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Air pollution and economic growth in Dubai a fast-growing Middle Eastern city

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ABSTRACT

This paper discusses the impact of rapid economic development on air quality in the Emirate of Dubai, United Arab Emirates (UAE). Dubai is one of the fastest-growing cities in the world, with a population increase of approximately 80× over the last 60 years. The concentrations of five criteria air pollutants (CAPs) including carbon monoxide (CO), nitrogen dioxide (NO_2), particulate matter with diameter less than 10 μm (PM_{10}), ozone (O_3) and sulphur dioxide (SO_2) were studied from 2013 to 2021 at 14 regulatory monitoring stations. Results show that the biggest improvements in air pollution are for the primary air pollutants NO_2 and SO_2, with reductions of 54% and 93% respectively over the period studied. Gross domestic product (GDP), population growth and energy consumption are significantly and negatively correlated with NO_2 and SO_2 and strongly and positively correlated with PM_{10}. CO is positively correlated with the number of buildings completed, while the results for O_3 are inconclusive. Trends in NO_2 and SO_2 indicate that these two pollutants are decoupled from economic development, supporting, with caution, the Environmental Kuznets Curve hypothesis on the relationship between economic growth and environmental degradation. The improvement in the city's air quality is due to the effective implementation of local environmental policies, unaffected by large-scale development and urbanization. The monthly assessments of Dubai's air pollution for 2019 and 2020 show a 3–16% COVID-related improvement in the levels of the studied air pollutants, except for ozone, which increased by an average of 8%.

1. Introduction

Over the past half century, global production and trade have expanded, and living standards have risen in many parts of the world, particularly in Europe and North America, at an unprecedented pace in human history. Despite the benefits, economic development has also brought with it problems, such as air pollution and climate change (Sheehan et al., 2014; Simionescu et al., 2022). Outdoor air pollution is a major global public health issue (Cohen et al., 2017) leading to 4.1 million non-accidental premature deaths in both urban and rural areas worldwide in 2019 (Vos et al., 2020). The harmful effects of air pollution on human health and the environment have been studied in various regions of the world. For instance, a significant amount of research has demonstrated the impact of air pollution on human health in the Middle East, see e.g., (Akasha et al., 2023; Amoatey et al., 2019; Khaniabadi et al., 2017, 2019; Rashidi et al., 2023). This has led to much debate about how to reconcile economic development with environmental well-being, e.g., (Holdren and Ehrlich, 1974; Meadows et al., 1972).

Various air pollution control strategies (policies) have been implemented around the world to reduce environmental degradation while reaping the benefits of a growing economy. As examples of such emission control policies, it can refer to China's new environmental protection regulatory regime (Zhang et al., 2017), European Council Directive 2008/50/EC in Europe (UNION, 2008; Gov, 2015). Despite ambitious findings on their effectiveness ((Castells-Quintana et al., 2021; Zhang et al., 2022)), there are some reports showing smaller than expected changes, for example, see the paper by (Liu et al., 2023) which analysed the impact of the Clean Air Zone (CAZ) in the city of Birmingham, UK.

The relationship between economic development and environmental degradation has often been approached from the perspective of the Environmental Kuznets Curve (EKC) (Kuznets, 1955). According to the EKC hypothesis, economic development contributes positively to environmental degradation until it reaches a threshold, after which the relationship between environmental degradation and economic development becomes negative, as technological progress and improvements in living conditions and incomes help to reduce emissions (Dogan and Inglesi-Lotz, 2020). This means that as economies get richer,

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environmental impacts first worsen but eventually reduce and then improve (Stern, 2018). The EKC has been broadly used in the environmental-energy-economy literature, and many researchers have tried to confirm the inverted U-shape between environmental degradation and income. The EKC has been evaluated in a wide variety of contexts including countries, time periods, variables, methodologies, etc., but no clear consensus has been reached, see the review of (Leal and Marques, 2022).

Over the years, several authors have studied various aspects of the relationship between environmental degradation and economic growth, and Chinese cities have been the subject of a considerable number of these studies (Zhang et al., 2023). Among the published studies, (Ding et al., 2019) examined $PM_{2.5}$ levels in 13 cities in the Beijing-Tianjin-Hebei region, the main economic growth poles in China from 1998 to 2016. The results show a significant inverted U-shaped pattern between economic growth and $PM_{2.5}$ pollution. (Wang et al., 2021) analysed the Government Work Report of 265 prefecture-level Chinese cities from 2004 to 2015 to investigate the correlation between government economic growth expectations and air pollution. The results indicate that when a city's economic growth exceeds 1–4% of growth expectations, there is a corresponding increase of 10–17% and 2–5% in SO_2 and $PM_{2.5}$ concentrations, respectively. (Li et al., 2021) analysed the relationship between regional economic growth and air pollution in key regions of air pollution control in China, namely the Beijing–Tianjin–Hebei region and surrounding areas (BTHS), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD). The study was based on data on GDP and the concentrations of SO_2, PM_{10}, and NO_2 for 31 provinces in China from 2000 to 2019. Results show a strong relationship between the levels of SO_2, PM_{10}, and NO_2 and economic growth, while government policies played a significant role in ameliorating the decoupling between air pollution and economic development. (Acheampong and Opoku, 2023) analysed data from 140 countries and found a linear relationship between GDP per capita and environmental degradation. The results suggest that economic activities and growth contribute significantly to environmental degradation. The inverse effect of air pollution on China's economic growth was studied by (Dong et al., 2021). Results show that the GDP per capita growth rate will decreases by almost 0.06% for every 1% increase in PM2.5 concentration.

However, most of the cited studies have been conducted for Chinese cities, whereby the literature reviewed by (AlKhars et al., 2022) confirms the lack of studies examining the relationship between air quality degradation and economic development in Bahrain, the United Arab Emirates (UAE), Saudi Arabia, Oman, Qatar, and Kuwait. It is important to note that although there have been numerous studies on air pollution and its negative health impacts in the Middle East and North Africa (MENA) region, such as those conducted by (Maleki et al., 2022; Neisi et al., 2017), the correlation between air quality and economic development has not been thoroughly investigated. The study considered most relevant is that of (AlKhars et al., 2022) which reviewed 38 research articles investigating the connections between environmental degradation, including CO_2 emissions, water and soil pollution, and economic development.

The oil market has experienced significant growth over the past four decades, leading to exponential economic development and urbanization in the MENA region (Olimat, 2023; Samiha, 2023; Habibi and Zabardast, 2020). This economic prosperity has been accompanied by a corresponding increase in population (Shokoohi et al., 2022), which raises serious concerns about human exposure to air pollution in the region. According to (Akasha et al., 2023), the Arabian Peninsula and the neighbouring region (APNR) not only experience significant air pollution, of which PM, NO_2 and SO_2 are of particular concern, but are also dramatically affected by climate change-related events such as desert dust.

The cities in the MENA region provide interesting case studies for examining the links between oil-based economic development and air pollution. These studies can be translated and generalized to other cities around the world, with appropriate caveats, especially in cities in Latin America where development has been driven by the discovery of oil.

Dubai, one of the most important cities in the MENA region, will be used as a case study in this paper. Dubai has undergone rapid economic development in the past decade. However, the correlation between economic development and air quality degradation has not been thoroughly analysed. This paper examines the correlation between the levels of air pollutants such as PM_{10}, CO, NO_2, and SO_2 and socio-economic factors, and highlights the main environmental policies related to Dubai and their impact on air quality. Air pollutant concentrations were studied between 2013 and 2021 during a period of significant vertical and horizontal expansion in the city. The selected dates include all publicly available air quality data up to the end of 2021. The emissions inventories for 2015–2019 are also discussed to provide new insights into the contributions of different sectors to Dubai's air pollution.

2. Materials and methods

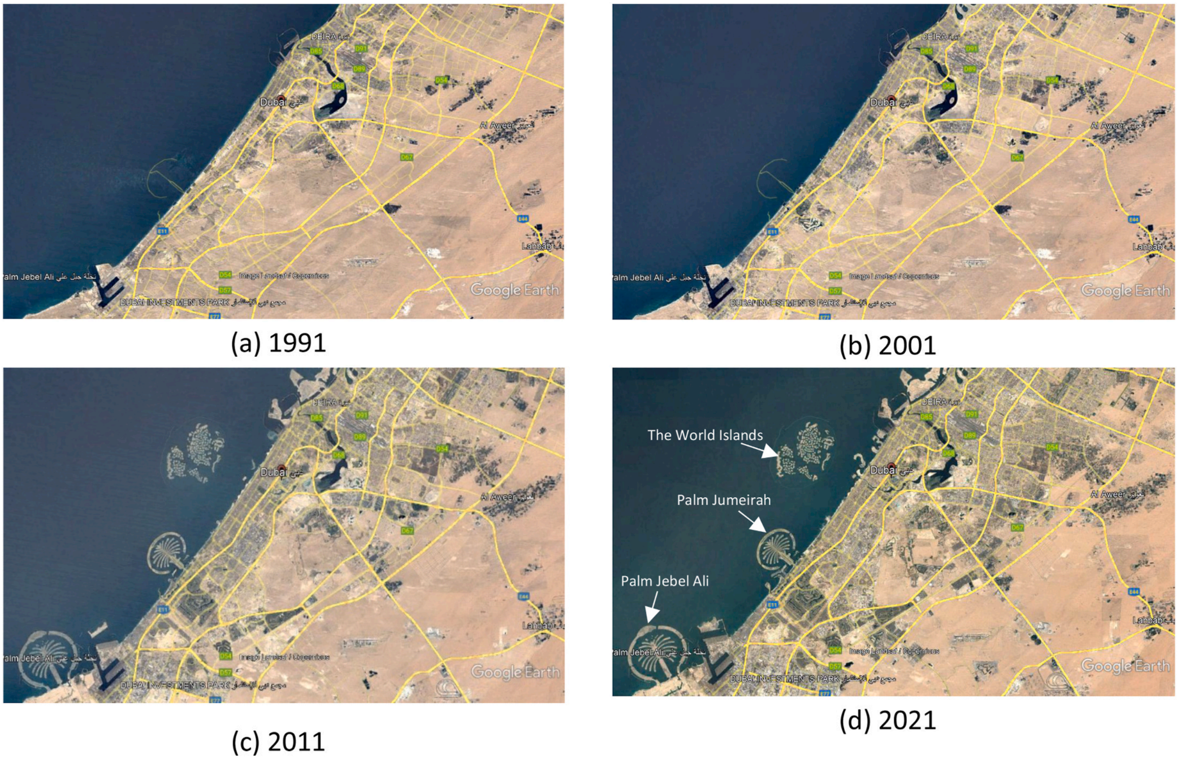
2.1. Study area

The emirate of Dubai is the second-largest emirate in the UAE. It is geographically located in the Middle East (23.5°N 54.5°E), and is one of the fastest-growing urban areas in the world (Nassar et al., 2014). Although it does not fall under the megacity classification in terms of population, with a population of less than 10 million (Warah, 2006), Dubai has been ranked among the World's top megacities for construction in 2019, according to data compiled by (GlobalData, 2019). Over the past 30 years, the landscape has undergone significant changes, influenced by the strategic shift of the economy from oil and gas to real estate, infrastructure construction and tourism (Elhacham and Alpert, 2021). In addition, incentive-based policies have attracted foreign companies that have helped transform Dubai into an international business and financial hub. This has created new employment opportunities, helping to drive population growth. We look at the development indicators and air pollution of the city for the years 2013–2021.

Dubai's population has grown massively, from 40,000 in 1960 to 3.3 million in 2020, an increase of about 80× (Dubai, 2022). In 2021, around 92% of its population were non-Emirati citizens attracted by the job possibilities in Dubai (DSC, 2021c). The male population accounted for 70% of the population in 2021, with the majority holding intermediate degrees to meet demand in the catering, entertainment and construction industries, the two main industries driving Dubai's economic growth (DSC, 2021b).

The urban and built area of the city has grown significantly in the last four decades. In 1975, the urban area was 54 km^2, which increased to 977 km^2 by 2015, an increase of about 18× (Elessawy, 2017; Dubai, 2022). The rapid urban development is dominated by the construction of residential, tourist and industrial facilities (Elgaali et al., 2019). Most strikingly, Dubai has constructed a series of artificial islands along its coast, providing increased opportunities for the construction of waterfront residential areas and tourist facilities. Dubai's development is illustrated in Fig. 1, which shows satellite images of the city from the following years – 1991, 2001, 2011 and 2021. The Landsat images were generated using the Google Earth Pro Engine version 7.3. The figure shows massive construction and significant landscape transformation over the past 3 decades, including on the coastline with the emergence of several artificial islands.

Dubai is meteorologically located in an area of high pressure, where the climate is classified as arid, with significant variations in temperature and humidity (Syed et al., 2019). The climatology of Dubai has been studied by a few previous researchers. For example, (Elhacham and Alpert, 2021) explored the impact of the extreme and rapid coastal urbanization on temperature patterns in Dubai, using surface temperature extracted from MODIS (Moderate Resolution Imaging Spectroradiometer) and OLS (Ordinary Least Square) methods. Their results show



(a) 1991

(b) 2001

(c) 2011

(d) 2021

Fig. 1. Landscape change in the Dubai coastline for the years (a) 1991, (b) 2001, (c) 2011 and (d) 2021. Data was taken from the Google Earth Pro Engine application (https://earth.google.com), and all images were taken on the 31st of December of their respective years.

higher temperatures along the heavily urbanised coastline compared to the adjacent less urbanised areas. (Chowdhury et al., 2016) applied statistical tests, including a bootstrap analysis, to study the variability of various hydroclimatic parameters in the northern regions, including Dubai. Moreover, (Aldababseh and Temimi, 2017) investigated the variability of low visibility events in the UAE and their relationship with climate dynamics indicating a strong relationship between low visibility, and fog and storm events.

2.2. *Dubai air quality policies*

Dubai's environmental policies are taken from the Ministry of Climate Change and Environment (MOCCAE, 2023) and the Official Website. They are presented chronologically in Table 1.

Since 1993, environmental policies have been introduced in Dubai and the UAE as a whole to protect the environment and manage the country's development in an environmentally sustainable manner (MOCCAE, 2022). The chronological order of the main environmental policies in Dubai is shown in Table 1 above. Dubai air quality guidelines were adopted in accordance with Federal Law No. (24) of 1999 for the Protection and Development of the Environment and implemented by Cabinet Decree No. (12) of 2006 for the Regulation Concerning Protection of Air from Pollution. To determine compliance with national standards, the Dubai Air Quality Network continuously measures ambient levels of CAPs and compares them with locally implemented guidelines, which are the maximum allowable levels for a particular pollutant, as shown in Table 2. The WHO classification and threshold values for CAPs are also shown in Table 3. CAPs are those identified as posing a serious threat to human health and the environment. Similar to many other regulatory regimes, Dubai's monitoring guidelines are higher than the WHO guidelines for all pollutants (WHO, 2021). Dubai's air quality standards (AQS) do not include limit values for $PM_{2.5}$. The Dubai AQS guideline includes some air pollution exposure limits that are not available in the WHO guidelines, such as 1-h and 8-h limits for CO and hourly limits for O_3, NO_2 and SO_2.

In response to the analysis of the current air quality situation of the

Table 1
Chronological timeline of dubai air quality-related policies.

Year	Environmental Policy	Type
1993	Federal law No. 7 Establishment of the Federal Environment Agency	Law
1999	Federal law No. 24 of 1999 for the Protection and Development of the Environment	Law
2006	Cabinet Decree No. (12) Regulation Concerning Protection of Air from Pollution	Law
2018	UAE National Agenda Towards 2021-Improve Air Quality Index	Agenda
2021	The United Arab Emirates General Environmental Policy	Policy
2022	The National Air Quality Agenda 2031	Agenda

Table 2
Air quality standards (AQS) for dubai (MOCCAE, 2020). WHO air quality guidelines (AQG) in 2005 and 2021.

Criteria air pollutants (CAPs)	Averaging Time	Unit	Duba AQS 2020	WHO AQG 2005	WHO AQG 2021
PM_{10}	Annual	µg/m^3		20	15
	1 day (24 h)		150	50	45
$PM_{2.5}$	Annual	µg/m^3	NA	10	5
	1 day (24 h)		NA	25	15
CO	1 h	mg/m^3	30	–	–
	8 h		10	–	–
	1 day (24 h)		–	–	4
O_3	1 h	µg/m^3	200		
	8 h		120	100	100
NO_2	Annual	µg/m^3		40	10
	24-h		150	–	25
	1-h		400	–	–
SO_2	Annual	µg/m^3	60		
	24-h		150	20	40
	1-h		350		

Table 3
List of Dubai air quality stations, type, and summary of data availability (showing dates where data is missing). Q4 refers to Quarter 4 (October to December).

Station Name	Subset/type	PM_{10}	NO_2	SO_2	O_3	CO
Deira	Residential	2013–2016	Q4* 2013, 2014	Q4* 2013 & 2014	2014	2014
Karama	Residential	2015	Q4* 2013		2013–2015	
Jabel Ali Port	Industrial	2017–2021	Q4* 2013, 2016, 2019		2013–2014 2020–2021	2016, 2019,2020
Mushrif	Remote	2013–2016	Q4* 2013			2014–2015
Zabeel Park	Residential	2013–2016	Q4* 2013	Q4* 2013 and 2014	2013–2015	
Warsan	Industrial	2013–2021	Q4* 2013	2013–2015		2013–2015
Emirates Hills	Residential		Q4* 2013	2014		Q4* 2013
Jebel Ali Village	Residential	2013–2016	Q4* 2013	2014		
Dubai Airport	Industrial	2013–2015	Q4* 2013	2014	2013–2015	
Hatta	Remote	2017–2021	Q4* 2013			
Sheikh Zayed Road (SZR)	Traffic		Q4* 2013	2013–2015	2013–2015	
Shk. Mohd. Bin Zayed Road (SMBZ)	Traffic		Q4* 2013	2013–2014	2013–2015	
Dubai Investment Park *(DIP)*	Residential	2013–2018	2013–2018	2013–2018	2013–2018	2013–2018
Al Qusais	Residential	2013–2018	2013–2018	2013–2018	2013–2018	2013–2018

UAE and in an attempt to adhere to international standards, the Ministry of Climate Change and Environment (MOCCAE) published the latest strategy “The National Air Quality Agenda 2031” in 2022, which is a general framework introduced to manage air quality and reduce air pollution (MOCCAE, 2022). The agenda is built on three main pillars: monitoring, mitigation and management. The agenda has identified projects to improve air quality from traffic, electricity, waste generation and construction activities.

2.3. Socio-economic data

To study the socio-economic trends in Dubai, annual data are extracted from the Dubai Statistic Centre (DSC, 2023) and the Open Data Platform (Bayanat, 2023) for four metrics as indicators of Dubai’s urban and economic development: population growth, energy consumption, number of buildings completed, and GDP growth. The metrics are identified by the World Bank as world development indicators (The World Bank, 2022).

The DSC adopts a general framework of the Charter of Quality of Statistical Data to cover various aspects of data collection, processing, and dissemination, following international recommendations and best practices in the field of quality control of statistical data. The data available on the websites of the DSC and Bayanat are open to the public for free access and download, according to the General Model of the Charter of Quality Assurance element “Ensuring data accessibility”. It should be noted that the authors of this paper did not contribute to the data collection procedures, quality assurance and quality control (QA/QC) at the network level.

2.4. Air quality data, limitations, and analysis methods

Research has shown that ground-level ozone (O_3), fine particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$), and nitrogen dioxide (NO_2) are the most harmful urban air pollutants in terms of human health effects, see e.g., (Cakaj et al., 2023; Sicard et al., 2023). Additionally, the level of sulphur dioxide (SO_2) has been found to strongly correlate with industrial activities in the studied region (Hosseiniebalam and Ghaffarpasand, 2015). Meanwhile, the most published papers that study the links between air pollution and economic growth such as (Acheampong and Opoku, 2023; Li et al., 2021; Wang et al., 2021) investigated the level of SO_2 for the studied period. On the other hand, there is a close relationship between the activity of the natural emission sources in the study area and the level of PM_{10}, as shown in (Ghaffarpasand et al., 2020a). This study aimed to identify potential correlations between air pollution in Dubai and economic development over the past decade by analysing the variations of PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO and O_3.

Monthly concentrations of the criteria air pollutants are downloaded from the Dubai Statistic Centre (DSC, 2023) and the Open Data Platform (Bayanat, 2023). The data is collected from the 14 air quality monitoring stations spread across the emirate. They are classified by the competent authorities according to the type of location, into four categories: residential, industrial, traffic and remote. Fig. 2 shows the location of Dubai’s air quality monitoring stations. In addition to the 13 stationary monitoring stations, there is a remote ‘Hatta’ station located 135 km east of the centre of Dubai. The list of stations, names, types, and summary of data availability is shown in Table 2.

As is common with air quality networks in developing countries, there are limitations in terms of the availability of air pollution data. The monitoring of certain air pollutants has not been consistent across all stations in Dubai, resulting in data gaps. Although data availability has improved in recent years, there are still some serious limitations. Air quality data are more consistent from 2017 onwards, with most missing data found in the earlier years of the study period. NO2 data were consistently missing for all stations in the last quarter of 2013. In 2019, two new stations, DIP and Al Qusais, were added to the air quality monitoring network to monitor air quality in newly developed residential areas.

Although 10-year time-series of data is usually considered long enough to assess short-term changes, see e.g., (Sicard et al., 2020; Khaniabadi and Sicard, 2021), the current database covers only the period from 2013 to 2021 and has not yet been updated. On the other hand, machine learning techniques are used to exclude the impact of weather conditions and parameterise the role of planned or unplanned interventions, e.g., (Calatayud et al., 2023; Ghaffarpasand et al., 2024). High-resolution data is necessary for machine learning algorithms, but it is not publicly available in Dubai. $PM_{2.5}$ data is only available for the years 2013 and 2014 and has therefore been excluded from the analysis.

From the regulatory data, two averaged sets of data are calculated. Firstly, monthly average concentrations for pollutants across all stations are calculated to understand the overall trend in Dubai, across the study period for each pollutant. Hatta is excluded from the overall trend as it falls outside the inhabited part of Dubai. Secondly, the monthly average concentrations for pollutants, subset by station type, are calculated, to evaluate the source-specific influence on Dubai air quality. The analysis of the air quality data was carried out using the Openair package, developed by (Carslaw and Ropkins, 2023). The trends in the air pollution level are estimated by Theil-Sen method which tends to yield accurate confidence intervals even with non-normal data and heteroscedasticity (non-constant error variance).

The analysis of how development affects air pollution involved splitting the research timeline into two distinct periods: one before 2017 (spanning from 2013 to 2016) and one after 2017 (from 2017 to 2021). This division was chosen to assess how significant development activities up to the conclusion of 2016 influenced the local air quality by comparing the changes in air pollution rates between these two designated time frames. The annual rate of air pollution was calculated using

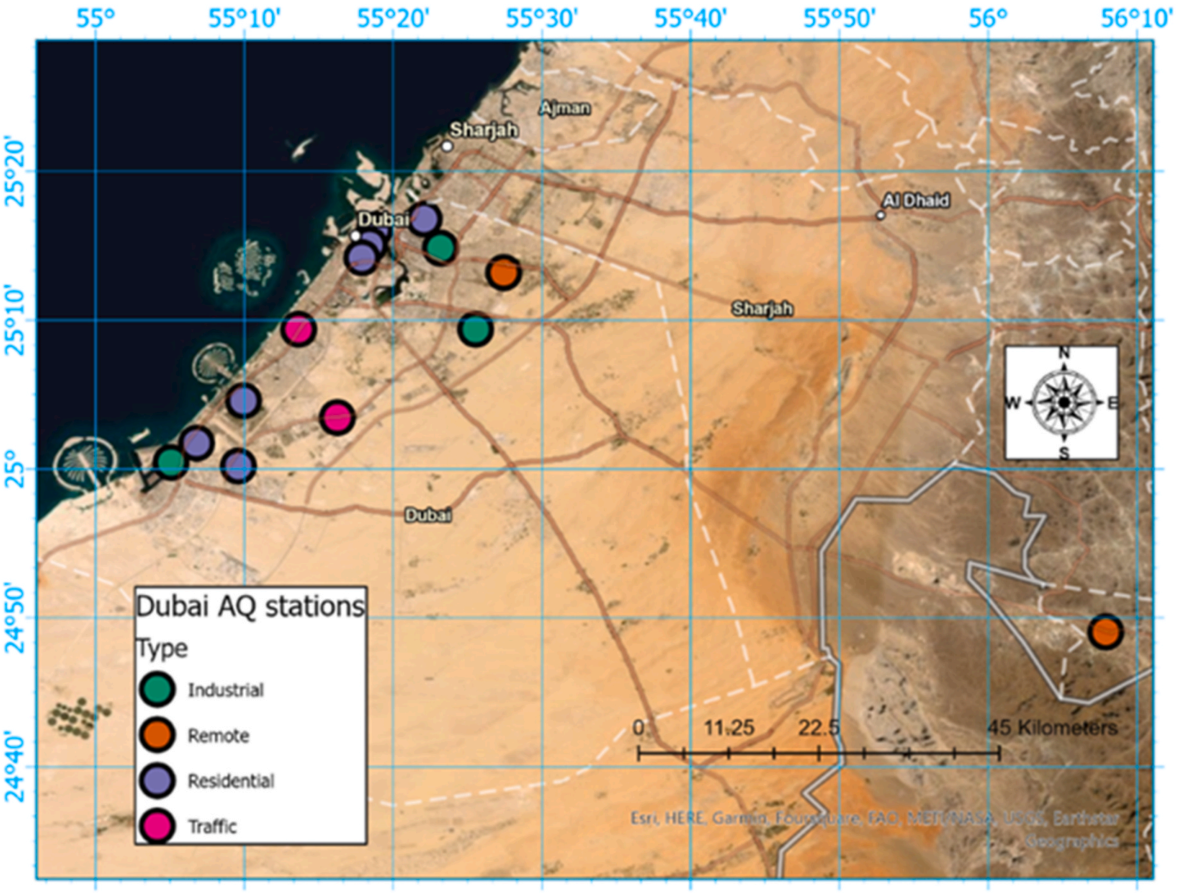


Fig. 2. Locations and designations of air quality monitoring stations in Dubai.

the Theil-Sen estimator function in the Openair package.

2.5. *The impact of the COVID-19 pandemic on dubai air pollution*

The period from 2013 to 2021 includes the COVID-19 pandemic period of 2019–2020, during which air pollution and human activities were significantly affected. Many studies have analysed the impact of the pandemic on air pollution. However, there has been a rigorous debate on the methods used, particularly on the role of weather conditions on air pollution (Singh et al., 2022). It has been argued that weather conditions should be excluded from time series of air pollutant concentrations by using machine-learning techniques to achieve a reliable and trustworthy assessment (Ghaffarpasand et al., 2024). However, these techniques require hourly air quality data, which, as noted before, has not been made accessible to the public in Dubai. This study aims to estimate the relative difference in monthly air pollutant concentration levels between 2019 and 2020, both as business as usual and during the COVID-19 pandemic, in order to provide insights into the impact of the pandemic on air quality in Dubai. The results were then compared with studies that used almost the same approach.

3. Results and discussion

3.1. *Dubai's development dimensions for 2013–2021*

3.1.1. *Population*

Changes in the population of Dubai between 2013 and 2021 are shown in Fig. 3 and Table 4. The population of Dubai increased by almost 54% between 2013 and 2021. The male population grew by 50% while the female population grew by 65%. Between 2013 and 2014, the female population shows the highest growth rate, which slows down to 4% the following year, then increases again between 2015 and 2019, and drops significantly between 2019 and 2020, reaching its lowest level at 2.4%. Male population growth rates are slightly different, starting low at the beginning of the study period, then gradually increasing to peak at 10.9% between 2015 and 2016, then gradually decreasing after 2017, reaching its lowest point at 1.3% between 2019 and 2020. The Covid-19 pandemic is the likely cause of the reduced growth between 2019 and 2020. Population growth for both males and females reflects a small recovery between 2020 and 2021. The peak in the male population

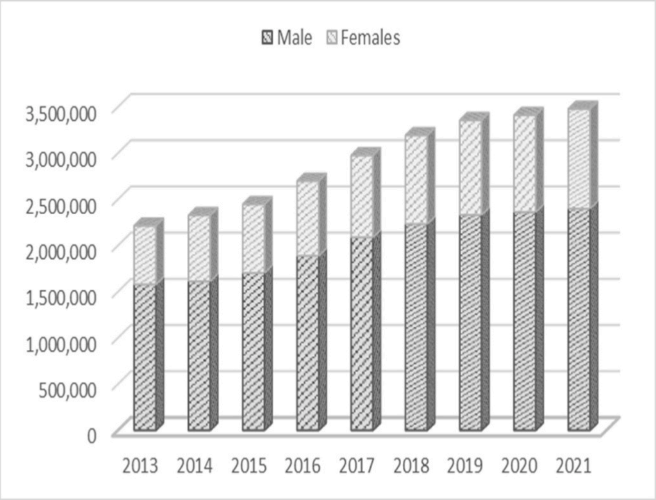


Fig. 3. Dubai population 2013–2021 (*DSC, 2021c*).

Table 4
Population growth (%) in Dubai 2013–2021.

Year	% growth male population	% growth female population	% growth total population
2013			
2014	2.2	13	5.1
2015	5.6	4.1	5.1
2016	11	9.0	10
2017	11	9.6	10
2018	6.9	8.0	7.3
2019	4.4	6.8	5.1
2020	1.3	2.4	1.6
2021	1.6	2.8	2.0
Overall growth	50	65	54

between 2015 and 2016 can be attributed to the demand for foreign workers to support the construction boom in Dubai.

3.1.2. *Urbanization, development, and energy consumption in dubai*

The number of buildings completed each year is shown in Fig. 4(a), which includes private villas, investment villas, industrial buildings, public commercial buildings and multi-storey buildings (Dsc, 2013–2021). The most significant observation is the marked increase in the number of buildings completed between 2015 and 2016, which represents a 78% increase from the previous year. This construction boom explains the spike in male population growth between 2015 and 2016, as developers pushed their projects towards completion deadlines in 2016. Dubai's energy consumption is shown in Fig. 4(b). Energy consumption has consistently increased throughout the study period, with the exception of 2020. The impact of Covid-19 on Dubai's energy consumption can be seen in the reduction in 2020. This is due to reduced industrial activity during the pandemic.

3.1.3. *GDP and economic development*

Gross Domestic Product (GDP) growth, financial development and energy consumption are linked to industrialization and urbanization and can lead to an increase in the level of harmful emissions and contribute negatively to environmental performance (Wang et al., 2020). Despite efforts to shift away from GDP as a measure of a nation's prosperity and success, GDP is still commonly used as a metric of economic growth and monetary wealth of economies/nations (Costanza et al., 2014). The percentage growth in Dubai's GDP is shown in Fig. 5. Significant growth in GDP in 2016 is consistent with growth in population, energy consumption and construction. GDP growth is driven by growth in arts and entertainment (12%), electricity gas and water supply (9%), information and communication (8%) and real estate activity (8%) (DSC, 2021a). The significant drop in GDP in 2020 is most likely a reflection of the impact of Covid-19 on the economic growth in Dubai, like many regions around the world.

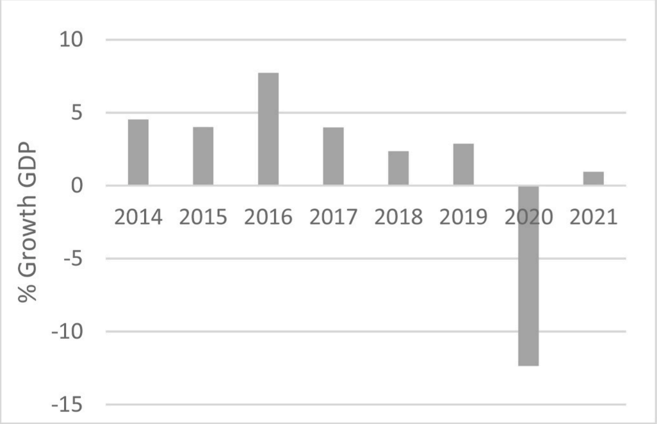


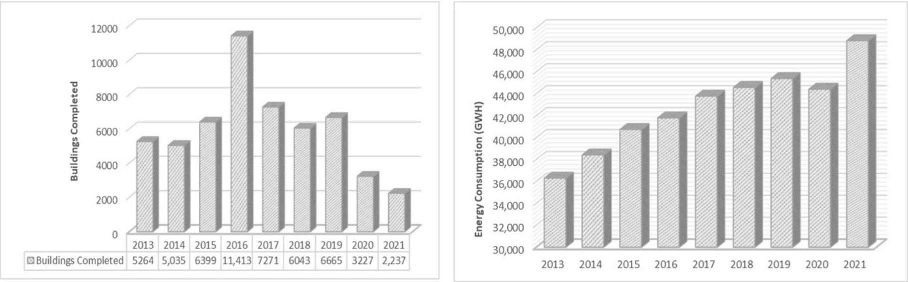
Fig. 5. GDP growth (%) in Dubai city from 2013 to 2021, GDP is expressed in current prices National Accounts, see www.dsc.gov.ae.

3.2. *Dubai air quality for 2013–2021*

The time series of monthly concentrations of the studied air pollutants are shown in Fig. 6, both as an average of all available station data, and as a subset by station type (residential, industrial, traffic, or remote). The monthly data averaged over all years (2013–2021), from all available air quality stations, are shown in Fig. 7. The summary of the average air quality data for Dubai 2013–2021 is presented in Table 5. Regression plots of the rate of change of air pollution before and after 2017 are presented in Fig. 8. A summary of the rate of change of different pollutants throughout the study period (2013–2021), before 2017 (2013–2016) and after 2017 (2017–2021) is shown in Table 6.

Fig. 6(a) shows an increasing trend in the PM_{10} level over the study period. A significant increase in PM_{10} levels is observed for the years 2013–2017, which flattens out after 2017. The PM_{10} concentration increased at an overall rate of 4.38 μg/m^3/year. From 2017 to 2021 there is a high consistency between the measurements at different station types, whereas before 2017, the variation is greater. After 2017, data were no longer available for stations in industrial areas, but the remaining station types show a similar trend. The peak in total monthly average PM_{10} in 2016 reflects the peak in PM_{10} in residential areas, while the peak in 2017 reflects the PM_{10} peak in traffic locations (Fig. 6(b)). The trends in the areas monitored by the remote station do not show much difference from the urban monitoring sources. The highest monthly average concentration of PM_{10} is found in residential areas with 107 μg/m^3, followed by remote, traffic and industrial areas with 103, 98 and 92 μg/m^3, respectively. Fig. 6(a) shows that PM_{10} has a clear seasonality, with PM_{10} concentrations decreasing in winter (minima in December/January) and increasing in summer (peak in July).

Desert dust has a dramatic effect on the levels of PM_{10} in cities that



(a) (b)

Fig. 4. (a) Number of buildings completed and (b) energy consumption (GWh) including residential, industrial, and commercial type consumption in Dubai 2013–2021.

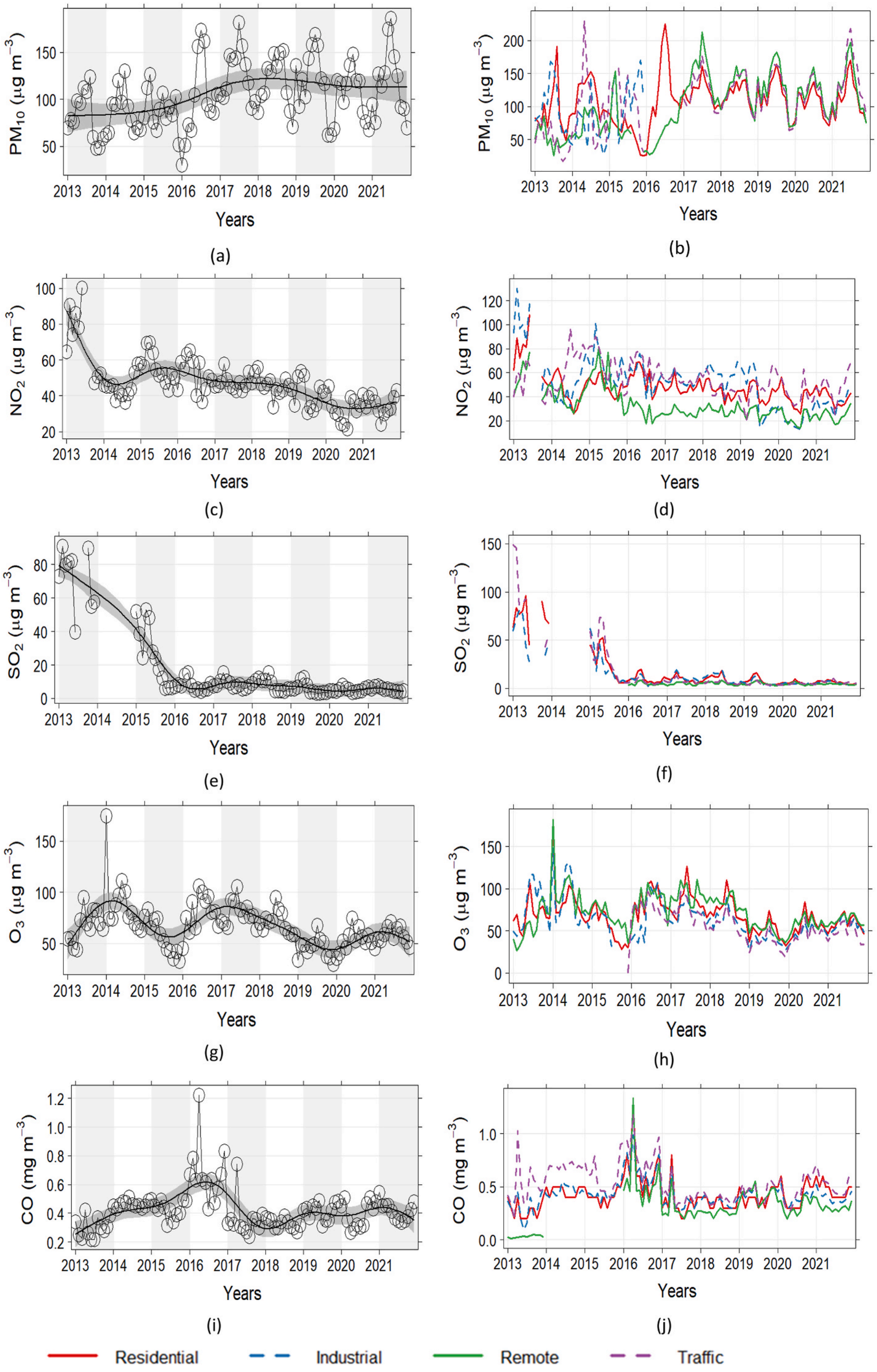
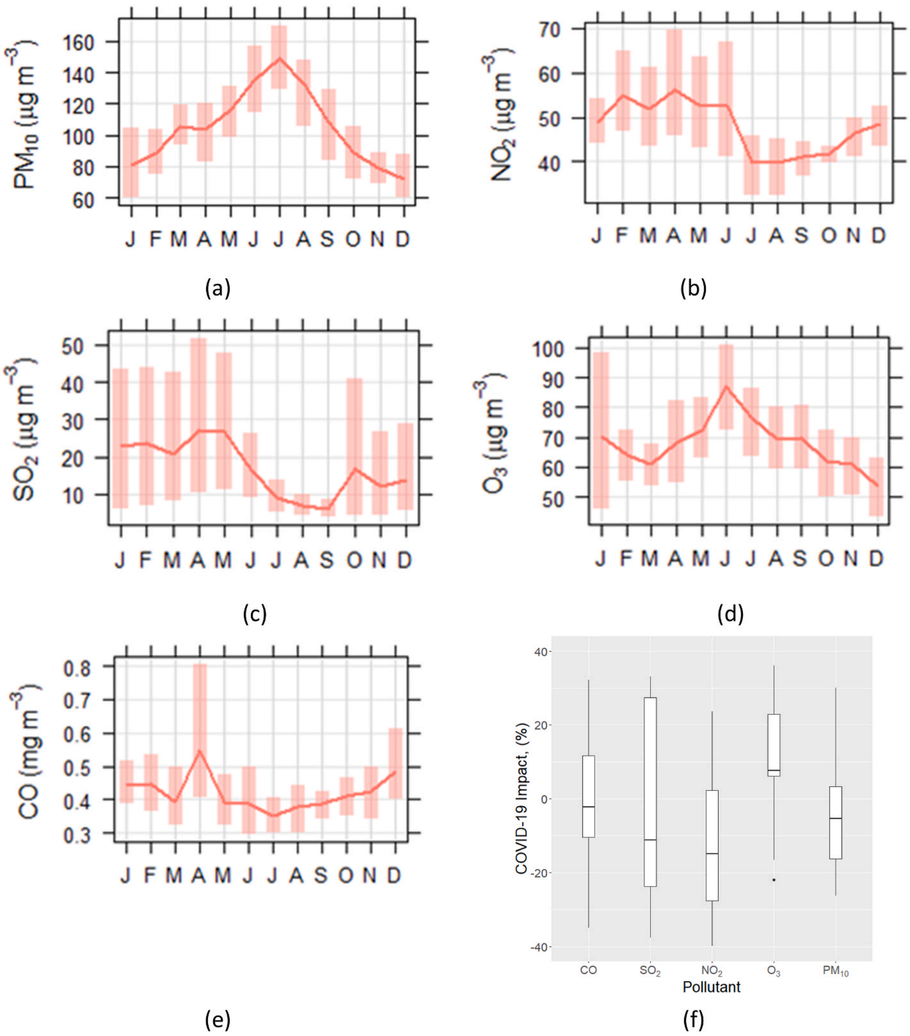


Fig. 6. Monthly variation over all stations and time trend of (a) & (b) PM$_{10}$, (c) & (d) NO$_2$, (e) & (f) SO$_2$, (g) & (h) O$_3$, and (i) & (j) CO for 2013–2021, respectively.

are close to or located in deserts. Two of the stations examined here fall into the remote station category, namely Mushrif Station and Hatta Station (the remote station near the border of the emirate shown in Fig. 5). PM$_{10}$ data for Hatta station are only available for 2013–2015, while data for Mushrif station are available from 2017. Fig. 6(b) shows the PM$_{10}$ peak in remote stations in early 2014, which is a reflection of dust-generated PM$_{10}$ measured at a remotely located Hatta station. Given its distant location, availability and analysis of long-term data at Hatta station would have been beneficial to differentiate between desert-generated PM$_{10}$ and anthropogenic dust generated at urban and traffic locations. The existing PM$_{10}$ concentration profile makes it challenging to distinguish the contribution of PM$_{10}$ concentrations from anthropogenic and natural sources.

The PM$_{2.5}$/PM$_{10}$ ratio is an almost reliable proxy that has been used by previous researchers to discuss the contribution of anthropogenic and natural emission sources to ambient particulate matter. (Abuelgasim and Farahat, 2020) studied the PM$_{2.5}$/PM$_{10}$ ratios in Abu Dhabi (120 km away from Dubai) and found that the majority of the airborne pollutants are primarily produced by natural processes. However, as mentioned above, PM$_{2.5}$ data for Dubai were only available for two years, 2013 and 2014, so the PM$_{2.5}$ analysis was excluded from the current study.

PM$_{10}$ data from Mushrif station is particularly interesting, it is currently classified as a remote station. Mushrif station is located in Mushrif National Park, a 5.25 km^2 land rich with wildlife and greenery.



(a) (b) (c) (d) (e) (f)

Fig. 7. Average monthly variation of (a) PM$_{10}$, (b) NO$_2$, (c) SO$_2$, (d) O$_3$, and CO concentration at 99% ($p = 0.001$) confidence interval in mean; (f) the impact of COVID-19 pandemic on the Dubai air pollution, see section 2.5 for more information on the method.

Table 5
Summary of air quality data for Dubai 2013–2021.

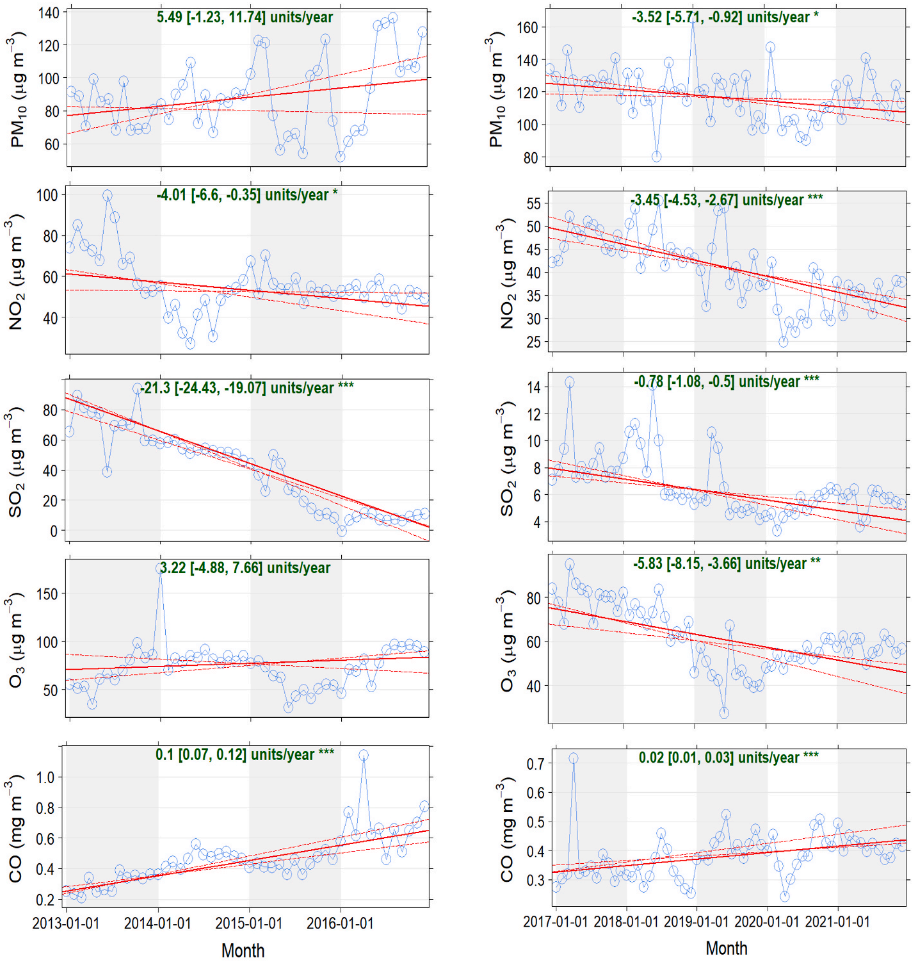
Pollutant Concentration	Total Average[a]	Max	Min	Residential	Industrial	Traffic	Remote
PM$_{10}$ (µg/m3)	104	230	26.0	107	91.8	98.6	103
NO$_2$ (µg/m3)	48.2	130	13.0	49.0	53.4	55.3	34.3
SO$_2$ (µg/m3)	17.2	149	2.20	18.3	15.2	17.9	4.70
O$_3$ (µg/m3)	68.0	182	18.7	70.2	65.1	56.7	73.6
CO (mg/m3)	0.42	1.34	0.01	0.42	0.43	0.54	0.31

[a] Total Average: Annual average concentration of all air quality stations.

Prior to the large construction boost around the location, which involved the development of multiple residential areas and a large shopping mall, Mushrif was considered a remote location in the Emirate. It might be more accurate now to re-categorize Mushrif station as a residential station. Having more consistent data for Mushrif station prior to 2016 would have been useful in highlighting the impact of urbanization on air quality.

Fig. 6(c) shows significant improvement in the NO$_2$ concentration from 2013 to 2021. A rapid reduction in NO$_2$ occurred between 2013 and 2014, while a much lower and gradual reduction occurred between 2015 and 2021. NO$_2$ reduced at an overall rate of -3.21 µg/m^3/year, equivalent to 54% total concentration reduction. Table 5 shows that NO$_2$ concentration was 30–38% lower in remote locations than concentrations at the other site types, most likely due to reduced traffic movement in remote areas. Fig. 6(d) shows that, in residential and industrial areas, NO$_2$ concentration was the highest in 2013, at the beginning of the study period, then dropped afterwards, following a period of missing data during the final quarter of 2013. NO$_2$ at traffic locations peaked in 2014, dropping again in consecutive years.

The most NO$_2$ exceedances worldwide occur in urban areas, especially in city centres with vehicle fleets with a high proportion of diesel cars (Degraeuwe et al., 2017). Therefore, the traffic stations would have recorded much higher NO$_2$ concentrations, especially the monitoring stations near the two main motorways in Dubai: Sheikh Zayed Road and Mohammad bin Rashid Road. However, Dubai is a small and congested emirate, with most residential, industrial and traffic areas in close proximal distance to one another. This explains the similarity in the concentrations of NO$_2$ in residential, industrial and traffic sites with



(a) before 2017 (b) after 2017

Fig. 8. The rate of change of air pollution (units/year) (a) before 2017 (b) after 2017. The symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: $p < 0.001 = * * *$, $p < 0.01 = **$, $p < 0.05 = *$. The TheilSen function $p < 0.1 = +$. The values between brackets are the 95 % confidence intervals in the slope which is represented by the dashed lines.

Table 6
Rate of change of air pollution for the whole study period, before 2017 and after 2017.

Pollutant (Units)	Rate of Change (Units per year)*	p	Rate of Change (Units per year)*	p	Rate of Change (Units per year)**	p
	2013–2021		Before 2017		After 2017	
PM_{10} (µg/m3)	4.38	0.001	5.49	0.100	−3.52	0.050
NO_2 (µg/m3)	−3.21	0.001	−4.01	0.050	−3.45	0.001
SO_2 (µg/m3)	−4.5	0.001	−21.3	0.001	−0.78	0.001
O_3 (µg/m3)	−2.89	0.001	3.22	0.100	−5.83	0.050
CO (mg/m3)	0.00	0.000	0.10	0.001	0.02	0.001

average means of 49, 53, and 55 µg/m^3, respectively. The significant reduction in NO_2 concentrations at residential, industrial and traffic locations also demonstrates the effectiveness of environmental policies in reducing NO_2 concentrations over the period studied here.

Fig. 7(b) shows a seasonal trend in the monthly variation of NO_2 concentrations. The concentration of NO_2 is lowest in the summer season. This may be due to reduced traffic movement during the summer months as residents travel to cooler destinations, either for tourism or to visit their home countries. This could be particularly significant in Dubai, where non-Emirati residents accounted for 92% of the total Dubai population (DSC, 2021c). In addition, Dubai has developed a strong brand globally attracting tourists from around the world (Anthonisz and Mason, 2019), particularly between September and March (U.S, 2022), which is reflected in the higher NO_2 concentrations in the winter.

Figs. 7(e) and 6(f) show the trends in SO_2 concentrations. Initially, data availability was poor in 2013 and non-existent in 2014. Overall, the concentration of SO_2 reduced at a rate of −6.5 µg/m^3/year from 2013 to 2021, equivalent to a 92% total concentration reduction. The reductions in SO_2 are the largest observed for any of the monitored air pollutants, particularly, a sharp drop in SO_2 concentrations is observed between 2013 and 2016. The values reached by the end of 2016 (average 6 µg/m^3) are maintained for consecutive years. This reduction demonstrates the effectiveness of the environmental policy in controlling SO_2 pollution. The highest SO_2 concentrations are observed in 2013, reaching an average of 92 µg/m^3 in February 2013, which is still lower than the daily local allowable limit of 150 µg/m^3, but higher than the annual limit of 60 µg/m^3.

The average SO_2 concentration, over the whole study period, for residential, industrial, traffic and remote areas is 18.3, 15.2, 17.9 and 4.7 µg/m^3, respectively. It is surprising that lower concentrations of the pollutant are observed in the industrial area than in the residential and traffic areas. This may require a more detailed air pollution dispersion analysis of SO_2 to reflect its dispersion from the source of generation and to evaluate the locations affected by industrial air pollution. Residential areas such as Emirates Hills, al Farjan and Deira are located close to Jebel Ali and Dubai Airport industrial areas and have the highest SO_2 concentration compared to other more distant residential areas. Remote stations show the lowest concentration of SO_2, which is expected as pollution exposure decreases with distance from the source. The maximum monthly concentration reached 149 μg/m^3 and was observed at an industrial site in 2013. The monthly variation of SO_2 in Fig. 7(c) shows that the pollutant concentrations are seasonal, being lowest in the summer season and highest from January to May. SO_2 and NO_2 concentrations show similar seasonal trends that can be attributed to the decrease in traffic density and industrial emissions during the summer holidays. The same was previously observed in the study by (Alejo et al., 2013).

Table 6 shows that the annual average concentration of O_3 decreased at an overall rate of −2.89 μg/m^3/year from 2013 to 2021, but with large oscillations within the time series. O_3 is a secondary pollutant that is typically regional, its production is a function of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) concentration, temperature and sunlight (Taheri et al., 2022). Although the results in Table 6 may give a positive picture, given the nature of tropospheric ozone production, a real evaluation of the O_3 reduction mandates a deeper analysis of the changes in NO_x and VOCs concentrations (National Research Council, 1991). Average concentrations of the pollutant for residential, industrial, traffic and remote are 70, 65, 57 and 74 μg/m^3, respectively, showing the highest value at remote locations. The maximum concentration of 182 μg/m^3 was observed in January 2014 at the remote location, see Fig. 7(h). As the peak in 2014 is observed in all areas studied, it cannot be attributed to measurement errors at the monitoring stations. A similar spike in PM_{10} concentrations, a pollutant recognized for its regional influence, is also observed during this period. O_3 is a secondary pollutant, and its formation is linked to sunlight and temperature, hence, trends in O_3 are expected to be seasonal as observed in Fig. 7(d), with O_3 peaking in summer and decreasing in winter.

The concentration of CO appears to fluctuate between 0.2 and 0.6 mg/m^3 with a mean annual value of 0.42 mg/m^3. The overall rate of change in CO was negligible (almost zero). Throughout the study period, the concentration of CO was maintained at less the 1 mg/m^3, except for one exceedance in 2016 at the Mushrif remote location. Nevertheless, the monthly concentration of CO is significantly lower than the daily local and WHO allowable limits for ambient pollutants. Therefore, there is no real public health concern with regard to CO concentrations. The mean values for residential, industrial, traffic and remote locations are 0.42, 0.43, 0.54, and 0.31 mg/m^3, respectively. Since CO is mainly generated from burning fossil fuels, remote stations are expected, contrary to findings, to produce a much lower concentration than other locations. This is possibly due to the development of the Mushrif area, which is mirrored in the peak in remote location concentration in 2016. The peak in CO concentration in 2016 can be attributed to the construction boom, as marked by the peak in the number of buildings completed in that year, see Fig. 4(a). The overall trend in air pollution (see Fig. 6) shows almost a turning point around 2017, so we split the data into two periods to analyse Dubai's air pollution trends before and after 2017. We examine the rate of change through trend analysis of the pollutants studied. It is calculated using the Theilsen function in the open-air package (see section 2.4), which is a useful function in determining air pollution trends over several years. It should be noted that the data has been de-seasonalized to eliminate the seasonal cycle in the trends.

As can be seen from Fig. 8 and Table 6, there are different variations in the trends for the different pollutants. The rate of PM_{10} and O_3 pollution increased at 5.49 μg/m^3/year and 3.22 μg/m^3/year, respectively, before 2017, while it decreased after 2017 at a rate of −3.52 μg/m^3/year and −5.83 μg/m^3/year, respectively. The rate of NO_2 pollution decreased at a similar rate of −4.01 and −3.45 μg/m^3/year, with a slightly lower rate after 2017. The largest difference between the two split periods is for SO_2 pollution rate. Before 2017, the rate of pollution sharply decreased at a rate of −21.3 μg/m^3/year, whereas after 2017, much smaller reductions in SO_2 pollution took place at a rate of −0.78 μg/m^3/year. The largest improvement in air quality in the emirate is reflected in SO_2 pollution reductions. CO pollution increased at a rate of 0.1 mg/m^3/year before 2017, while reduced to 0.02 mg/m^3/year after 2017. During the study period, Dubai witnessed the greatest rate of development concerning buildings completed between 2013 and 2016 which might have contributed to the variation between the two split periods.

The Environmental Kuznets Curve (EKC) hypothesis, which suggests that economic development degrades the environment until it reaches a threshold (Dogan and Inglesi-Lotz, 2020), can be observed in Fig. 8. However, it is important to treat this hypothesis here with caution. Looking at the trends for PM_{10}, NO_2, and O_3 for the periods studied before and after 2017, a partial turning point can be observed. Specifically, all pollutants studied, except CO, show a decreasing trend after 2017. Although the evidence partially supports the EKC hypothesis, assessing its certainty in Dubai requires a longer period of analysis than is currently available. This can be seen as one of the future research directions resulting from this current study.

(Sicard et al., 2023) assessed the trends in concentration exposure of global urban populations to O_3 and NO_2 (and $PM_{2.5}$ which is not in the scope of the current study) between 2000 and 2019 in over 13,000 urban areas. Results show that mean annual NO_2 concentrations increased in 71% of cities worldwide (on average + 0.4 % per year), with improvements in North America and Europe and increases in exposure in sub-Saharan Africa, the Middle East, and South Asia. Global exposure of urban populations to O_3 also increased by an average of +0.8% per year in 89% of the stations studied. The current study shows an almost similar variation in ozone levels, while NO_2 levels in Dubai improved with an average of 6.75% per year, which is higher than the average of the other urban areas studied by (Sicard et al., 2023).

Fig. 7(f) illustrates the impact of the COVID-19 pandemic on air pollution in Dubai. The box plots display the monthly variations of air pollutant levels for 2019–2020. On average, COVID-19 reduced the concentration levels of CO, SO_2, NO_2, and PM_{10} by 3–16%, while increasing the level of ozone by nearly 8%. This trend variation has been observed in most published studies that evaluated the impact of COVID-19 on air pollution, e.g., (Ghaffarpasand et al., 2024). As previously mentioned, numerous studies have investigated the correlation between COVID-19 and air pollution using various methods. (Broomandi et al., 2020) conducted a study in Tehran, the capital of Iran, located in the Middle East, using the same methodology as this study. Their findings indicate that the COVID-19 pandemic led to a reduction in the concentrations of SO_2, NO_2, CO, and PM_{10} by 5–28%, 1–33%, 5–41%, and 1.4–30%, respectively. (Rashidi et al., 2023) used also the same method for the city of Khoramabad and found an 8% increase in the ground-level ozone.

3.3. The influences of socio-economic factors and environmental policy on air pollution

Pearson correlation coefficients between the socio-economic factors, including urban population growth, urban GDP, energy consumption and the number of buildings completed, and the concentration of air pollutants studied here are reported in Table 7, to deepen the insights into the relationship between economic development and air pollution.

The concentrations of NO_2 and SO_2 show a significant negative correlation with population, GDP and energy consumption, indicating that the two pollutants are decoupled from development metrics. On the other hand, PM_{10} concentration shows a significant positive correlation with population, GDP and energy consumption. CO shows a significant

Table 7
The correlation between socio-economic metrics and CAPs. (r values with $p = 0.05$).

	PM_{10}	NO_2	SO_2	CO	O_3
Population	0.83	−0.77	−0.81	−0.12	−0.49
GDP (AED)	0.92	−0.53	−0.82	0.07	−0.25
Buildings[a]	0.14	0.23	−0.22	0.74	0.33
Energy Consumption (GWH)	0.89	−0.76	−0.94	0.02	−0.41

[a] Number of completed buildings.

positive correlation only with the number of buildings completed while showing no correlation with other socio-economic factors. O_3 is a regional secondary pollutant, therefore the correlation of O_3 with socio-economic factors is showing an unsurprisingly inconclusive result. Although the results suggest that the Emirate's development has had an impact on the concentration of PM_{10}, it is noted, that a large portion of PM_{10} pollution is attributed to natural desert dust sources rather than urban pollution sources. This is indicated by the higher PM_{10} concentrations in remote and residential areas compared to the other station types. Transboundary regional pollution is impacting the distribution of PM_{10} across the Arabian Peninsula where millions of dust particles are carried from the Arabian desert into the coastline (Akasha et al., 2023). Proper management of PM_{10} pollution will require a regional, inter-governmental approach to manage the onset and escalation of regional dust activity. Attempts to mitigate PM_{10} pollution may manifest in a declining pollution trend after 2017. Nevertheless, managing PM_{10}, given its substantial natural regional source originating from desert dust, presents a significant challenge.

As shown in Table 1 in section 2.2, countrywide environmental policies have been emerging in the UAE since 1993 in the form of Laws or Agendas/Strategies. The impact of environmental policy on air quality can be realized through reductions in the criteria air pollutant concentrations. The results from this study show a reduction in locally generated pollutants (NO_2 and SO_2) in Dubai, whereas PM_{10} pollution with wider natural regional sources shows increases over the time period of interest. The overall results highlight the effectiveness of Dubai's environmental policies on local sources of pollutants leading to large reductions in NO_2 and SO_2 (54% and 93%) during the studied period. These reductions are particularly impressive when they are put in the context of the increasing urbanization and construction of Dubai.

4. Summary, conclusions, and policy implications

The concentrations of criteria air pollutants (CAP) at 14 locations within Dubai Emirate of UAE for the years 2013–2021 are evaluated in this paper. On average, throughout the study period, the air pollution, with the exception of PM_{10}, decreases indicating improving air quality within the Emirate. PM_{10} pollution rate increases from 2013 to 2017 and then decreases after that. Regardless of increases in population count and energy consumption in the Emirate, CO, NO_2 and SO_2 concentrations remain low.

The findings of this paper hold significant relevance for other cities, especially those planning to reform old urban areas and design new cities. The study demonstrates improved air quality in Dubai for primary urban pollutants, despite rapid economic growth and urbanization, and demonstrates the effectiveness of environmental policies in reducing pollution from industrial and transport sources. The success in controlling pollutants like NO_2 and SO_2 can serve as valuable lessons for urban planners and policymakers globally, offering insights into sustainable development strategies to combat air pollution.

Currently, the air quality monitoring guidelines in Dubai exceed the 2021 WHO guidelines for all monitored criteria air pollutants. This indicates a need for future revisions to improve air quality. The recently published environmental strategy, 'The National Air Quality Agenda 2031′, addresses this issue by outlining UAE's main programs and action plans to reduce air pollution. Reducing air pollutant emissions is a logical approach to improving air quality. Additionally, green urban infrastructure, particularly urban trees, can also help to mitigate air pollution (Manzini et al., 2023; Roeland et al., 2019; Sicard et al., 2022). The challenges faced in managing PM10, which predominantly originates from natural regional desert dust sources, underscore the need for comprehensive and region-specific approaches to tackling air pollution in cities.

Regarding the research limitations, the main issues encountered are the lack of access to air quality data prior to 2013 and the absence of continuous data from remote locations. The absence of data results in a less comprehensive understanding of the long-term trends of air pollution in Dubai, particularly in relation to the impact of desert dust on the environment and population. It also prevents a comprehensive assessment of the relevance of the EKC hypothesis to Dubai's air quality. Long-term, continuous and high-resolution data is extremely useful for understanding the real impact of economic development and urbanization on Dubai's air quality. Continuous remote station data would significantly aid in understanding the impact of desert dust on Dubai's air pollution profile and distinguishing between natural and anthropogenically generated pollution. Missing data can also impact policy recommendations and implementation. Future studies can usefully compare the measured concentrations of criteria air pollutants with emission inventories. An emissions inventory is a comprehensive list of sources that emit pollutants. It provides insight into the contribution of different sectors to air pollution and assesses the effectiveness of policies implemented to improve air quality, see e.g., (Ghaffarpasand et al., 2020b). While it has been announced that the Dubai emissions inventory is being prepared, it has not yet been made publicly available. Emission inventories for the whole of the UAE, from the Ministry of Climate Change and Environment, are available for 2015 and 2019, but they only investigate anthropogenic emissions (UAE, 2019; UAE, 2023).

Since 1999, laws and policies have been introduced in the UAE to protect the environment and encourage sustainable development. Recently, more emphasis has been placed on improving air quality to protect human health and the environment, reflecting positively on the improvement of Dubai's air quality. The growth of Dubai over the last 30 years has been unprecedented. This growth was anticipated to cause long-term deterioration of local air quality. However, this case study shows that Dubai has managed to develop rapidly and sustainably without long-term detriments to its air quality. Nevertheless, new policies can address the management of the construction sector to limit its impact on local air quality if further future massive development is anticipated and the development of long-term management of dust storms in collaboration with regional and global entities.

This paper identifies limitations, and the importance of long-term, continuous, and high-resolution data that can guide other researchers and authorities in adopting robust monitoring and assessment practices. Ultimately, the research contributes to the worldwide knowledge pool on air quality management, offering valuable implications for improving public health and environmental well-being in cities around the globe.

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CRediT authorship contribution statement

Heba Akasha: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Omid Ghaffarpasand:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing. **Francis D. Pope:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Writing –

review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is publicly available as stated in the paper, and links are provided.

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