



Air Quality in Kabul, Afghanistan: Progress, Persistent Challenges and pathways for Sustainable improvement

*Engineer Rahmatullah Seeyall¹, Nazeefullah Ibrahimi¹, Waheed Ullah Hafiz¹

¹Basic Science Department, Faculty of Medicine, Bayazid Rokhan University, Kabul, Afghanistan

| DOI: xxxxxx

| Corresponding Author Email: rahmatullahseeyall2023@gmail.com

Received: 07/Jan/2025

Accepted: 20/Jan/2025

Published: 21/Dec/2025

Absrtact

Air quality plays a pivotal role in public health, environmental sustainability, and urban livability, especially in rapidly developing cities like Kabul. This study analyzes trends in six major air pollutants (PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃) from 2018 to 2024 to assess the effectiveness of air quality management measures and identify persistent challenges. By evaluating comprehensive data, the research aims to provide actionable insights for evidence-based policymaking and sustainable urban development. Data was collected by the National Environmental Protection Agency (NEPA) from six monitoring stations (2018–2020) and one station (2021–2024). Monthly and annual pollutant concentrations, along with AQI values, were analyzed, with sampling conducted 3–4 times per month and pollutant-specific durations observed. Seasonal variations were studied using Afghan solar months aligned with Gregorian months to capture pollution patterns across different periods. Results reveal significant improvements in SO₂ levels, which dropped from 283.3 µg/m³ in 2018 to under 2 µg/m³ by 2021, and substantial AQI reductions in Q1 and Q2, reflecting effective regulatory measures. However, resurging PM_{2.5} and PM₁₀ levels in 2023–2024 and rising ozone concentrations post-2020 indicate ongoing challenges. The reduction in monitoring stations since 2021 limits spatial representation, and reliance on monthly averages obscures extreme pollution events. This study highlights both progress and the need for sustained interventions, including stricter emission standards, cleaner energy adoption, and robust air quality monitoring systems and banning the use of biofuels during winter months. The results of practical guidance for policymakers and urban planners aiming to enhance air quality and fosters sustainable development in Kabul.

Keywords: Afghanistan, Air Quality Index, Kabul, Particular Matter, Seasonal Pollution, Variations

Introduction

According to the World Health Organization (WHO), air pollution is the “Contamination of the inside and open-air environment by any chemical, physical or biological agent that changes the natural properties of atmosphere”. [1]. It involves combination of gases and elements discharged into the atmosphere in harmful quantities as a result of both natural and anthropogenic activity [2].

Pollutants can originate from natural sources, artificial activities, or man-made activities. Natural pollution sources include things that release harmful compounds and exert damaging impacts on the environment. For example, volcanic eruptions and forest fires release various air pollutants, including sulfur dioxide (SO₂), carbon dioxide (CO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), and sulfate particles. In contrast, anthropogenic causes including the burning of fossil fuels, pollution from industrial production processes and



transportation are the main providers to air pollution. These anthropogenic activities release a wide range of pollutants, such as hydrogen, oxygen, nitrogen, sulfur, metal compounds, and particulate matter [3].

As the worldwide population increases and economies develop, the demand for energy has risen dramatically. The extensive dependence on fossil fuels has led to many environmental issues that are getting considerable attention due to their negative effects on human health and the natural world [4, 5, 6]. Air pollution has emerged as a critical issue worldwide, with two primary concerns: its impact on human health, particularly cardiovascular diseases, and its environmental consequences, which include acid rain, climate change, and global warming [7].

Exposure to these toxic substances has serious health implications, contributing to respiratory disorders, cardiovascular diseases, damage to the nervous system, skin conditions, and chronic illnesses such as cancer. Moreover, air pollution negatively influences various environmental aspects, which can directly or indirectly affect human health by exacerbating diseases like asthma, lung cancer, autism, retinopathy, and low birth weight [8].

While the Global Exposure Mortality Model (GEMM) offers valuable insights into the global health impacts of air pollution, the situation in specific cities, such as Kabul, Afghanistan, underscores the challenges faced in regions with limited data and monitoring infrastructure. In Kabul, anthropogenic sources primarily generate air pollutants, including emissions from power plants, smelters, wood-burning stoves, gas-powered generators, and motor vehicles. In addition, residents often resort to burning plastic tires and coal for heating. Regrettably, the phenomenon of air pollution in Kabul has not yet been systematically studied [9, 10].

The negative health impacts associated with breathing polluted air in Kabul are directly correlated with observed pollution levels, particularly during months with elevated PM_{2.5} readings. Inhalation of contaminated air can lead to persistent chest infections and various respiratory ailments as well as irritation of the eyes, mouth, nose, and throat. Chronic obstructive pulmonary disease (COPD), which encompasses disorders such as bronchitis and emphysema, is prevalent among the population. Prolonged exposure to plastic fumes may elevate cancer risk, as many emitted materials carry carcinogenic properties. Furthermore, exposure to toxic chemicals and elements like cyanide, mercury, and lead can inflict lasting damage to the nervous system, resulting in chronic fatigue, cognitive impairment, and a heightened risk of fatal heart attacks or strokes. Symptoms such as headaches and increased vulnerability to illnesses can also significantly diminish the quality of life. Additionally, carbon monoxide (CO) emissions can result in rapid fatalities, particularly in poorly ventilated homes. According to a spokesperson from the Ministry of Public Health of Afghanistan, air pollution is responsible for over 3,000 deaths annually in the country, with at least 700,000 individuals suffering from various respiratory diseases in Kabul alone. This figure reflects only those who sought treatment at government hospitals, excluding many others [11].

The Afghan government has not yet created a comprehensive list of air pollutant emissions. Additionally, no source analysis studies have been performed to identify the relative contributions of different sources to aerosols in the air. The absence of such data is largely attributable to an insufficiency of monitoring stations capable of recording air quality and meteorological data. Consequently, satellite remote sensing of aerosols may serve as an effective alternative method for assessing aerosol levels in areas that lack robust air quality monitoring infrastructure [12].

The World Health Organization says that air pollution accounts for roughly 2.4 million fatalities annually. An article insists that release of greenhouse gases, especially carbon dioxide, are among the major contributors to climate change in Afghanistan. The harmful effects of climate change in the country include flooding, drought, increasing temperature, risks to food security, elevated poverty levels and attacks on human rights.

Based on these findings, if Afghanistan collaborates with other members of the IPCC, UNFCCC, Kyoto Protocol, and Paris agreement, and executes targeted policies that reduce climate change and its effects, it might achieve various advantages as specified in global agreements [14]. This study seeks to investigate the interconnected challenges of air pollution and climate change in Afghanistan, analyzing their health, environmental, and socioeconomic impacts.

2.0 Materials and Methods

2.1 Study Area

Kabul city, the capital of Afghanistan, was chosen as the study area for evaluating the Air Quality Indices (AQI) over the past six years. Located at $34^{\circ} 32' 38.0256''$ N and $69^{\circ} 9' 38.3472''$ E and situated 1.8 km above sea level, Kabul experiences an arid, continental climate with four distinctive seasons. Rapid urbanization and population growth, with an estimated population of 5–6 million far exceeding its infrastructure designed for 3 million, have significantly impacted the city's environment. These changes, coupled with the conversion of rangelands into urban areas, make Kabul a critical area for assessing air quality trends [15].

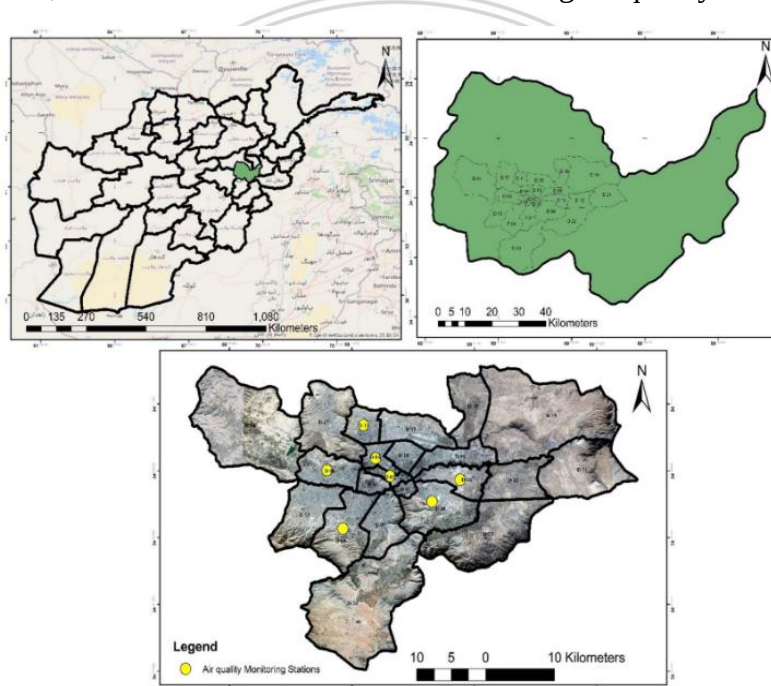


Figure 1: Map presenting the locations of Air Quality Monitoring Stations in Kabul City [16]

2.2 Data Collection

In this study, air quality data spanning 2018 to 2024, collected by the **National Environmental Protection Agency (NEPA) of Afghanistan**, was analyzed to evaluate six standard air pollutants: PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃, in Kabul city. From 2018 to 2020, data was gathered from six monitoring stations located across municipal districts D2, D5, D6, D7, D11, D13, and D16. These stations employed mobile air quality monitoring devices with a sampling frequency of 3–4 times per month, adhering to standard sampling durations (8 hours for O₃, 1 hour for CO, and 24 hours for PM_{2.5}, PM₁₀, SO₂, and NO₂) and average concentrations of criteria air pollutants O₃, NO₂, SO₂, PM₁₀, PM_{2.5} in $\mu\text{g}/\text{m}^3$ CO in mg/m^3 . Since 2021, air quality monitoring has been limited to a single active station (D6), reducing spatial coverage. The data, presented in **Tables 1–7**, includes monthly and annual averages of pollutant concentrations and AQI values, highlighting trends and variations in air quality over the study period.



The Afghan solar months referenced in the tables align with specific Gregorian months and days as follows: **Hamal** (March 21–April 20), **Sawr** (April 21–May 21), **Jawza** (May 22–June 21), **Saratan** (June 22–July 22), **Asad** (July 23–August 22), **Sunbola** (August 23–September 22), **Mizan** (September 23–October 22), **Aqrab** (October 23–November 21), **Qaws** (November 22–December 21), **Jaddi** (December 22–January 20), **Dalwa** (January 21–February 19), and **Hoot** (February 20–March 20). This alignment provides essential context for understanding seasonal variations in air quality data. The transition from six monitoring stations to one underscores the need for reinstating comprehensive spatial monitoring to ensure effective air quality management in Kabul city.

Month	O ₃	NO ₂	SO ₂	CO	PM ₁₀	PM _{2.5}	AQI
Hamal	103	61	242	0	259	191	266
Sawar	84	0	564	1.3	267	255	360
Jawza	57	0	44	0.3	129	180	255
Sartan	2.5	2	35	0	254	179	245
Asad							
Sunbola							
Mizan	8.62	82	0	0	208	198	273
Aqrab	3.14	185	88	23	602	282	414
Qaus	5	193	102	19	1002	361	571
Jaddi	0	212	168	11	511	194	269
Dalwa	0	193	106	7.1	165	88	174
Hoot	125	182	83	7.4	176	68	160

Table 1: Monthly average concentrations of criteria air pollutants and their AQI (1397)

Month	O ₃	NO ₂	SO ₂	CO	PM ₁₀	PM _{2.5}	AQI	Month	O ₃	NO ₂	SO ₂	CO	PM ₁₀	PM _{2.5}	AQI
Hamal	85	88	40	3.5	101	95	200	Hamal							
Sawar	75	58	6	0.7	62	65	125	Sawar	46	79	2.6	0.9	89	44	122
Jawza	24	20	9	0.4	94	95	216	Jawza	83	315	8.8	1.3	93	49	134
Sartan	23	15	8	0	86	93	210	Sartan	28	134	4	1.4	99	74	164
Asad	3	37	17	0.7	102	125	284	Asad	36	149	4	9	129	79	168
Sunbola	9	33	15	2	103	120	276	Sunbola							
Mizan	34	47	40	2.6	173	155	327	Mizan							
Aqrab	52	192	19	3	155	117	287	Aqrab							
Qaus	87	90	43	3	108	101	237	Qaus							
Jaddi	60	423	89	6	158	141	427	Jaddi							
Dalwa	83	396	55	5	102	75	397	Dalwa	130	109	83	7	141	92	177
Hoot	87	90	43	3	108	101	237	Hoot	112	53	7.7	3.8	108	69	161

Table 2: Monthly average concentrations of criteria air pollutants and their AQI (1398)

Table 3: Monthly average concentrations of criteria air pollutants and their AQI (1399)

Month	O ₃	NO ₂	SO ₂	CO	PM 10	PM 2.5	AQI	Month	O ₃	NO ₂	SO ₂	CO	PM 10	PM 2.5	AQI
Hamal	72	144	75	3	141	61	177	Hamal							
Sawar	87	257	36	5	96	88	321	Sawar	46	79	2.6	0.9	89	44	122
Jawza	109	323	24	1	72	63	322	Jawza	48	79	0.7	1	101	63	156
Sartan	1	131	7	4	106	96	231	Sartan							
Asad	0.5	196	12	3	101	106	283	Asad	32	67	1.4	1.4	67	39	110
Sunbola	45	10	14	3	245	146	303	Sunbola	36	82	1.8	1.6	84	31	92
Mizan	54	11	17	4	275	165	327	Mizan	61	75	10	2.5	111	25	81
Aqrab	51	178	16	3	150	131	290	Aqrab	94	53	11	2.7	97	30	90
Qaus	89	431	97	5	233	191	445	Qaus	133	34	102	5.1	166	74	164
Jaddi	60	408	80	6	150	139	410	Jaddi	180	29	107	6.5	198	109	189
Dalwa	77	392	58	5	107	139	339	Dalwa	180	6.7	25	5.3	172	87	173
Hoot	70	327	47	5	102	123	339	Hoot	109	35	6.02	3.3	168	77	166

Table 4: Monthly average concentrations of criteria air pollutants and their AQI (1400)

Table 5: Monthly average concentrations of criteria air pollutants and their AQI (1401)

Month	O ₃	NO ₂	SO ₂	CO	PM 10	PM 2.5	AQI
Hamal	94	31	2.02	0	144	57	152
Sawar	56	63	2.1	0	151	64	157
Jawza	28	81	1.19	0	181	98	181
Sartan	14	107	1.5	0	211	126	201
Asad	15	100	1.7	3.1	165	88	174
Sunbola	26	85	0.8	3.9	186	100	182
Mizan	62	53	0.6	5.1	177	78	167
Aqrab	80	60	9.2	5.3	191	79	168
Qaus	108	40	103	8.9	214	93	177
Jaddi	126	21	135	10	207	101	183
Dalwa	136	9	62	10	155	74	164
Hoot	0	30	3	7	127	58	153

Table 6: Monthly average concentrations of criteria air pollutants and their AQI (1402)

Month	O ₃	NO ₂	SO ₂	CO	PM 10	PM 2.5	AQI
Hamal	32	4.3	5.4	114	48	32	94
Sawar		48	8.7	4.7	99	42	117
Jawza	111	85	16	3.8	134	47	129
Sartan	87	85	14	4.1	153	61	155
Asad	38	96	26	4.4	164	62	156
Sunbola		71	33	4.8	176	62	156
Mizan		65	36	4.2	167	58	153
Aqrab		44	106	4.6	212	70	161

Table 7: Monthly average concentrations of criteria air pollutants and their AQI (1403)

2.3 Data Analysis

The collected data was processed and analyzed using Microsoft Excel, where monthly and annual averages were calculated, and the Air Quality Index (AQI) values were derived and compared. Additionally, quarterly comparisons were performed to identify seasonal trends, and the most polluted and least polluted periods were determined. Yearly trends in AQI and pollutant concentrations were also analyzed to evaluate long-term variations in air quality over the study period.

3.0 Results

Our results highlight the trends and variations in air pollutant concentrations and AQI values across different quarters, revealing significant patterns and key insights.

3.1 Trends and Analysis of Air Pollutant Concentrations and AQI in Q1 (1397–1403)

The analysis of 1st quarter air pollutant data from 1397 to 1403 reveals significant trends. O₃, SO₂, PM₁₀, and PM_{2.5} concentrations have steadily declined, reflecting improvements in air quality management. SO₂ showed the most dramatic reduction, dropping from 283.3 µg/m³ in 1397 to below 2 µg/m³ by 1401 (Table 8). AQI improved markedly from 293.66 in 1397 to 113.33 in 1403, indicating overall better air quality. However, notable anomalies include a spike in CO concentrations to 40.83 mg/m³ in 1403 and significant fluctuations in NO₂ levels, highlighting areas requiring further investigation and intervention.

Quarter	O ₃	NO ₂	SO ₂	CO	PM ₁₀	PM _{2.5}	AQI
Q1 1397	81.3	20.3	283.3	0.53	218	208.6	294
Q1 1398	89.3	241.3	45	3	103	70.6	273
Q1 1399	61.3	55.33	18.3	1.53	85.6	85	180
Q1 1400	64.5	197	5.7	1.1	91	46.5	128
Q1 1401	47	79	1.65	0.95	95	53.5	139
Q1 1402	59.3	58.33	1.77	0	158	73	163
Q1 1403	71.5	45.76	10.03	40.8	94	40.33	113

Table 8: 1st quarter average concentrations of criteria air pollutants and their AQI (1397-1403)

3.2 Trends and Analysis of Air Pollutant Concentrations and AQI in Q2 (1397-1403)

The analysis of Q2 air pollutant data from 1397 to 1403 reveals fluctuating trends in pollutant concentrations and AQI, with PM₁₀ and PM_{2.5} emerging as dominant contributors to poor air quality (Table 9). The AQI peaked in 1398 (272.33) and showed improvement by 1401 (101), but later years, such as 1402 and 1403, reflected a resurgence of pollution. Notably, ozone levels exhibited substantial variability, peaking in 1403 (62.5 µg/m³), while NO₂ spiked in 1398 and 1400, suggesting intense combustion activities during those years. SO₂ levels remained relatively low but peaked in 1403, pointing to isolated industrial contributions. CO levels were consistently within limits but showed localized increases in 1400 and 1403. The data underscores the critical influence of particulate matter (PM₁₀ and PM_{2.5}) on AQI, emphasizing the need for sustained efforts in managing emissions to achieve consistent air quality improvements.

Quarter	O ₃	NO ₂	SO ₂	CO	PM ₁₀	PM _{2.5}	AQI
Q2 1397	2.5	2	35	0	254	179	245
Q2 1398	15.5	112	11	3.3	151	116	272
Q2 1399	11.7	28.3	13.3	0.9	97	113	257
Q2 1400	32	142	4	5.2	114	76.5	166
Q2 1401	34	74.5	1.6	1.5	75.5	35	101
Q2 1402	18.3	97.3	1.33	2.3	187.	105	186
Q2 1403	62.5	84	24.3	4.4	164	62	15

Table 9: 2nd quarter average concentrations of criteria air pollutants and their AQI (1397-1403)

3.3 Trends and Analysis of Air Pollutant Concentrations and AQI in Q3 (1397-1403)

The data for the third quarter reveals significant fluctuations in air pollutant concentrations and AQI, with a general trend of improvement in air quality over time, barring inconsistencies (Table 10). The AQI was alarmingly high in 1397 (419.33), driven by elevated PM₁₀ (604 µg/m³) and PM_{2.5} (280.33 µg/m³) levels, which were the highest across all years. A notable improvement occurred by 1401 (AQI 111.66), with substantial reductions in particulate matter and gaseous pollutants. However, 1402 and 1403 showed moderate rebounds in pollutant levels, with SO₂ peaking in 1403 (71 µg/m³), likely reflecting industrial activity. Interestingly, ozone (O₃) concentrations steadily increased post-1400, peaking in 1402 (83.33 µg/m³), highlighting increased photochemical activity. The absence of data for 1400 indicates potential anomalies in monitoring or reporting. The findings emphasize the critical impact of particulate matter and suggest the need for consistent emissions management and robust monitoring systems to sustain long-term air quality improvements.

Quarter	O ₃	NO ₂	SO ₂	C O	PM 10	PM 2.5	AQI
Q3 1397	5. 5	153. 3	63. 3	14	604	280. 3	419
Q3 1398	65	206. 6	43. 3	4	219. 3	162. 3	354
Q3 1399	58	109. 7	34	2. 9	145. 3	124. 3	283
Q3 1400	0	0	0	0	0	0	0
Q3 1401	78	64	10. 5	2. 6	104	27.5	112
Q3 1402	83	51	37. 6	6. 4	194	83	171
Q3 1403	0	54.5	71	4. 4	189. 5	64	157

Table 10: 3rd quarter average concentrations of criteria air pollutants and their AQI (1397-1403)

3.4 Trends and Analysis of Air Pollutant Concentrations and AQI in Q4 (1397-1403)

The analysis of fourth-quarter air quality data from 1397 to 1403 reveals significant fluctuations in pollutant levels and AQI, reflecting variations in emission sources and environmental conditions (Table 11). The AQI reached its peak in 1398 (362.66) and 1399 (353.66), driven by elevated NO₂, SO₂, and particulate matter (PM₁₀ and PM_{2.5}) concentrations. A notable improvement is observed in 1400 and 1401, with AQI values dropping to 169 and 176, respectively, likely due to reduce NO₂ and particulate matter levels. Ozone (O₃) concentrations show a rising trend, peaking in 1401 (156.33 µg/m³), indicating increased photochemical activity. The steep decline in NO₂ levels post-1399, coupled with stable CO levels, suggests effective mitigation of combustion-related emissions. Data absence for 1403 introduces uncertainty, underscoring the importance of consistent monitoring. The findings highlight the critical role of particulate matter and NO₂ in driving poor air quality during Q4 and emphasize the need for sustained pollution control efforts

to achieve long-term improvements.

Quarter	O ₃	NO ₂	SO ₂	CO	PM 10	PM 2.5	AQI
Q4 1397	41.6	196	119	8.5	284	117	201
Q4 1398	69	375.6	61.6	5.33	120	134	363
Q4 1399	77	303	62.3	4.66	123	106	353.66
Q4 1400	121	81	45.35	5.4	124.5	80.5	169
Q4 1401	156.3	23.5	46	5.03	179.33	91	176
Q4 1402	87.33	20	66.66	9	163	77.66	166.66
Q4 1403	0	0	0	0	0	0	0

Table 11: 4th quarter average concentrations of criteria air pollutants and their AQI (1397-1403)

3.5 Comparative Analysis of Quarterly AQI Trends (1397–1403)

The quarterly AQI data from 1397 to 1403 shows significant seasonal and annual trends in air quality (Table 12). Q1 (winter) initially recorded high AQI values, peaking at 293.66 in 1397, likely due to heating emissions and atmospheric stability, but steadily improved to 113.33 by 1403. Q2 (spring) experienced fluctuating AQI levels, with a peak in 1398 (272.33) and a significant drop to 101 by 1401, though moderate increases in 1402 and 1403 suggest intermittent pollution episodes. Q3 (summer) consistently displayed the highest AQI values in earlier years, with a peak in 1397 (419.33), driven by particulate matter and photochemical pollutants. While improvements are seen in later years, the absence of data for 1400 obscures trends. Q4 (autumn) mirrored Q3 in earlier years, with AQI peaks in 1398 (362.66) and 1399 (353.66), but improved significantly by 1400 (169), maintaining better levels through 1402. Overall, the AQI shows a declining trend across all quarters from 1397 to 1401, reflecting improved air quality, though a slight rebound in 1402 underscores the need for consistent emission controls and monitoring.

Year	Q1	Q2	Q3	Q4
1397	293.66	245	419.33	201
1398	273.33	272.33	354	362.66
1399	180.33	256.66	283.66	353.66
1400	128	166	0	169
1401	139	101	111.66	176
1402	163.33	185.66	170.66	166.66
1403	113.33	155.66	157	0

Table 12: Quarterly comparison of Average AQI 1397 - 1403

3.6 Comparison of the Most Polluted and Least Polluted Quarters (1397–1403)

Figure 2 illustrates a comparison of the most polluted and least polluted quarters in Kabul from 1397 to 1403. From 1397 to 1403, Kabul's air quality showed a clear improvement, with AQI levels peaking in 1397 and 1398 due to severe pollution in Q3 and Q4. A significant turning point occurred in 1400, with substantial reductions in AQI, particularly in Q1 and Q2. The trend continued in 1401, recording some of the lowest AQI values, though a slight rebound in 1402 indicated persistent seasonal challenges. By 1403, air quality further

improved in Q1 and Q2, but missing Q4 data limits a full assessment. The overall trend reflects progress, though consistent efforts are needed to maintain improvements.

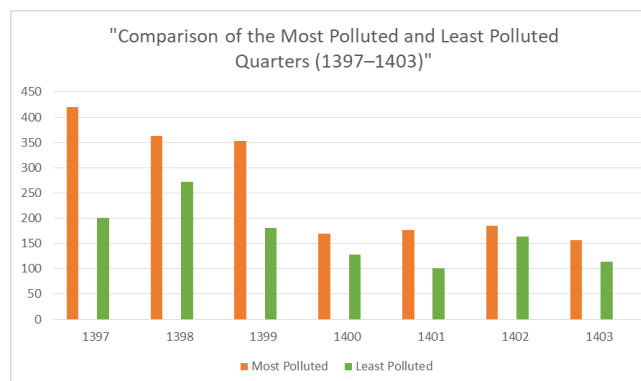


Figure 2: Comparison of the Most Polluted and Least Polluted Quarters (1397–1403)

4. Discussion

Air quality is a serious determinant of public health, economic productivity, and overall urban livability. Poor air quality, predominantly in developing cities, contributes significantly to respiratory and cardiovascular diseases, reduces life expectancy, and obstructs sustainable development. Kabul, which has been nominated in 2019 as the world's most polluted cities, serves as a case study to understand these impacts and evaluate policy interventions. Our study offers an inclusive analysis of air pollutant trends and the AQI across 1397–1403, emphasizing the importance of targeted interventions in combating pollution and improving urban health.

The results disclose a mixed narrative of progress and persistent challenges. Significant improvements in air quality were observed, especially in Q1 and Q2 of 1401, with AQI values reducing from dangerous levels in earlier years to healthier levels. Prominent achievements include the dramatic reduction in SO_2 concentrations, from $283.3 \mu\text{g}/\text{m}^3$ in 1397 to under $2 \mu\text{g}/\text{m}^3$ by 1401, largely attributed to regulatory measures. However, a resurgence of pollutants like PM_{10} and $\text{PM}_{2.5}$ in later years highlights the need for sustained efforts. The data also emphasize the critical influence of seasonal energy use patterns and industrial activities on pollutant levels, underlining the importance of comprehensive air quality management strategies.

Our results align with global research on urban air quality trends in developing cities. Studies indicate that particulate matter (PM_{10} and $\text{PM}_{2.5}$) and NO_2 are major contributors to air pollution, often linked to vehicular emissions, industrial processes, and the use of low-quality fuels [17, 18]. In Kabul, the average $\text{PM}_{2.5}$ concentration of $92.2 \mu\text{g}/\text{m}^3$ in 2019 far exceeds the WHO guideline of $25 \mu\text{g}/\text{m}^3$, consistent with reports from other megacities like Delhi and Dhaka [19].

Correspondingly, seasonal variations in pollutant levels are well-documented globally, with winter months showing higher $\text{PM}_{2.5}$ levels due to increased heating emissions and atmospheric inversion [20]. Our study corroborates these trends, with December consistently being the most polluted month in Kabul.

Further, the resurgence of ozone levels post-1400 parallels findings in other urban centers, where increased vehicular emissions and photochemical activity contribute to secondary pollution [21]. The study by Sarker (2024) on urbanization and environmental impact emphasizes the challenges of balancing economic growth and air quality improvements, which is also evident in Kabul's context [22]



While our results emphasize notable progress, such as the reduction in SO₂ levels, they also reveal gaps in monitoring and enforcement. This aligns with research from Jakarta and similar cities, where inconsistent implementation of air quality measures limits long-term improvements [22]

To sustain and expand improvements in air quality, policymakers must focus on interventions supported by global evidence. First, transitioning to cleaner energy sources, such as expanding access to electricity and natural gas, can reduce reliance on wood and coal, as demonstrated in urban planning studies [23]. Second, implementing stringent vehicular emission standards, including phasing out outdated vehicles and improving fuel quality, has been effective in cities like Delhi [24]. Third, urban greening initiatives can mitigate particulate matter and offer long-term ecological benefits, as highlighted in sustainability research [25]. Finally, vigorous air quality monitoring systems and public awareness campaigns are essential to promote accountability and community engagement in air quality management [22, 18].

4.1 Policy Implications and Recommendations

1. **Strengthen Vehicle Emission Standards:** As vehicular emissions are the largest contributor to air pollution, stricter regulations on vehicle imports and maintenance are essential.
2. **Promote Clean Energy:** Expanding access to electricity and natural gas, especially during winter months, could significantly reduce reliance on coal and wood for heating.
3. **Robust Monitoring Infrastructure:** Continuous air quality monitoring and public dissemination of real-time data are crucial for timely interventions.
4. **Urban Greening Initiatives:** Increasing green spaces can help alleviate the impacts of urban heat islands and improve air quality.
5. **Community Engagement:** Public awareness campaigns about the health impacts of air pollution and the significance of cleaner energy sources can foster collective action.

5. Conclusion

This study highlights both the achievements and challenges in improving air quality in Kabul from 1397 to 1403. The sharp reduction in sulfur dioxide levels and significant improvements in AQI demonstrate the positive impact of regulatory measures and targeted interventions. However, recurring issues such as the resurgence of particulate matter in 1403 and the rise in ozone levels after 1400 underscore the need for ongoing efforts to sustain these improvements.

The findings point to a need for comprehensive strategies, including better vehicle and industrial emission standards, cleaner energy access, and urban greening projects to combat particulate pollution. Strengthened monitoring systems and public awareness campaigns will also play a critical role in addressing the gaps. This work not only tracks Kabul's journey toward cleaner air but also provides valuable lessons for other cities facing similar urban pollution challenges, paving the way for sustainable growth and healthier communities.

"While this study provides critical insights into air quality trends in Kabul, certain limitations must be recognized to contextualize the outcomes and guide future research efforts."

6. Limitations

- **Reduction in Monitoring Stations:** The number of active monitoring stations decreased from six (2018–2020) to one (since 2021), significantly limiting spatial coverage and the ability to capture localized air quality variations across Kabul.



- **Low Sampling Frequency:** Air quality data was collected only 3–4 times per month, which may not accurately reflect short-term pollution spikes or capture daily variability in pollutant concentrations.
- **Sampling Duration Variability:** Different pollutants were sampled over varying durations (e.g., 8 hours for ozone, 1 hour for CO, and 24 hours for PM_{2.5}, PM₁₀, SO₂, and NO₂), potentially affecting the comparability of data across pollutants.
- **Data Gaps:** The absence of data for certain years, such as 1400, introduces gaps in the analysis, limiting the ability to track trends or detect anomalies during those periods.
- **Seasonal Generalization:** The alignment of Afghan solar months with Gregorian months provides a broad framework for seasonal analysis but may oversimplify intra-seasonal variations in atmospheric and pollution dynamics.
- **Averaging Effects:** The reliance on monthly and annual averages can mask extreme pollution events or high-pollution days, which are critical for understanding health impacts and informing responsive policy measures.
- **Technological Limitations:** The use of mobile air quality monitoring devices may have inherent limitations in accuracy and consistency compared to more advanced or stationary monitoring systems.

These limitations highlight the importance of reinstating comprehensive, high-frequency air quality monitoring across Kabul and incorporating more granular temporal and spatial data to improve the reliability and scope of future analyses.

References

1. Fischer G, Van Velthuis H (2019) Islamic Republic of Afghanistan: agro-ecological zoning atlas. Climate, Biodiversity, Land and Water Dept. International Inst. for Applied Systems Analysis, Laxenburg (Austria) FAO, Rome (Italy)
2. Afghan FR, Habib H, Akhunzada NA, Wafa W, Shirzad MD, Sahak K, Hashimi SK, Mujeeb M, Wardak K, Ahmadzai MR. Customization of GIS for spatial and temporal analyses of Air Quality Index trends in Kabul city. *Modeling Earth Systems and Environment*. 2022 Nov;8(4):5097–106.
3. Hahad O, Lelieveld J, Al - Kindi S, Schmitt VH, Hobohm L, Keller K, Rösli M, Kuntic M, Daiber A. Burden of disease in Germany attributed to ambient particulate matter pollution: Findings from the Global Burden of Disease Study 2019. *Herz*. 2024 Sep 10;1-9. (1)
4. Kemp, A.C.; Horton, B.P.; Donnelly, J.P.; Mann, M.E.; Vermeer, M.; Rahmstorf, S. Climate related sea - level variations over the past two millennia. *Proc. Natl. Acad. Sci. USA* 2011, 108, 11017 – 11022
5. Bai L, Wang J, Ma X, Lu H. Air pollution forecasts: An overview. *International journal of environmental research and public health*. 2018 Apr; 15(4):780. 3
6. Kemp, A.C.; Horton, B.P.; Donnelly, J.P.; Mann, M.E.; Vermeer, M.; Rahmstorf, S. Climate related sea - level variations over the past two millennia. *Proc. Natl. Acad. Sci. USA* 2011, 108, 11017 – 11022. 4
7. Song, Y.; Qin, S.; Qu, J.; Liu, F. The forecasting research of early warning systems for atmospheric pollutants: A case in Yangtze River Delta region. *Atmos. Environ*. 2015, 118, 58 – 69
8. Kumar, A.; Goyal, P. Forecasting of daily air quality index in Delhi. *Sci. Total Environ*. 2011, 409, 5517 – 5523
9. Wang, J.; Jiang, H.; Zhou, Q.; Wu, J.; Qin, S. China's natural gas production and consumption analysis based on the multicycle Hubbert model and rolling Grey model. *Renew. Sustain. Energy Rev*. 2016, 53, 1149 – 1167.



10. (Waseq WM. The impact of air pollution on human health and environment with mitigation measures to reduce air pollution in Kabul Afghanistan. *Int J Healthc Sci.* 2020;8(1):12.)
11. W. Khpalwak, W. A. Jadoon, S. M. Abdel -dayem, and H. Sakugawa, "Polycyclic aromatic hydrocarbons in urban road dust, Afghanistan: Implications for human health," *Chemosphere*, vol. 218, pp. 517 –526, 2019, doi: 10.1016/j.chemosphere.2018. 11.087.
12. H. Wingfors, L. Hägglund, and R. Magnusson, "Characterization of the sizedistribution of aerosols and particle-bound content of oxygenated PAHs, PAHs, and n-alkanes in urban environments in Afghanistan," *Atmospheric Environment*, vol. 45, no. 26, pp. 4360–4369, 2011, doi: 10.1016/j.atmosenv.2011.05. 049.
13. Jawadullah Jahed, Ping Fang (2023); Impact of air pollution on human health in Kabul City; *International Journal of Scientific and Research Publications (IJSRP)* 13(07) (ISSN: 2250- 3153), DOI: <http://dx.doi.org/10.29322/IJ SRP.13.07.2023.p13929>
14. Torabi SE, Amin M, Phairuang W, Hata M, Furuuchi M. Preliminary discussion about the air pollution status in Afghanistan from Aerosol Optical Depth. *InIOP Conference Series: Earth and Environmental Science* 2023 Jul 1 (Vol. 1199, No. 1, p. 012022). IOP Publishing.
15. SIERRA-VARGAS MP, Teran LM. Air pollution: Impact and prevention. *Respirology*. 2012 Oct;17(7):1031-8.
16. Zaki N. An Overview of Climate Change in Afghanistan: Causes, Consequences, Challenges and Policies.
17. Rautela KS, Goyal MK. Spatio-temporal analysis of extreme air pollution and risk assessment. *J Environ Manage*. 2025;234:105-17.
18. Islam MT, Rahman MM, Habib A. Forecasting energy demand in urban areas: A machine-learning approach. *Qual Quant*. 2024;58:1-15.
19. IQAir. World Air Quality Report 2019. Available from: <https://www.iqair.com>
20. AirVisual I. World air quality report. Region & City PM2. 2018;5.
21. Monks PS, Granier C, Fuzzi S, Stohl A, Williams ML, Akimoto H, Amann M, Baklanov A, Baltensperger U, Bey I, Blake N. Atmospheric composition change–global and regional air quality. *Atmospheric environment*. 2009 Oct 1;43(33):5268-350.
22. Sarker S. Exploring Economic Dynamics and Urbanization in the Context of Environmental Impact: A Study on Capital Flows, Investment Trends, and Urban Growth. *Economics and Applied Informatics*. 2024(3):119-27.
23. Mage D, Ozolins G, Peterson P, Webster A, Orthofer R, Vandeweerd V, Gwynne M. Urban air pollution in megacities of the world. *Atmospheric environment*. 1996 Mar 1;30(5):681-6.
24. Andrade A, D'Oliveira A, De Souza LC, Bastos AC, Dominski FH, Stabile L, Buonanno G. Effects of air pollution on the health of older adults during physical activities: Mapping review. *International Journal of Environmental Research and Public Health*. 2023 Feb 16;20(4):3506.
25. Xia C, Zhang J, Zhao J, Xue F, Li Q, Fang K, Shao Z, Li S, Zhou J. Exploring potential of urban land-use management on carbon emissions—a case of Hangzhou, China. *Ecological Indicators*. 2023 Feb 1;146:109902.