases in SO_2 and particulate matter during winter suggest the influence of residential heating and limited atmospheric dispersion. Therefore, the findings should be interpreted as evidence of important air-quality management challenges rather than as a direct epidemiological assessment of local health outcomes.

4. Limitations

The empirical scope of this study is restricted to ambient air quality monitoring data from stations in Adana Province, including pollutant concentration levels, exceedances of regulatory limit values, and indicators of data completeness. Because time- and station-resolved clinical health data suitable for linkage were not accessible within the framework of this research, we were unable to quantify effect sizes or to conduct a direct statistical assessment of associations between pollutant levels and respiratory morbidity, and no causal epidemiological testing was performed. Accordingly, any discussion of public health implications should be interpreted as a literature-informed appraisal of potential impacts in light of locally observed pollutant patterns, rather than as causal inferences validated with Adana-specific clinical datasets.

In Adana Province, eight monitoring stations are affiliated with the Mediterranean Clean Air Center (Doğankent, Meteoroloji, Valilik, Çatalan, Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova). As of 2020, four of these stations (Seyhan, Turhan Cemal Beriker, Yakapınar, and Çukurova) were reported to produce data on a regular basis. It has also been indicated that $PM_{2.5}$ measurements are not available at the Doğankent and Meteoroloji stations. Because the publicly accessible data stream does not include verifiable event logs specifying the station-level causes of missing data (e.g., instrument failure, maintenance/calibration, power or communication outages, or meteorology-related interruptions), the present study could not reliably attribute data gaps to station-specific sources.

Data integrity was evaluated at the station–pollutant level using the annual percentage of valid data, measurement frequency, and the number of missing days. Data-capture rates falling below 60% at certain stations increase uncertainty in annual mean and trend assessments and limit inter-station comparability. In addition, the concentration of stations within the urban core, together with limited representation of rural and background conditions, constitutes a further source of uncertainty by reducing the spatial generalizability of the findings at the provincial scale. Additionally, the study did not quantify socioeconomic gradients (e.g., income, housing type, fuel use, or population distribution) in exposure or risk; hence, the environmental justice dimension was not assessed empirically.

The empirical scope is limited to air quality monitoring measurements and data completeness metrics. Because time- and station-resolved, linkable clinical health data were not available, no direct statistical association was established between pollutant levels and respiratory morbidity; potential health implications were instead discussed within a literature-based framework informed by local pollutant patterns.

Station-specific causes of data gaps in the national monitoring network (e.g., instrument malfunction, maintenance/calibration, power or communication outages, or weather-related interruptions) could not be verified through publicly available incident records; consequently, missingness could not be reliably attributed at the station level. Data capture rates falling below 60% at certain stations increase uncertainty in annual mean and trend assessments and limit comparability across stations; accordingly, low-completeness station–pollutant series were excluded from annual mean and trend calculations as described above. In addition, seasonal clustering of missing data (e.g., during the winter heating season or the summer photochemical period) may introduce bias into annual means and trend indicators, requiring cautious interpretation. Finally, the spatial concentration of monitoring stations within the urban core and the limited representation of rural/background conditions reduce provincial-scale spatial generalizability. Moreover, because socioeconomic gradients in exposure or risk (e.g., income, housing type, fuel use, or population distribution) were not evaluated quantitatively, the environmental justice dimension could not be tested empirically. Additional uncertainty arises from the spatial concentration of monitoring stations within urbanized zones and the limited representation of rural or background environments, which constrains province-wide spatial generalization. Furthermore, the study did not quantify socioeconomic gradients in exposure or risk (such as income, housing structure, fuel use, or population distribution); therefore, environmental justice implications are discussed only in a general literature context rather than as empirically demonstrated local inequalities.

5. Conclusions and Suggestions

This assessment of air quality management in Adana has revealed the significant burden imposed by air pollution, stemming primarily from industrial operations, residential heating, and vehicular traffic. By combining pollutant concentration data, exceedance assessment, source-related information, and monitoring-data completeness indicators, this study provides a data-based assessment of air pollution management challenges in Adana Province. The evaluation focused on key pollutants—$PM_{2.5}$, PM_{10}, SO_2, NO_2, NO_x, CO, and O_3— measured across multiple monitoring stations, highlights critical deficiencies in data acquisition. Incomplete records and instances of negative values reported at several stations raise substantial concerns regarding the reliability and continuity of the existing monitoring infrastructure, thereby compromising the integrity of long-term assessments.

The persistent reliance on fossil fuels, particularly within the industrial sector, remains a principal driver of elevated pollution levels. High concentrations of SO_2, notably, underscore an ongoing dependence on solid fuels for industrial energy generation. During winter months, emissions from residential heating emerge as the dominant contributor to deteriorating air quality, exceeding the impact of both traffic and industrial sources, especially concerning SO_2 and PM_{10}.

Beyond seasonal heating influences, perennial factors such as extensive urban redevelopment, intensive construction activities, and inadequately maintained road networks contribute to consistently high ambient concentrations of PM throughout the year. Furthermore, prevailing agricultural practices, specifically the widespread stubble burning occurring between June and September as farmers prepare fields for secondary cropping, lead to pronounced spikes in PM_{10} levels.

Traffic emissions constitute a major and growing source of pollution within Adana. Escalating vehicle numbers, the predominance of private car usage, the insufficient capacity of the light rail system to mitigate urban congestion, and peak-hour traffic associated with school and work commutes collectively drive the decline in air quality. The central location of major transportation hubs, including the airport and intercity bus terminal, further amplifies the dispersion and impact of traffic-related pollutants.

Findings from this study indicate that air pollution in Adana has reached critical levels, posing a substantial threat to public health. In response, the following policy recommendations are proposed to mitigate environmental and health risks:

- Minimize the environmental impact of coal-fired thermal power plants;
- Expand access to natural gas, particularly for residential heating;
- Enhance public transportation infrastructure to reduce traffic-related emissions;
- Strengthen regulatory enforcement to prevent agricultural stubble burning;
- Improve the efficiency and reliability of air quality data collection at monitoring stations.

The implementation of these measures would significantly contribute to improving air quality in Adana, reducing the economic burden of pollution-related health care, and enhancing the overall well-being of residents.

Ultimately, achieving sustainable improvements in Adana's air quality necessitates a coordinated, multi-faceted strategy, demanding committed leadership from local authorities and active engagement from community stakeholders. Effective air quality management must be founded upon rigorous emission control policies, a robust and dependable monitoring system, the proactive promotion of clean energy alternatives, the expansion of sustainable urban mobility solutions, and heightened public awareness and participation. Only through such concerted, multi-stakeholder commitment can Adana realize a healthier, more breathable urban atmosphere conducive to public health.

From an environmental justice perspective, prior evidence suggests that exposure to air pollution—and the associated health burden—may be unevenly distributed across socioeconomic strata, reflecting residential patterns, housing quality, heating fuel choices, and unequal access to cleaner energy and healthcare services. In the present study, however, we did not include socioeconomic determinants (e.g., income proxies, housing characteristics, fuel-use patterns, or fine-scale population distribution) because these variables were not available in a harmonized format with station- and time-resolved resolution compatible with the monitoring dataset. Accordingly, any discussion of inequality should be interpreted as contextual background informed by the broader literature, rather than as an empirically demonstrated, Adana-specific environmental justice assessment.

In future studies, if access to health outcome data can be obtained within the framework of institutional and ethical approvals, short-term effects could be evaluated by applying time-series Poisson regression or distributed lag non-linear models (DLNM) while controlling for meteorological covariates and seasonality. For longer-term assessments, cohort-based or ecological study designs could be employed to estimate effect sizes at the Adana scale.

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