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ORIGINAL PAPER

Unveiling Seasonal Fluctuations in Air Quality Using Google Earth Engine: A Case Study for Gujarat, India

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Abstract
Presently, a significant portion of the global population resides in metropolitan areas where air pollution levels are usually high. The primary objective is to utilize satellite data to identify the concentration of pollutants, unlike the traditional method which utilizes a series of ground-based detectors. The study aims to analyze the distribution of different pollutants in the air over the Gujarat state, India. The study comprised the utilization of Sentinel 5-P data sets for mapping Carbon monoxide (CO), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Methane (CH_4), and Formaldehyde (HCHO). Google Earth Engine platform was used for the processing of satellite imagery and maps were prepared using ArcGIS 10.3. The satellite data sets of different pollutants were processed and assessed for three seasons i.e., winter, summer, and monsoon to analyze the effect of climatic conditions as well on the concentration level over the study area. The concentration of CO ranges between 0.0295–0.0401 mol/m^2. The average concentration of SO_2 is 0.00047 mol/m^2 whereas the average concentration of NO_2 ranges from 0–0.00021 mol/m^2 and formaldehyde concentrations values range from 0.00015 to 0.00026 mol/m^2 over the year. The concentration range for methane is 1780–1940 ppb for the study area. The results exhibit that the northern part of Gujarat mainly consisting of Kutch, Banas Kantha, and Patan renders the lowest concentration of all air pollutants while the central and southern regions consisting of cities like Valsad, Surat, Bharuch, Vadodara, and Ahmedabad have recorded the peak values in all the seasons. The findings suggest that the increase in the levels of different pollutants is caused by human activities, industrialization, and urbanization.

Keywords Air quality · Google Earth Engine · Seasonal variation · Sentinel 5-P

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Abbreviations

AQI	Air Quality Index
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EMR	Electromagnetic Radiation
HCHO	Formaldehyde
LULC	Land Use/Land Cover
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Compounds
O_3	Ozone
PM 2.5	Particulate Matter
ppb	Parts per billion
ppm	Parts per million
SDGs	Sustainable Development Goals
SO_2	Sulfur Dioxide
SO_x	Sulfur Compounds

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1 Introduction

Anthropogenic activities like the burning of fossil fuels, industrialization, land use and land cover (LULC), etc. lead to the accumulation of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) in the Earth's atmosphere, which lead to changes in the climate, global warming, and a considerable imbalance in the global energy [1–4]. The impacts of air pollution include major problems like global warming, rise in average temperature, acidic rain, depletion of the ozone layer, and ultimately adverse effects on human health. Air pollution includes particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxide and dioxide (NO, NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), etc. The WHO defined air pollution as the contamination of indoor and/or environments through chemical, physical, or biological factors that cause changes in the normal features of the ambient air. The ambient air pollution resulted in more than 4.2 million premature deaths worldwide in 2016, according to the World Health Organization [5]. The concerns about air pollution can be seen in three air pollution-related indicators of Sustainable Development Goals [6], i.e., health (Goal 3), sustainable and modern energy (Goal 7), and sustainable cities (Goal 11). The conditions of air and thermal pollution are a result of the fast urbanization that is happening with the development of industrial facilities. One distinct consequence of climate change is an increase in the average temperature of the Earth's surface by 0.74 °C over the past 100 years further the mean average temperature of the globe is estimated to increase up to 1.5 to 2 °C until the end of the twenty-first century further evidence shows that there would be increase in about 0.1 °C per decade [7, 8]. An increase in the average temperature results in the rising speed and severity of the water cycle of the globe which would contribute to destructive droughts [9–12], floods, storms [13, 14] and forest fires [15]. The change in the trend of precipitation also leads to the alteration in the water cycle causing various disastrous situations [16, 17]. The intensification of the severity of the water cycle affects every aspect of human life including the ecosystem, and human health, along the food chain [18, 19]. Recently planet Earth has experienced a disastrous effect in LULC change i.e., flood [20], soil erosion [21] and ultimately change in climate [22–24].

In recent decades, there has been a significant rise in coal-based electricity generation, leading to elevated emissions of sulfur dioxide (SO_2) [25, 26]. This increase in SO_2 levels stems not only from industrial activities such as ore extraction and natural events like volcanic eruptions but also from human activities like the combustion of fuels in vehicles, ships, and other transportation systems [27]. A prominent repercussion of heightened SO_2 presence in the atmosphere is the occurrence of acid rain. During acid rain episodes, SO_2 combines with rainwater to form sulfuric acid, resulting in the acidification of soil, harm to plant and aquatic life, and the erosion of sedimentary rocks like limestone. Another major air pollutant is Nitrogen dioxide (NO_2). It is produced from the making of nitric acid, usage of explosive chemicals, manufacturing for commercial and food products, refining of petrol, etc. [28, 29]. However, the major source of production of NO_2 is the combustion of fossil fuels such as coal and gas, especially in vehicles. The major consequences of NO_2 are an increase in respiratory infection and a reduction in lung function, especially in children. Also, NO_2 may turn into harmful acids, at higher concentrations, which may lead to the corrosion of building materials in the presence of moisture [5]. Other than incomplete combustion from vehicles, the total anthropogenic emissions contribute to 41% to the production of carbon monoxide (CO) [30], whereas the contribution from industrial and transportation sectors is estimated as 30 and 28%, respectively. Anthropogenic emissions, being the primary source of CO, are found highest over the megacities such as Mumbai, Ahmedabad, Delhi, Kolkata, Thiruvananthapuram, and the Indo-Gangetic Plain region [31, 32]. In terms of consequences, CO does not actively react with the atmosphere to produce pollutants, but it has 210 times more affinity for hemoglobin than oxygen (O_2). As a result, with continuous exposure to vehicular emissions, CO may cause severe CO intoxication and lower respiratory tract disorders such as cough and pain with inspiration [33].

The Google Earth Engine (GEE) platform is extensively utilized to compute LULC and air pollution levels utilizing data from Landsat and Sentinel-5P across major Indian urban areas [15, 34]. Sentinel-5P is also employed to examine the non-linear correlation between daily and yearly concentrations of air pollutants such as CO, NO_2, O_3, and SO_2 [34]. In Turkey, Sentinel-5P is employed for measuring air pollutants, while MODIS data is utilized to analyze the variation in Aerosol Optical Depth on the GEE cloud computing platform from January 2019 to September 2020 [35]. In India, widely used MODIS images are employed for estimating air pollutant levels from 2018 to 2021, employing the formulas specified by the GEE platform. Numerous researchers in India have conducted air quality assessments for environmental impact evaluations and analysis of human activities [36, 37].

Air pollution has become a significant issue in recent decades and is now a primary cause of early death and illness, particularly in developing nations such as India [38]. Despite some research having been conducted on air quality in different regions of India at an annual scale, there remains a dearth of studies focusing on the regional scale i.e., Gujarat state. The air quality was assessed at annual variation in different regions of the country but no assessments have been carried out to evaluate the seasonal/monthly air quality changes at the regional scale. Therefore, this study aims to fill this gap by examining the seasonal variation of air quality for winter, summer, and rainy seasons from 2022 to 2023 in Gujarat state, India. The study comprised the utilization of Sentinel 5-P data sets for the spatial assessment of various pollution parameters i.e., Carbon monoxide (CO), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Methane (CH_4), and Formaldehyde (HCHO). The spatial variation of the air quality parameters for different seasons was processed in GEE and mapped in ArcGIS 10.3 over the study area. A thorough comprehension of the spatial variations of various air quality parameters can aid in the development and implementation of strategies aimed at mitigating pollution.

2 Study Area

Geographically, Gujarat has the following coordinates: 20° 60′ N to 24° 42′ N (latitude) and 68° 10′E to 74° 28′E (longitude) illustrated in Fig. 1. Gujarat is geographically situated on the northwest coast of India, with its western border facing the Arabian Sea [39]. To the north and north-east, it shares its border with Rajasthan and in the south and southeast, it shares its border with Maharashtra. The state also shares an international border with Pakistan at the northwestern periphery. The state comprises two dry areas placed in the north of Kachchh and between Kachchh and mainland Gujarat which is characterized by greater salinity levels and a lack of vegetation [40]. The state covers a land area of about 196,030 square kilometers and a coastline of particularly 1600 km which makes it one of the most extensive among all the states.

The state is classified into three major regions, following its geography:

i. The Saurashtra peninsula, a rocky terrain with low-lying mountains

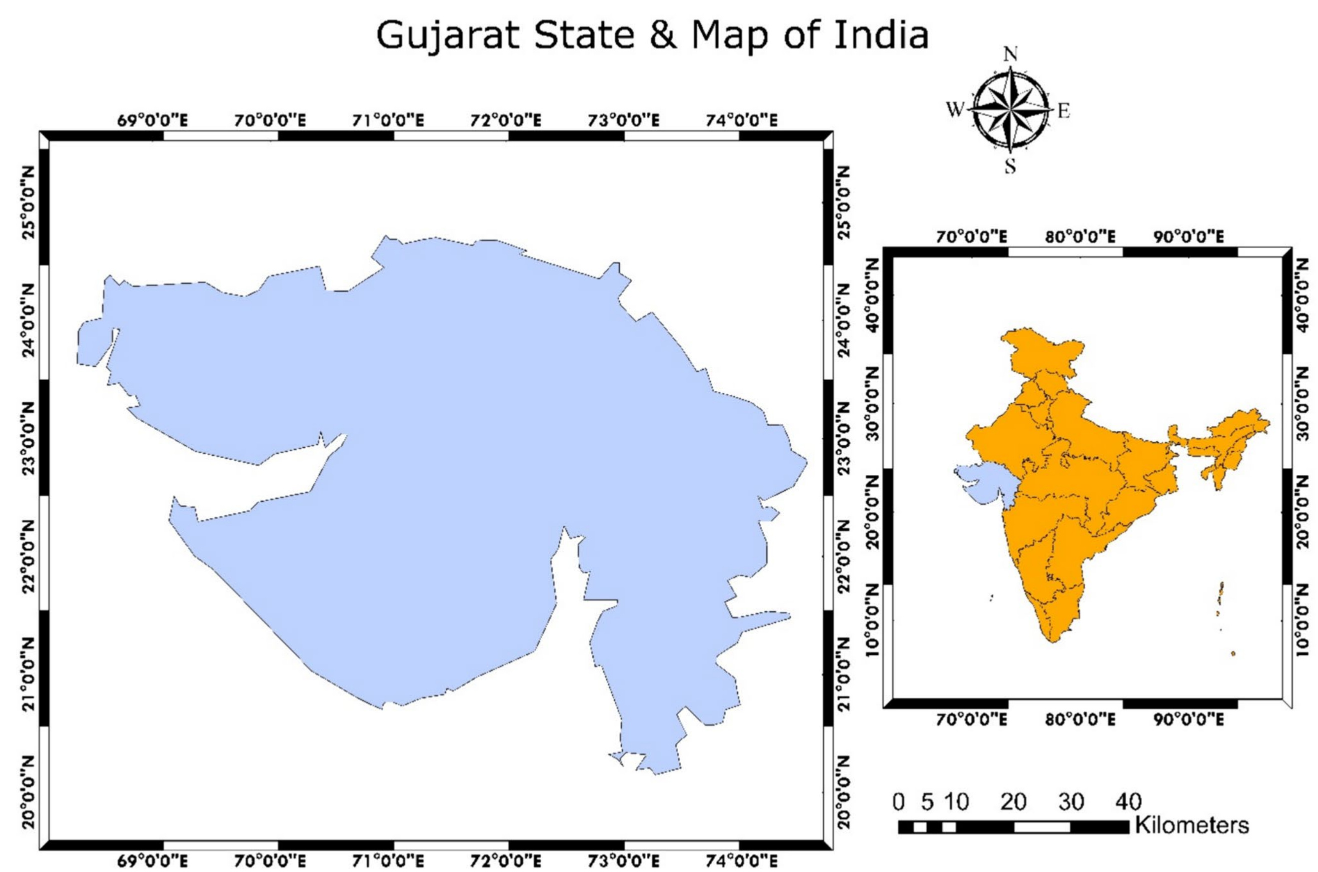


Fig. 1 Location of Gujarat state and India on the geographical map (study area)

ii. Kutch is present in the northeastern part of the state, which is barren and has a rough and rocky terrain. Kutch is accompanied by Rann which expands in the northern and eastern parts of Gujarat
iii. The mainland of Gujarat which lies between the Rann of Kutch and the Daman Ganga River. This patch of land is fertile and composed of alluvial soil.

Gujarat has 4 major rivers namely Narmada, originating from the Amarkantak plateau which merges with the Arabian Sea. Sabarmati rises from the Aravalli hills which run along for 370 km and finally merge with the Arabian Sea. Tapi river which has a length of more than 700 km flows from the east to the western part of India. However, for the Saurashtra region, the Aji River is a very critical water resource. Gujarat includes a wide range of minerals like calcite, limestone, ignite, manganese, bauxite, feldspar, quartz, etc. [41]. The regions of Ankleshwar and Khambhat serve as key hubs for oil extraction and as a natural gas resource [42].

3 Major Pollutants and Their Sources

The major pollutants that result in the deterioration of the air quality index thereby directly leading to the changes in the climate are carbon compounds, that is the oxides of carbon (carbon dioxide, CO_2), carbon monoxide (CO), sulfur compounds (SO_x), nitrogen compounds (NO_2, HNO_3), Ozone (O_3), hydrocarbons (benzene, benzopyrene, etc.), metallic pollutants (like nickel, vanadium, tin, etc.), petrochemical pollutants (like petrochemical smog, PAN, etc.), etc. [43]. Some of the major sources of pollutants across the study area are:

3.1 Power Plants

The Indian power sector is one of the largest emitters of CO_2. The power sector accompanied by industrial activities led to the release of a significant amount of SO_2 (around 8.5 Mt). The power plant in India is primarily driven by the combustion of coal which catalysis the emission of SO_2 however, it helps in providing 70% of total electricity generation and about 45% of the country's industrial output. To control the emission of such pollutants technologies like flue gas desulphurization can be used, but causes greater investment of time as well as money. To decrease the level of pollution caused by power plants Indian government came up with the Environment (Protection) Act Rules in 2015 for stabilizing the emission of various pollutants like $PM_{2.5}$, NO_x, and SO_2. The act demonstrates a 90% reduction in SO_2 emission by 2040 which would reduce the total amount of SO_2 emission through energy-related activities by 45% and NO_x by 50%. Renewable sources of energy also have a decent impact on the reduction of electricity carbon emissions. Rapid industrialization and the development of numerous industries in India have led to the emission of both SO_2 and CO_2 [44–46].

3.2 Vehicular Emission

Nearly 40% of all NO_x emissions come from vehicles, out of which more than half of which is emitted from heavy-duty vehicles [47]. The increase in road transportation is directly associated with the increase in population density. Such pollution activities are highly constricted close to the ground and are not subjected to dispersion [48–50]. The demand for vehicular fuel has increased to a great extent due to the rapid growth in the use of private vehicles instead of public transport which has resulted in the growth of particulate matter concentration in the atmosphere [51]. The introduction of the Bharat Stage VI emission standard has helped in reducing the concentration of pollutants conventionally as it forces industrialists to manufacture and distribute products with suitable sulfur content in the market [52]. The act regulates a sulfur content of 10 parts per million (ppm) in domestic fuel, specifically referring to petrol and diesel. The development in the vehicular sector and the adoption of electric vehicles (EVs) have showcased a significant improvement in fuel efficiency accompanied by environmental advantages [53]. Electrifying the vehicles will help in reducing air pollution which would reduce carbon emissions simultaneously [54].

3.3 Socio-Cultural

Besides such major sources, some of the small-scale activities also contribute greatly to worsening the air quality. Household cooking incorporated by incomplete traditional biomass burning via agricultural residue etc. initiates the emission of particulate matter, which is almost two-thirds of the total combustion-driven emission [55, 56]. The light source in a rural area, a kerosene lamp also contributes to indoor pollution as kerosene has a significantly lower smoke point value which leads to the emission of black smoke containing huge levels of $PM_{2.5}$ accompanied by black carbon [57, 58]. Using certain modern techniques such as clean cooking can reduce the count of premature deaths from 0.6 to 0.1 million. Other such sources are the burning of waste crops by farmers, seepage of methane through the landfills, uncertain volcanic eruptions and forest fires [15, 59], use of fertilizers and insecticides in agricultural activities which releases ammonia and other associated chemicals in the atmosphere, etc. However certain activities like demolition and construction of new structures also lead to the eruption of significant amounts of dust in the atmosphere which causes an increase in the concentration of particulate matter in the surroundings [60].

4 Materials and Methodology

The datasets used for the mapping of all pollutants over the study were obtained from the Copernicus open-access platform, provided by the European Space Agency. The data sets of pollution parameters in the present work are data sets collected by satellite Sentinel-5P.

4.1 Dataset Collection

Sentinel 5-P utilizes its onboard TROPOMI instrument which operates in a passive mode of remote sensing. The TROPOMI utilizes wavelength bands between the ultraviolet and shortwave infrared region of the EMR. The mode of data collection by the instrument is push broom, with a swath width of approximately 2600 km and each pixel represents 7 km × 3.5 km of area [61]. The sensor operates in the wavelength region that ranges between 270–500 nm (UV–visible) and 2305–2385 nm (shortwave infrared) electromagnetic spectrum. The onboard instrument as mentioned above is dedicated to collecting data regarding major pollutants that are present in the atmosphere such as CO, NO_2, SO_2, CH_4, HCHO, and AOD. Sentinel 5-P is capable of providing global coverage of the different pollutants every 24 h, and the onboard instrument collects the data for each pollutant in the form of column data, which depicts the coverage throughout the entire depth of the atmosphere [62]. The flow of the work is demonstrated in Fig. 2.

4.2 Methodology

The Gujarat state of the Indian subcontinent was utilized as the study area as it is home to 72.7 million individuals and the largest hub for chemical industries. The data sets were provided by Sentinel 5-P satellite using onboard instrument TROPOMI, include various spatial and temporal data types for mapping different pollutants which are major contributors to air pollution and possess harmful effects on the environment and humans. The GEE is an open-source Java-based online platform for processing satellite data with any region of interest. The code editor function available within the GEE was utilized and specific Java scripts were integrated for mapping different air pollutants using the Sentinel 5-P datasets over the study area.

In the mapping of CO, NO_2, SO_2, and HCHO pollutants, the earth radiance measurements in different spectral regions were utilized, which provided the data in the form of the vertically integrated column density of each above-mentioned pollutant and the output data represents the concentration in

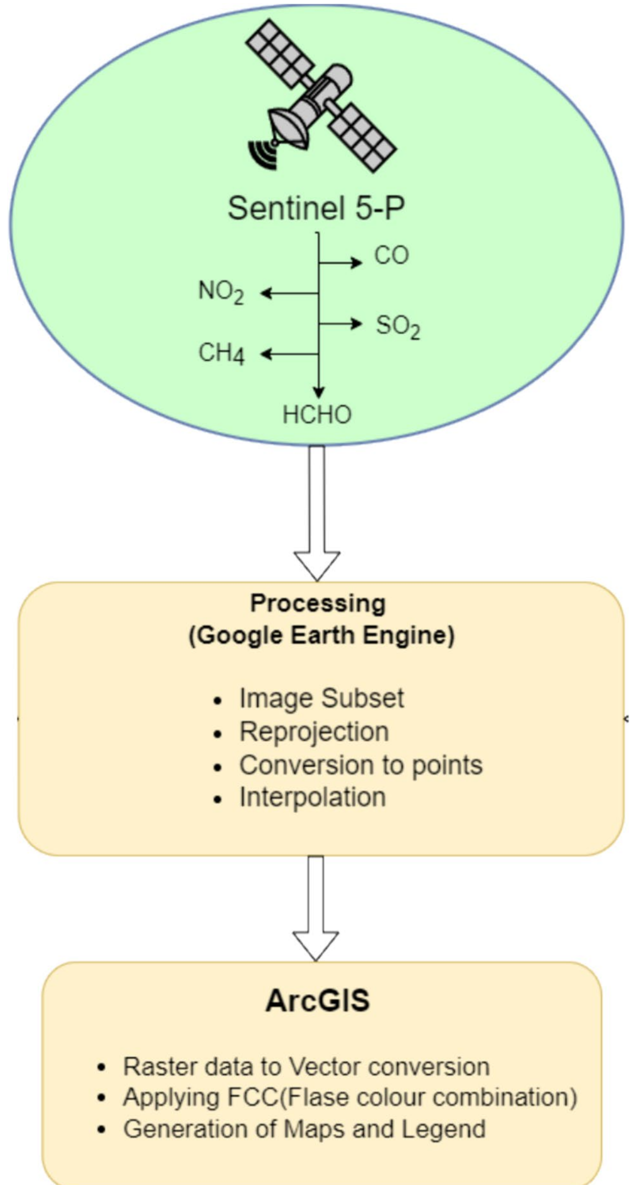
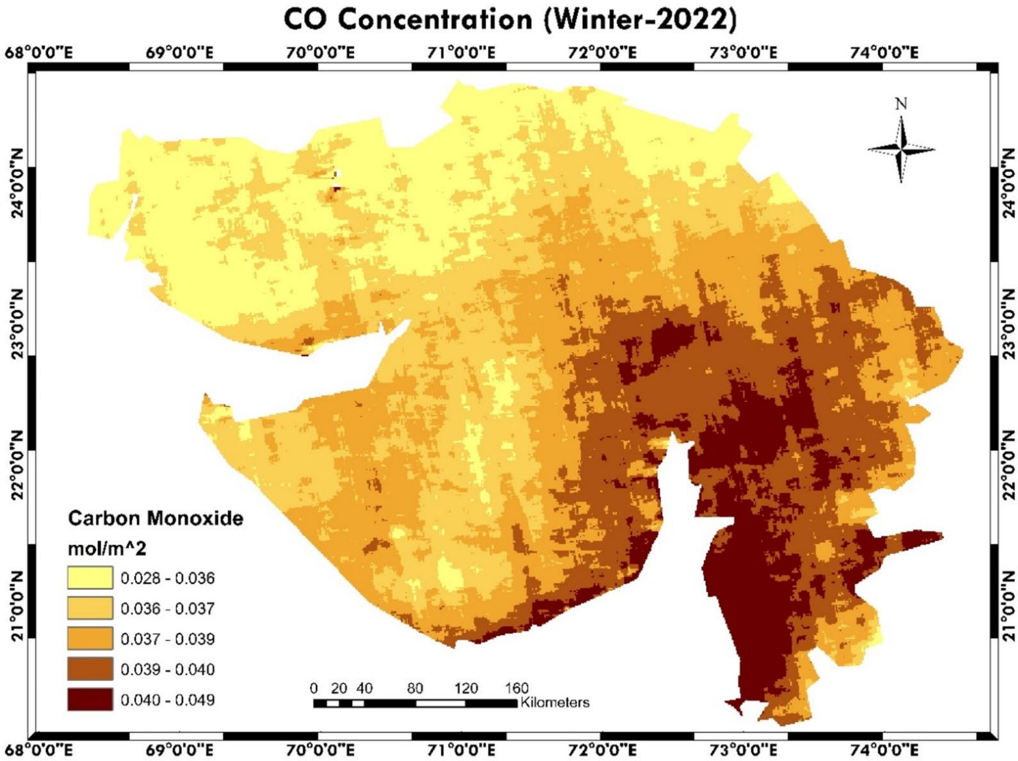


Fig. 2 Flow chart of research process

mol/m^2. For mapping of CH_4 concentration over the study area, the data provided was in the form of column volume mixing ratio and the output after processing the data would give the concentrations in ppb (parts per billion) of methane. The collection of data is classified into subcategories based on the different pollutants such as CO, NO_2, SO_2, CH_4, and HCHO. The data collection period for all the pollutants was based on three different seasons prevailing in the study area. Therefore, the satellite datasets were collected for each season i.e., the data collected from December 1 to 31, 2023 was for the winter season, the data collection period was from March 1 to 31, 2023 for the summer season, and the data collection period was from August 1 to 31, 2023 for



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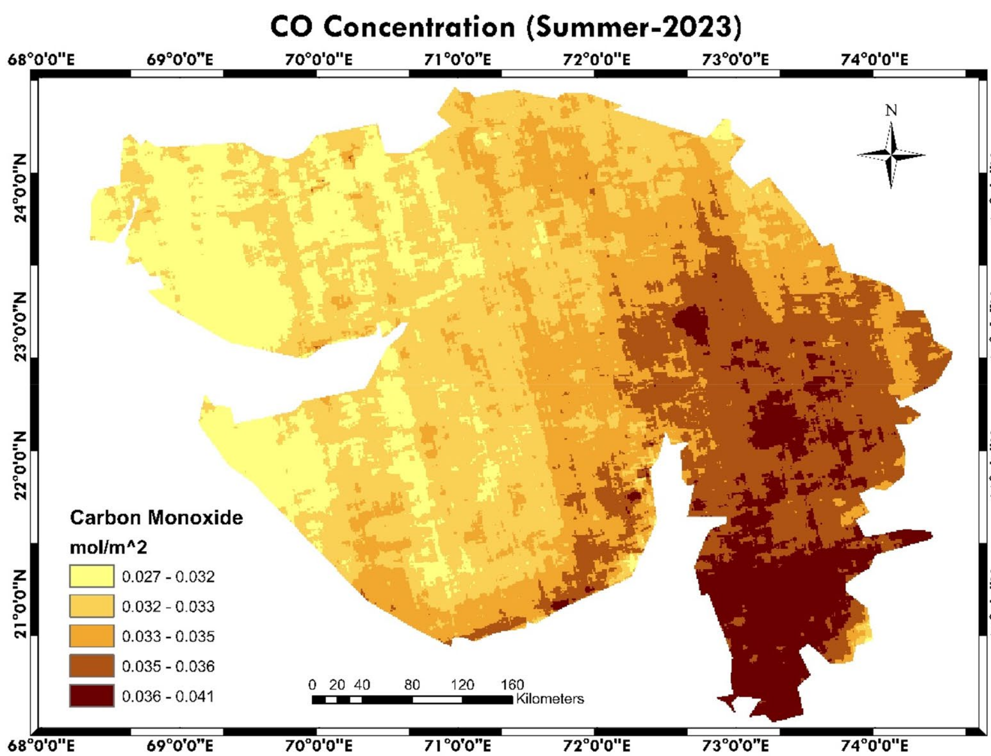
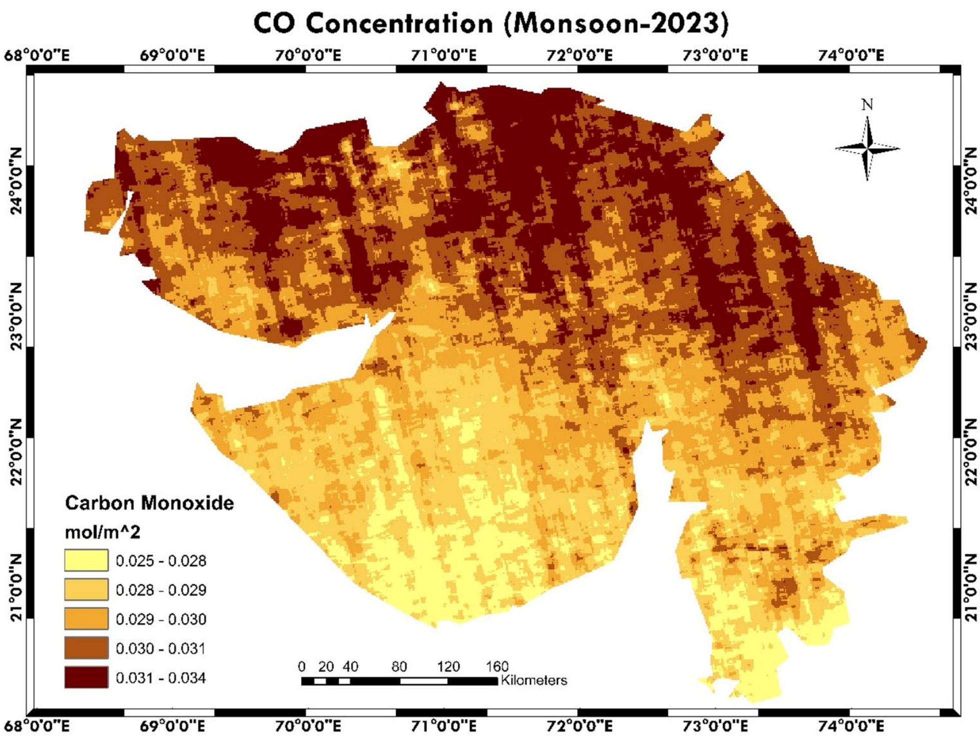


(b)

Fig. 3 Concentration of Carbon monoxide in various seasons in Gujarat (**a**) Winter 2022, (**b**) Summer 2023, (**c**) Rainy 2023, and (**d**) Yearly graph of CO concentration the monsoon season. The influence of seasons and climatic conditions on the concentration of different pollutants can be interpreted in a much easier way as climatic conditions majorly influence the distribution and concentration of pollutant molecules in the atmosphere.

In the GEE software, the concentration of the pollutants in major cities of Gujarat was collected using the inspector tool, which allows to obtaining of concentration data of pollutants at any point in the region of interest. Different Java scripts were used for mapping each pollutant in GEE by directly integrating the satellite data sets for the respective



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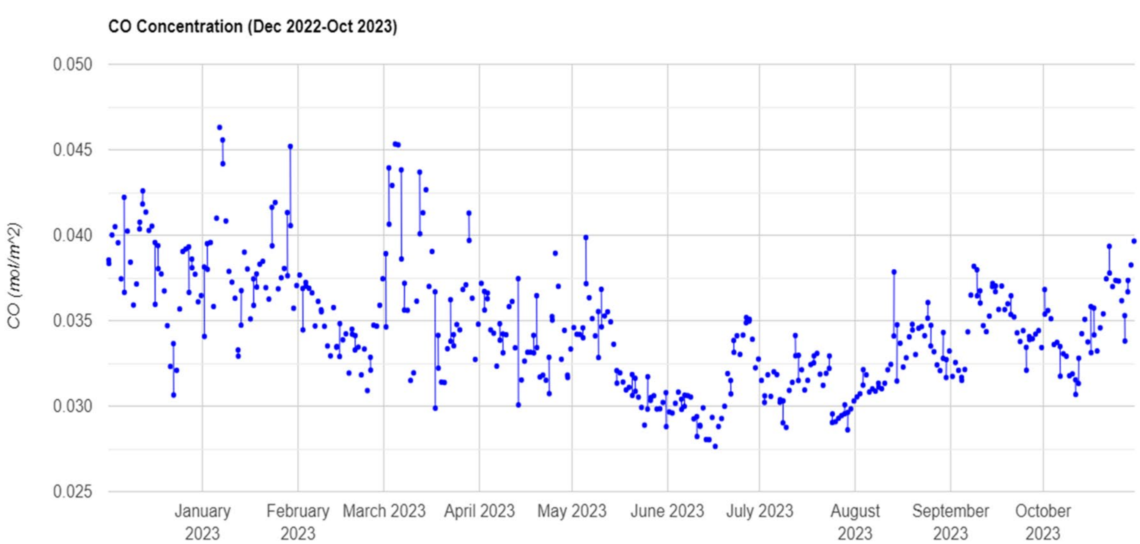


(d)

Fig. 3 (continued)

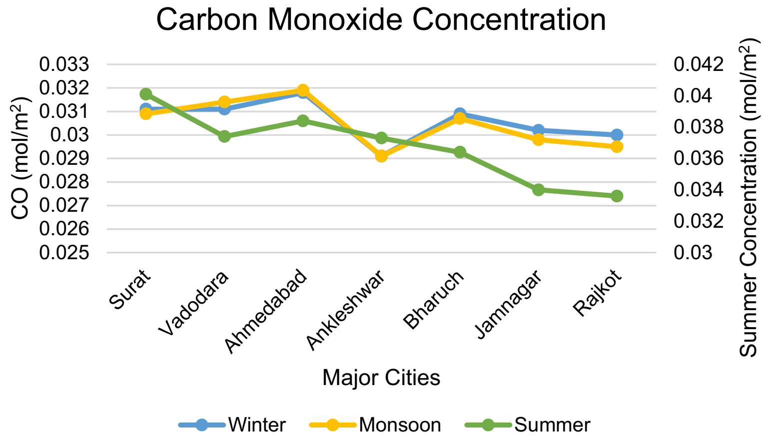


Fig. 4 CO concentration in major cities of Gujarat

period according to the different seasons, the output in GEE was generated in the form of a TIFF file format. The raster data were generated using GEE, and the raster data for all pollutants in different seasons were exported to ArcGIS software. The maps were prepared in ArcGIS 10.3 for each pollutant parameter for different seasons and were processed using raster data as an input file and different tools available within the ArcGIS.

5 Results

Seasonal data of various pollutants are collected and analyzed through GEE and ArcGIS respectively, depicting the following results:

5.1 Carbon Monoxide

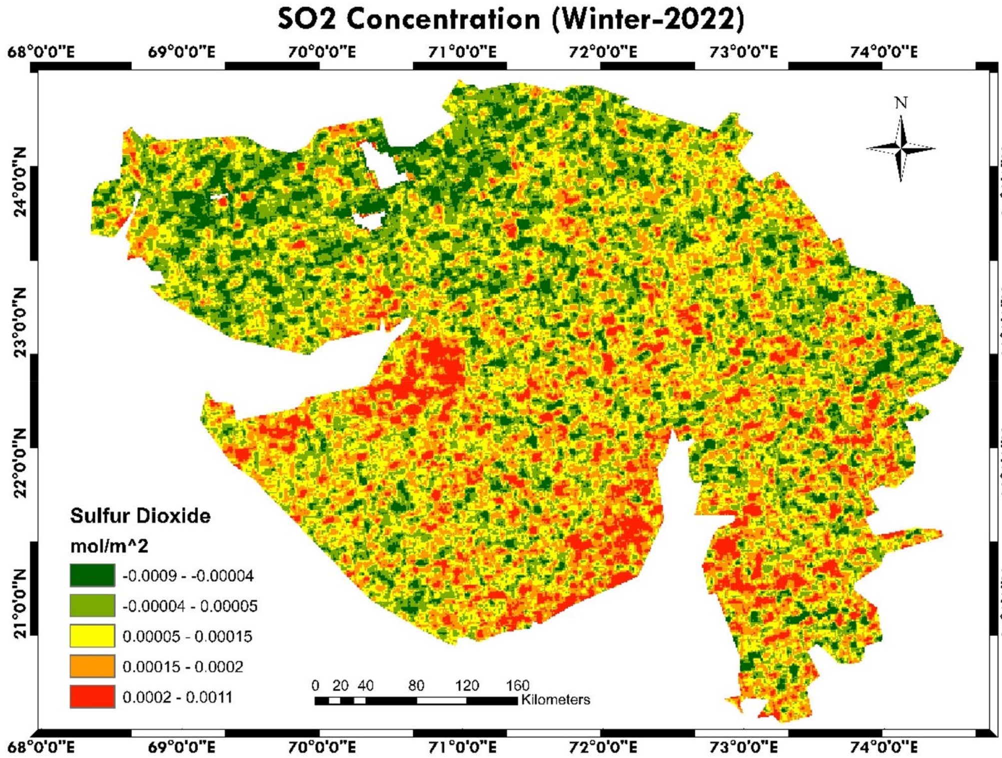
Carbon monoxide arises from the incomplete burning of hydrocarbon fuels, possessing a heightened ability to retain heat in the atmosphere, consequently elevating the Earth's surface temperature. Sentinel-5P data employs a spectral range of 2.3 micrometers in the short-wave infrared region to gauge CO levels in the troposphere. Fig. 3 depicts spatial and seasonal fluctuations of CO concentration.

Figure 3 depicts the concentration of Carbon monoxide in the state of Gujarat for three different periods, each time portraying different seasons prevailing in India. The Sentinal-5P data utilizes a 2.3 µm spectral range of short-wave infrared which helps in determining the amount of CO present in the troposphere. Figure 3a, b represent CO mapping in December 2022 and April 2023 wherein the concentration ranges between 0.028–0.05 mol/m^2 and 0.027–0.041 mol/m^2. The map exhibits that the northern part of Gujarat mainly consisting of Kutch, Banas Kantha, and Patan renders the lowest concentration of CO while the central and southern regions consisting of cities like Valsad, Surat, Bharuch, Vadodara, and Ahmedabad have recorded the peak values ranging between 0.04–0.05 mol/m^2 during winters and 0.036–0.041 mol/m^2 during the Summers. Consecutively Fig. 3c describes the CO mapping during August 2023 in which the coastal regions of the state have the least southern half of the state experiences the least concentration of CO which ranges between 0.025–0.029 mol/m^2. Figure 3d is a graph showing the average CO concentration of Gujarat for the timespan of one year, that is from December 2022 to October 2023. Figure 4 illustrates CO concentration in major cities of Gujarat.

5.2 Sulphur Dioxide

Sulfur dioxide plays a significant role in polluting soil and water bodies as it readily reacts with water, causing acid rain. A primary source of increased SO_2 concentration is the combustion of fossil fuels for electricity generation. Figure 5 depicts the spatial and seasonal changes in SO_2 levels.

Corresponding maps Fig. 5a, b, c portray the concentration of sulfur dioxide in various regions of Gujarat. The concentration of Sulfur dioxide ranges between 0–0.0014 mol/m^2. However, sulfur dioxide is uniformly distributed along the region but the area with greater human density shows intensification in the concentration. Analysis concerning the three major seasons depicts that SO_2 and surface temperature are related to one another that is the decrease in the temperature leads to an increase in the concentration of the compound. Ahmedabad has recorded the highest levels of sulfur dioxide concentration in the Gujarat region, from Fig. 5a, b it can be observed that the concentrations have a mean value of 0.0003 mol/m^2 in the winter season and 0.00041 mol/m^2 in the summer season. Similarly, from Fig. 5c it can be observed that for the monsoon season, the average concentration in Ahmedabad is 0.00047 mol/m^2. Similarly, cities like Vadodara, Surat, and Bharuch are among the cities in Gujarat that have recorded high concentrations of SO_2, and



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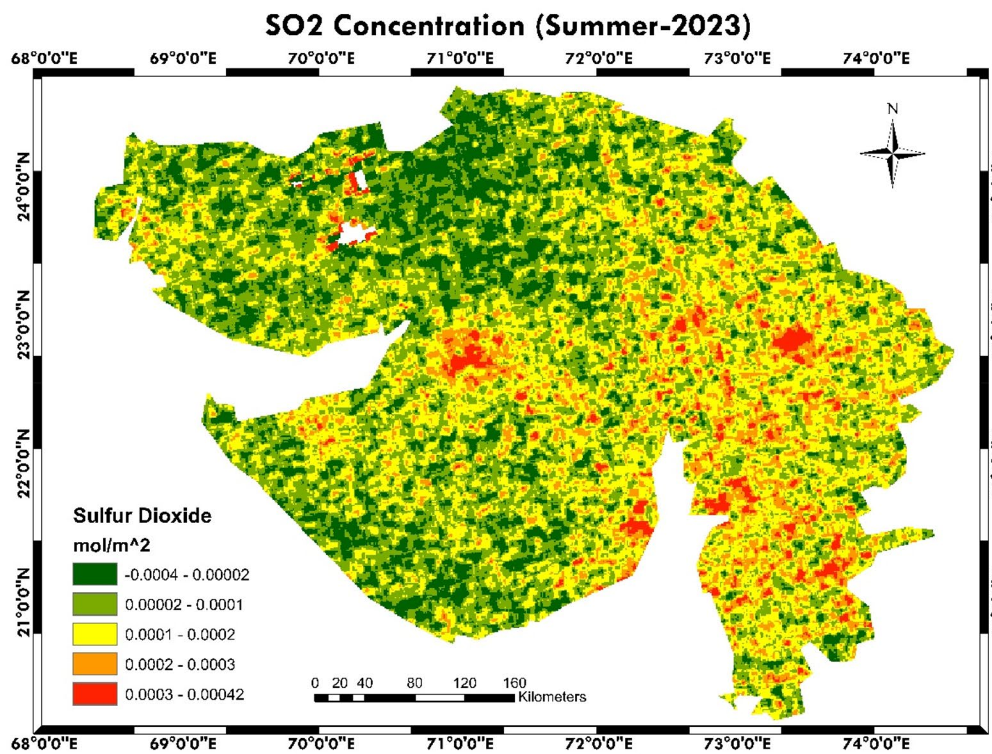
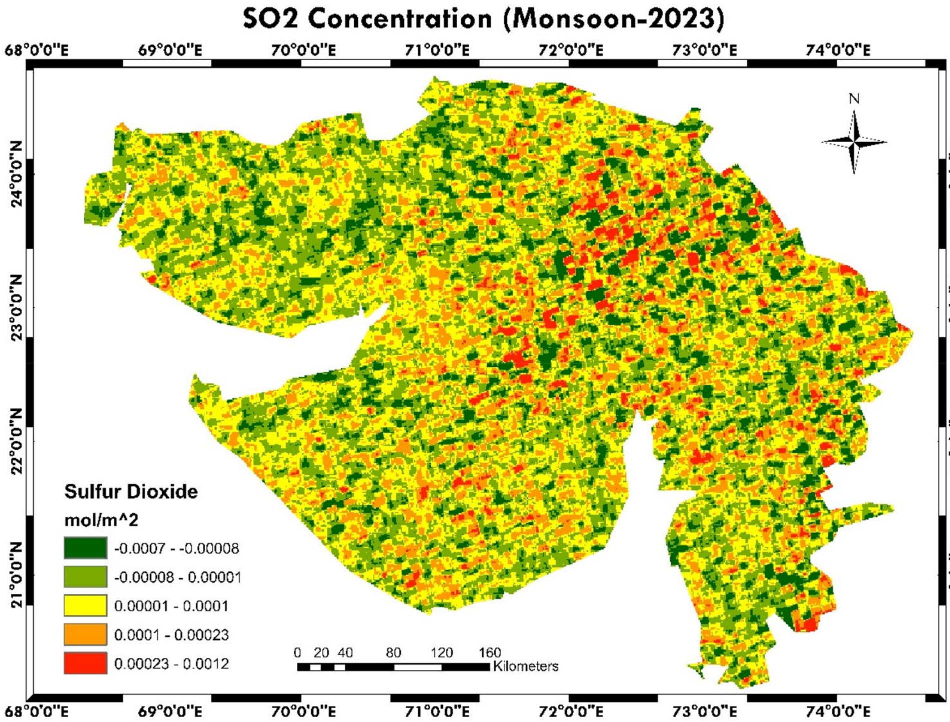


(b)

Fig. 5 The concentration of Sulphur Dioxide in various seasons in Gujarat (**a**) Winter 2022, (**b**) Summer 2023, (**c**) Monsoon 2023, and (**d**) Yearly graph of SO_2 emitted



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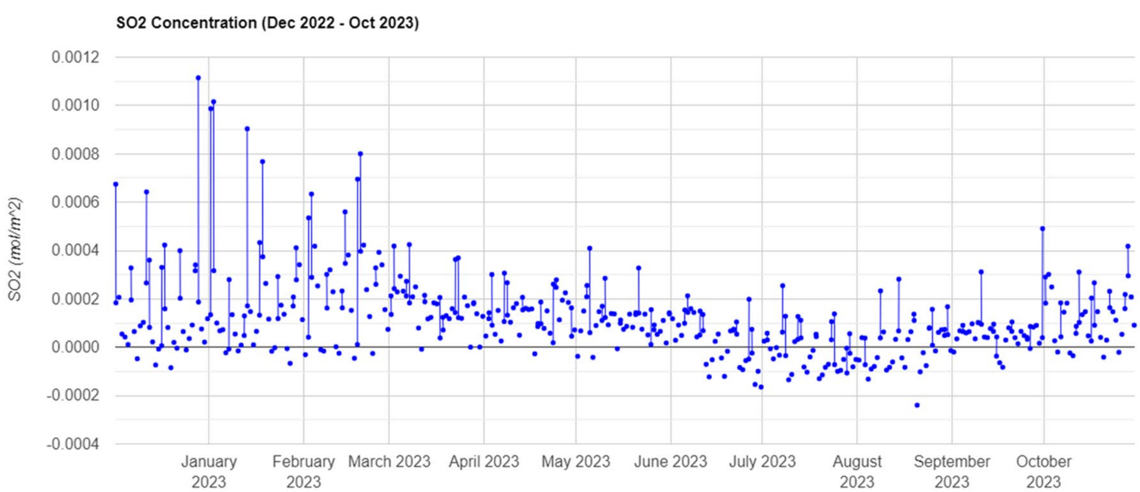


(d)

Fig. 5 (continued)

from Fig. 6 it can observe the variations in the concentration of SO_2 concerning different seasons. It is found that as the ambient temperature decreases the concentration of SO_2 in the air also decreases. Figure 5d is a graph showing the average SO_2 concentration of Gujarat for the timespan of one year, that is from December 2022 to October 2023.

5.3 Nitrogen Dioxide

Prominent origins of NO_2 include emissions from diverse hydrocarbon production sectors, fossil fuel combustion, and other human activities, resulting in significant outcomes such as the formation of ground-level ozone, particulate matter, acid rain, and even contributing to global warming.

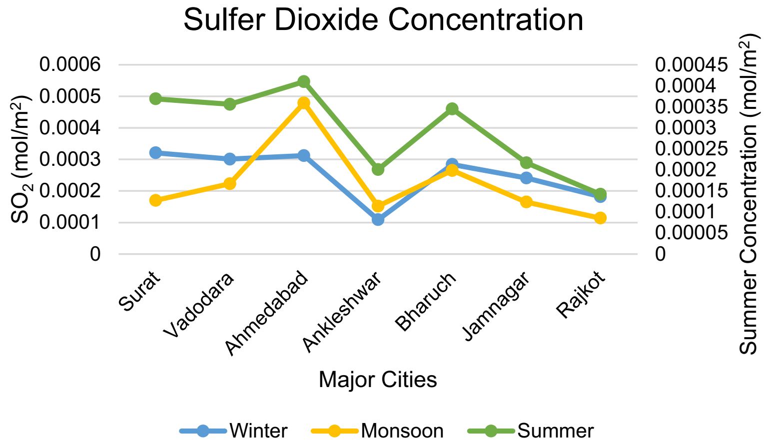


Fig. 6 SO_2 concentration in major cities of Gujarat

Figure 7 displays the spatial and seasonal fluctuations in NO_2 levels.

The above map Fig. 7a, b, c showcases the concentration of nitrogen dioxide over the Gujarat region. Each map represents concentration mapping during different seasons that are prevailing in the terrain which is directly associated with human activities and industrialization. Activities like the combustion of fossil fuel for the generation of electricity are one of the major sources of NO_2. The average concentration of NO_2 over Gujarat ranges from 0–0.00021 mol/m^2 over the year. The peak values are obtained in the regions with greater industrialization, where due to greater combustion and energy consumption the release of NOx is higher. From the map Fig. 7, it can observe that regions of different cities like Ahmedabad, Surat, Vadodara, and Jamnagar have the highest levels of NO_2 recorded for every season, the major reason behind them is these cities are the hub of many industries which generates NO_x pollutants. Figure 8 provides information about the concentrations in different major cities of Gujarat of every season and its yearly average concentration values. Figure 7d is a graph showing the average NO_2 concentration of Gujarat for the timespan of one year, that is from December 2022 to October 2023.

5.4 Methane

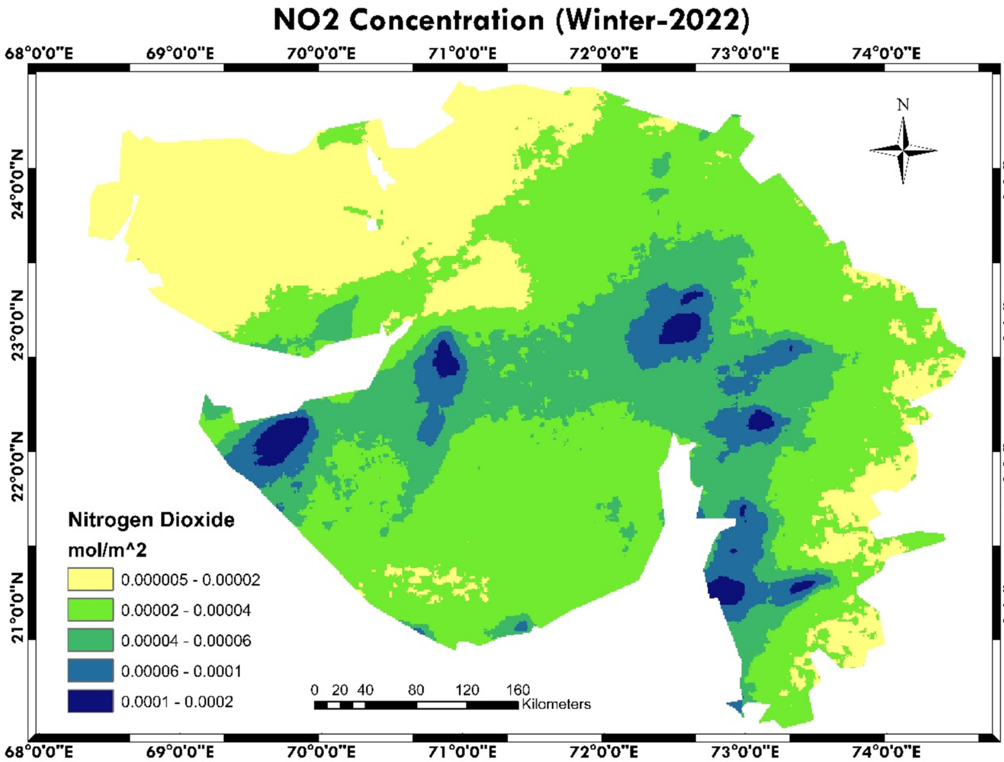
The substantial increase in methane (CH_4) emissions resulting from industrialization and urban expansion significantly impacts the surrounding environment and, consequently, human health. This effect is particularly evident in the increased formation of ground-level ozone. Figure 9 presents the spatial and seasonal fluctuations of CH_4 levels.

One of the major contributors of greenhouse gas is plotted above Fig. 9a, b, c which traps the heat over the surface of the Earth and hence increases the average temperature of the Earth's surface. Some of the major sources that emit methane gas are agricultural activities, fossil fuels, waste degradation, etc. All the mentioned sources are directly related to human activities hence it can see a uniform distribution of colors all over the topography. The concentration range for methane is 1780–1940 ppb. There are some patches with a grey true color combination in the maps Fig. 9, which indicates that the concentration of methane gas over that region is almost negligible and another possibility might be that the onboard instrument of Sentinel 5-P was not able to collect any data regarding methane gas over those regions. The generated maps of methane Fig. 9 depict that the northern region of Gujarat has had a comparatively higher concentration of methane even though those areas have comparatively fewer human activities than of central and southern parts of Gujarat. The southern part and central parts of Gujarat have a greater number of industries and vehicles, still, those areas are less subjected to methane emissions. Figure 9d is a graph showing the average Methane concentration of Gujarat for the timespan of one year, that is from December 2022 to October 2023. Figure 10. Methane (CH4) concentration in major cities of Gujarat.

5.5 Formaldehyde

Formaldehyde gas represents a significant contributor to indoor air pollution, exacerbating respiratory ailments and contributing to the formation of ground-level ozone. It falls under the category of volatile organic compounds (VOCs), primarily stemming from vehicle exhaust and industrial processes. Figure 11 depicts the spatial and seasonal fluctuations of formaldehyde levels.

The formaldehyde concentration mapping over the Gujarat region Fig. 11a, b, c showcases the formaldehyde distribution over the Gujarat region for different seasons. From Fig. 11a, b, c it can be observed that the central parts and southern parts of the Gujarat region are more subjected to formaldehyde concentrations, values ranging from 0.00015 to 0.00026 mol/m^2. This region mainly consists of the major cities of the state such as Ahmedabad, Vadodara, Bharuch,



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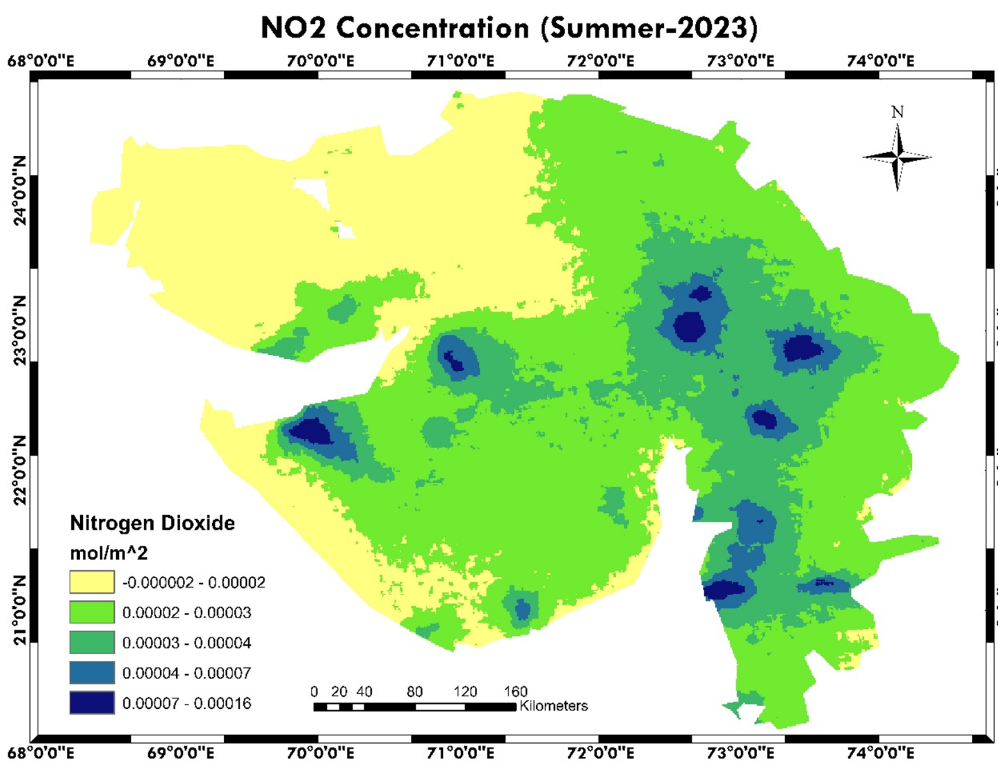
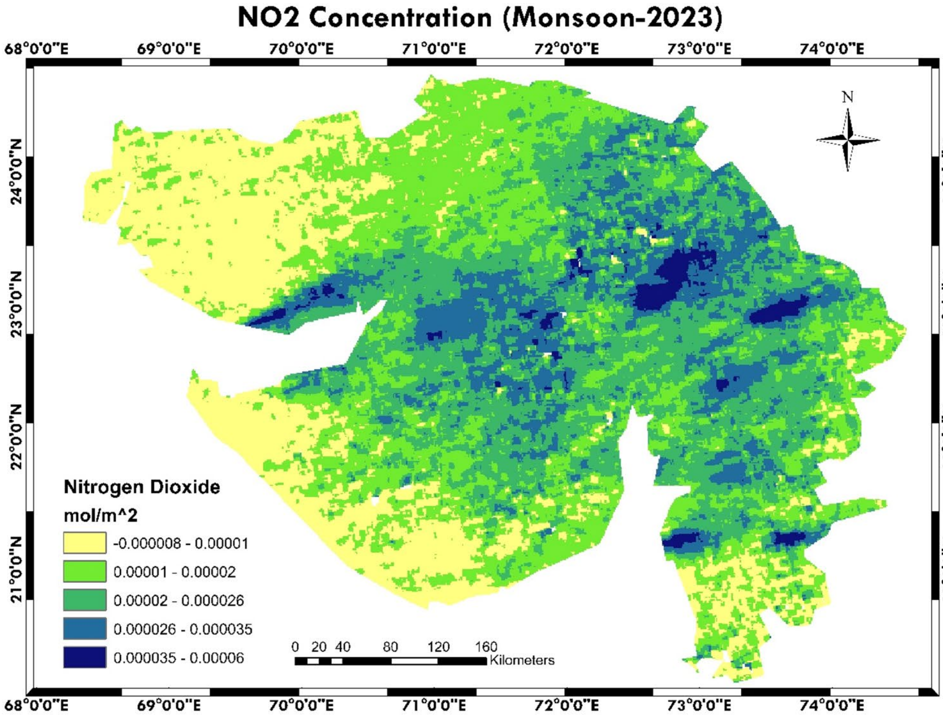
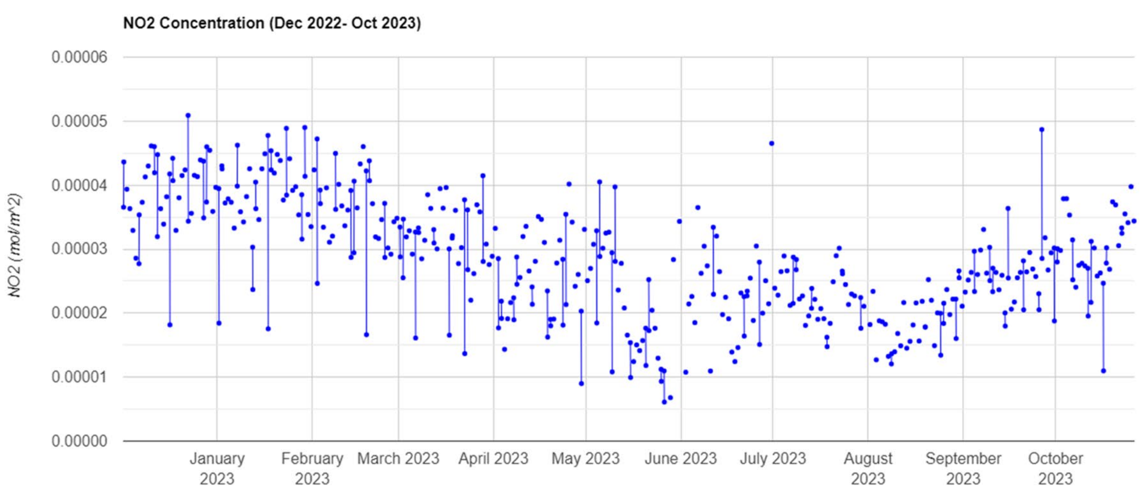


(b)

Fig. 7 Concentration of Nitrogen dioxide in various seasons over Gujarat (**a**) Winter 2022, (**b**) Summer 2023, (**c**) Rainy 2023, and (**d**) Yearly graph of NO_2 emitted



(c)



(d)

Fig. 7 (continued)

Surat, and Valsad. Industrial activities have also increased in these cities causing an increase in air pollution and degradation of the Air Quality Index. Although there is not much difference in the formaldehyde distribution over the Gujarat region in different seasons, there is a significant increase in the concentration of formaldehyde in the winter season all over the Gujarat region. Figure 12 illustrates the average values of formaldehyde concentration in different cities for each season and its yearly average value. Figure 11d is a graph showing the average formaldehyde concentration of Gujarat for the timespan of one year, that is from December 2022 to October 2023.

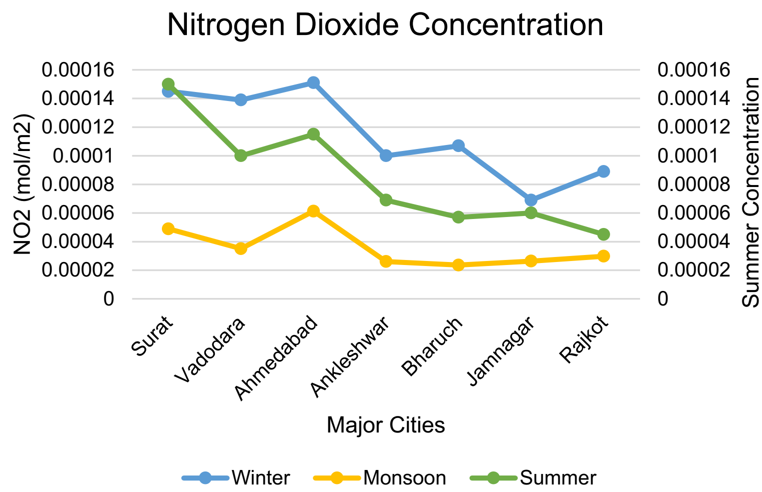
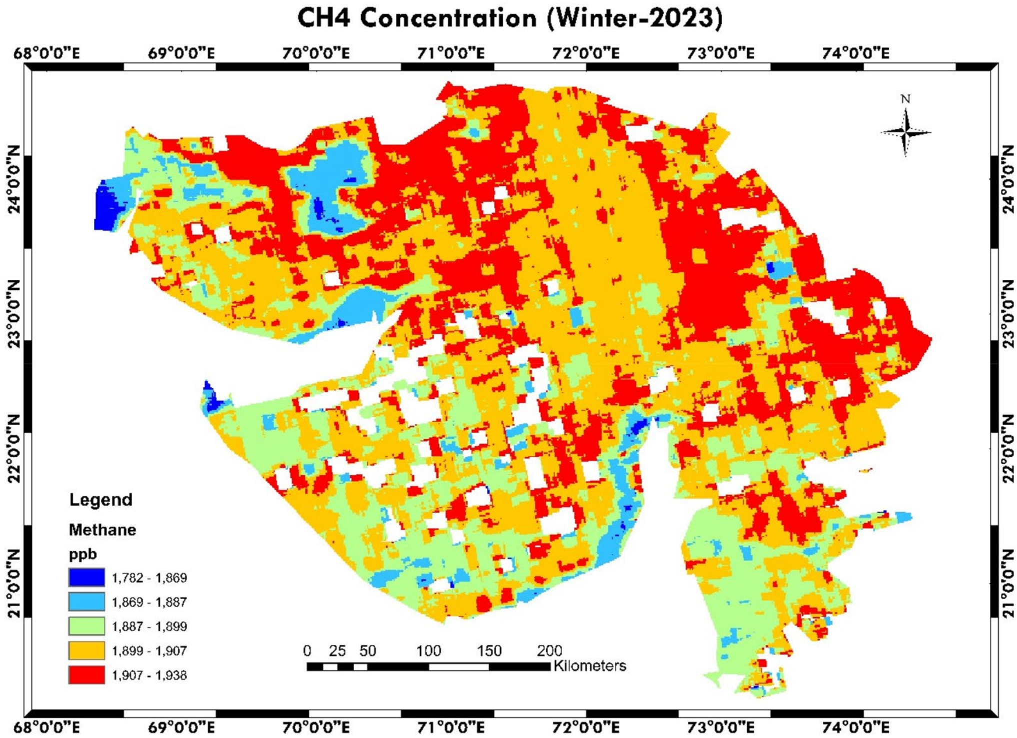


Fig. 8 NO_2 concentration over major cities of Gujarat

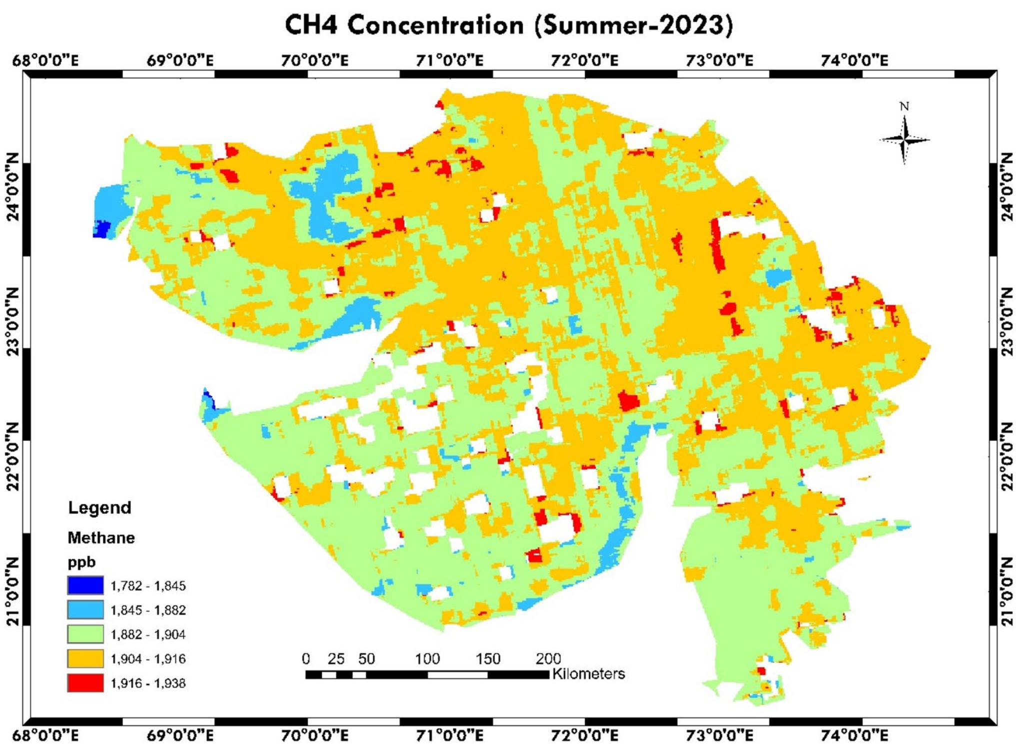
6 Discussion

The increase in the concentration of CO in the regions of central and southern Gujarat is due to the attributes of an increase in vehicular emissions and industrial activities [63, 64]. while on the other hand, lower concentrations are observed in the northern parts of Gujarat which showcases low anthropogenic activities. Pollutants like sulfur dioxide, nitrogen dioxide, and formaldehyde also portray consistently high values in some major cities of Gujarat due to some industrial and urban activities, however, the concentration of sulfur dioxide and formaldehyde is directly related to the temperature of the particular region, and the concentration increases as temperature decreases. High methane concentration can be observed in the northern region of the state due to agricultural practices and waste disposal, hence the concentration is lower in the southern parts. The study utilizes Sentinel 5-P satellite data sets to map the concentration of key pollutants, including CO, NO_2, SO_2, CH_4, and HCHO over Gujarat, India. Employing the GEE platform for image processing and ArcGIS 10.3 for map generation, the analysis spans three seasons–winter, summer, and monsoon—to capture the influence of climatic variations on pollutant levels. Results indicate significant spatial disparities, with urbanized and industrialized regions such as Valsad, Surat, Bharuch, Vadodara, and Ahmedabad exhibiting higher pollutant concentrations compared to less urbanized areas like Kutch, Banaskantha, and Patan in the north. These findings underscore the impact of human activities, industrialization, and urbanization on air quality, emphasizing the importance of targeted interventions to mitigate pollution and safeguard public health and environmental well-being in rapidly developing regions [65].

In the intricate connection of atmospheric dynamics, human activities, and sustainable progress, CO, NO_2, SO_2, CH_4, and HCHO exert far-reaching effects on societies [66], deeply intertwined with the aspirations of the Sustainable Development Goals. Carbon Monoxide, stemming chiefly from vehicular exhausts, industrial operations, and biomass combustion, not only imperils public health, contributing to respiratory ailments and cardiovascular disorders, but also exacerbates climate change as a potent greenhouse gas, thereby aligning with SDG 3's mandate of ensuring universal health and well-being [67, 68]. Nitrogen Dioxide, a byproduct of combustion in transportation, power generation, and industrial processes, not only aggravates health issues, exacerbating respiratory conditions and fostering ground-level ozone, but also undermines sustainable urban development and clean air, hence bolstering SDG 11's objective of fostering inclusive, safe, resilient, and sustainable cities. Sulfur Dioxide, primarily emitted from the burning of fossil fuels in industrial settings and energy production, not only catalyzes acid rain formation, impacting ecosystems and infrastructure, but also jeopardizes public health, underscoring the need for transitioning to cleaner energy sources as advocated by SDG 7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. Methane, a potent greenhouse gas emitted from diverse sources including agriculture, energy facilities, and waste management, poses a dual threat: intensifying climate change due to its high global warming potential and posing risks to human health and ecosystems, necessitating concerted action to mitigate emissions, in accordance with SDG 13's goal of taking urgent action to combat climate change and its impacts.

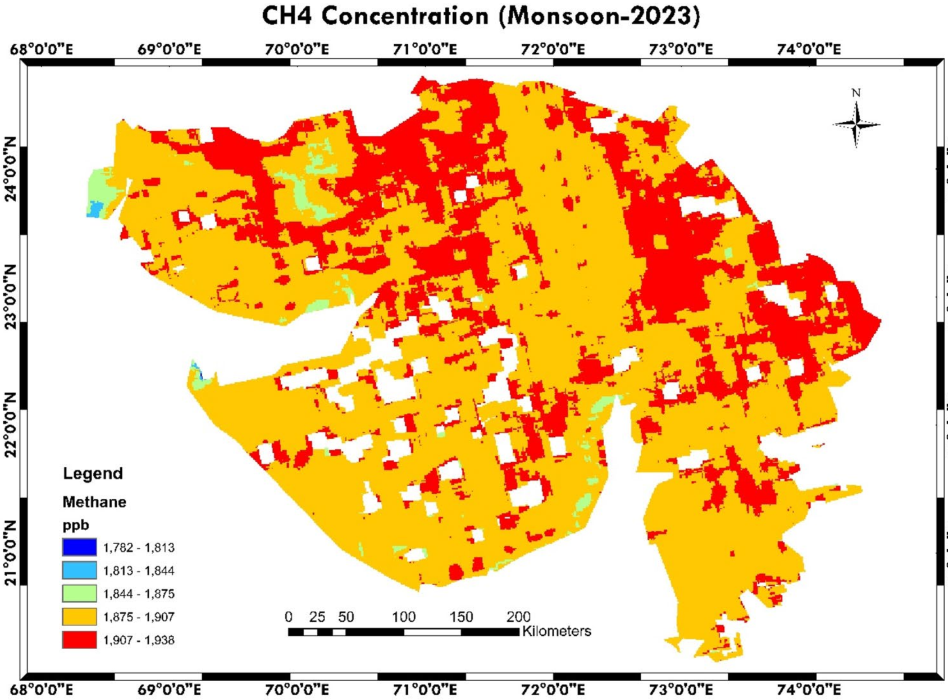


(a)



(b)

Fig. 9 Concentration of Methane in various seasons over Gujarat (**a**) Winter 2022, (**b**) Summer 2023, (**c**) Monsoon 2023, and (**d**) Yearly graph of CH_4 emitted



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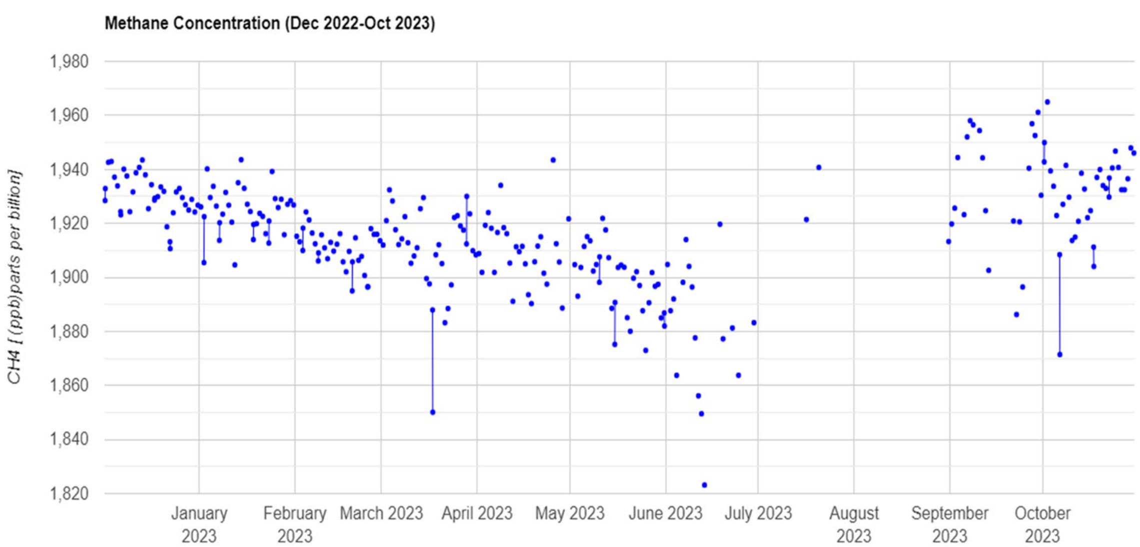


(d)

Fig. 9 (continued)

Formaldehyde, a volatile organic compound originating from combustion processes and natural occurrences such as forest fires, presents health hazards, causing respiratory discomfort and being classified as a carcinogen, highlighting the urgency of monitoring and curtailing emissions to safeguard human health and ecosystems, in accordance with SDG 3's target of ensuring healthy lives and promoting well-being for all at all ages, and SDG 15's aim to protect, restore, and promote sustainable use of terrestrial ecosystems. Ultimately, addressing the emissions of CO, NO2, SO2, CH4, and HCHO emerges as an imperative for advancing multiple SDGs, fostering a holistic approach to sustainable

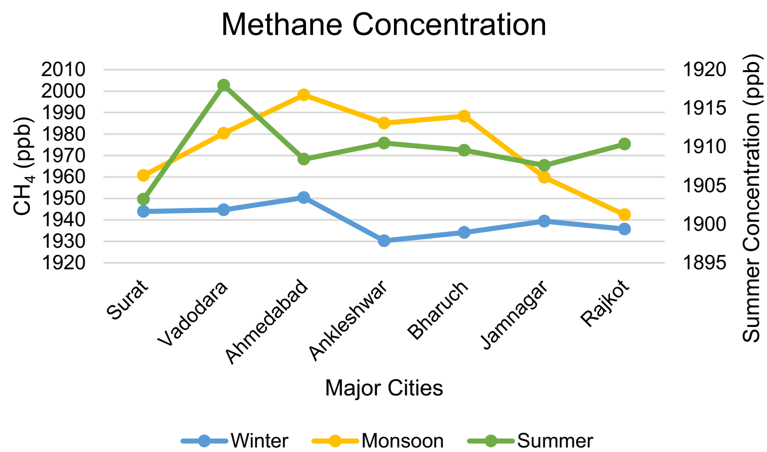


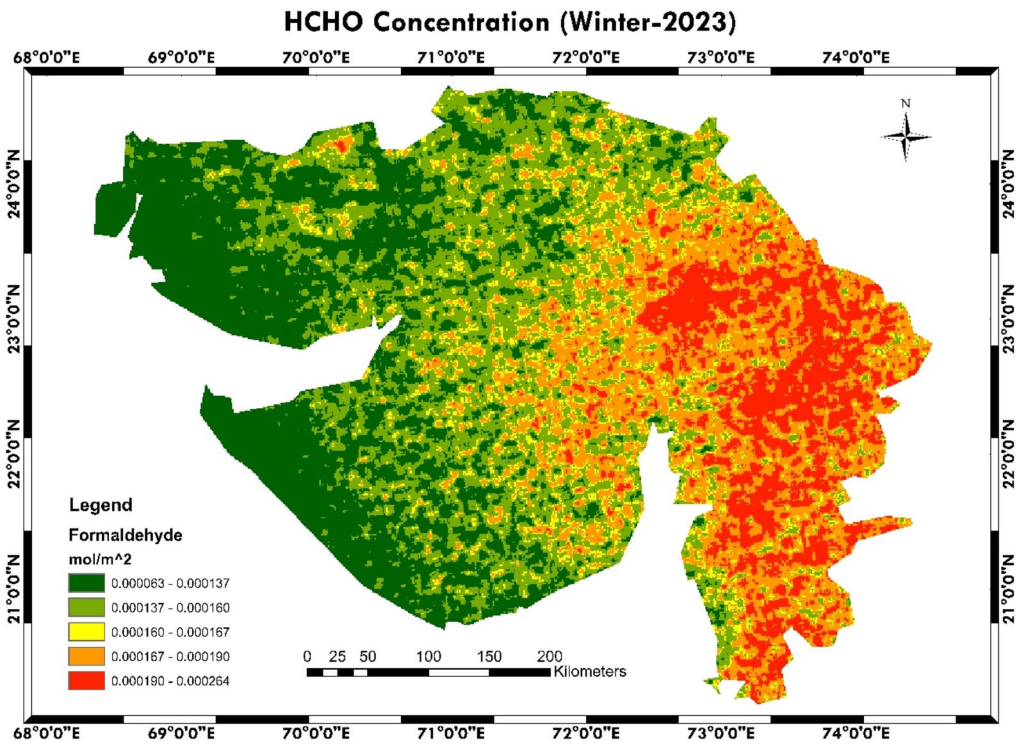
Fig. 10 Methane (CH_4) concentration in major cities of Gujarat

development that prioritizes societal welfare, environmental integrity, and resilience against climate change [69].

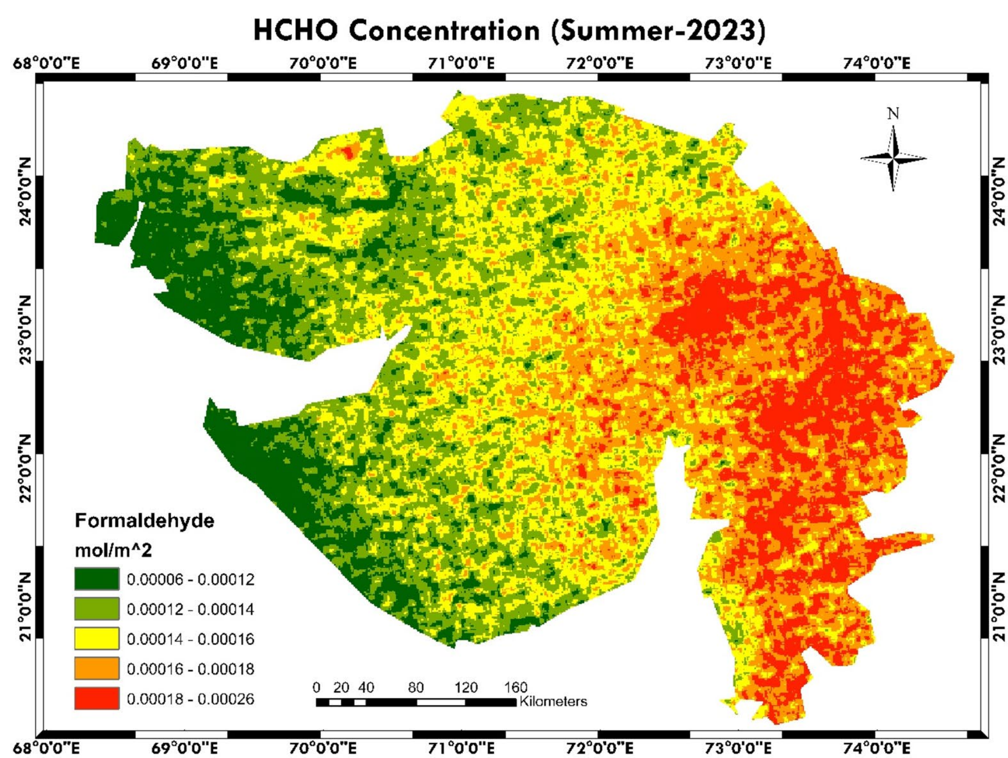
7 Conclusion

The study focus is on the impact of various pollutants on the state of Gujarat in India, particularly regarding carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), methane (CH_4), and formaldehyde (HCHO) concentrations. The study employs data collected from the Sentinel-5P satellite via its TROPOMI instrument to map and analyze these pollutants in different seasons: winter, summer, and rainy seasons. The findings indicate varying concentrations of pollutants in different regions of Gujarat during these different seasons. For instance, carbon monoxide (CO) concentrations show regional variations, with higher levels observed in central and southern regions of Gujarat, particularly in urban areas like Surat, Vadodara, Ahmedabad, and Bharuch, among others. Sulfur dioxide (SO_2) concentrations also demonstrate variations, with more intense levels in areas with higher population density. Similarly, nitrogen dioxide (NO_2) shows increased concentrations in urbanized regions, pointing to its direct correlation with human activities, industrialization, and combustion of fossil fuels. Methane (CH_4), a significant greenhouse gas, shows uniform distribution over the area, signifying its sources related to human activities such as agricultural practices and waste degradation. Additionally, formaldehyde (HCHO) concentrations reveal higher levels in regions with significant industrial and human presence.

The research study provides a comprehensive overview of the seasonal variations of these pollutants and their spatial distribution across Gujarat, where the concentration of CO ranges from 0.0295–0.0401 mol/m^2, while SO_2 has an average concentration of 0.00047 mol/m^2, NO_2, on the other hand, has its average concentration ranging from 0 to 0.00021 mol/m^2, formaldehyde ranging from 0.00015 to 0.00026 mol/m^2, however fuel gases like methane have their concentration ranging from 1780 to 1940 ppb. These findings hold significant implications for environmental and public health in the state, indicating areas where concentrations of these pollutants are notably higher. This information is crucial for developing targeted strategies and policies to address and mitigate air pollution and its associated risks. The spatial variations in pollutant concentrations offer insights into the regions that might be more vulnerable to air quality-related issues. These findings could aid local authorities and policymakers in implementing measures to control and reduce pollution, thereby improving air quality and public health in these areas. Furthermore, the use of Sentinel-5P data in mapping these pollutants demonstrates the efficacy of remote sensing and satellite technology in monitoring and analyzing environmental factors. This approach provides an efficient way to understand the spatial distribution of pollutants, enabling more informed decision-making and targeted interventions to combat air pollution. In conclusion, the research work thorough analysis of pollutant concentrations in Gujarat during different seasons offers valuable insights into the state's environmental challenges. The findings might serve as a foundation for policymakers, researchers, and local authorities to develop and implement measures aimed at

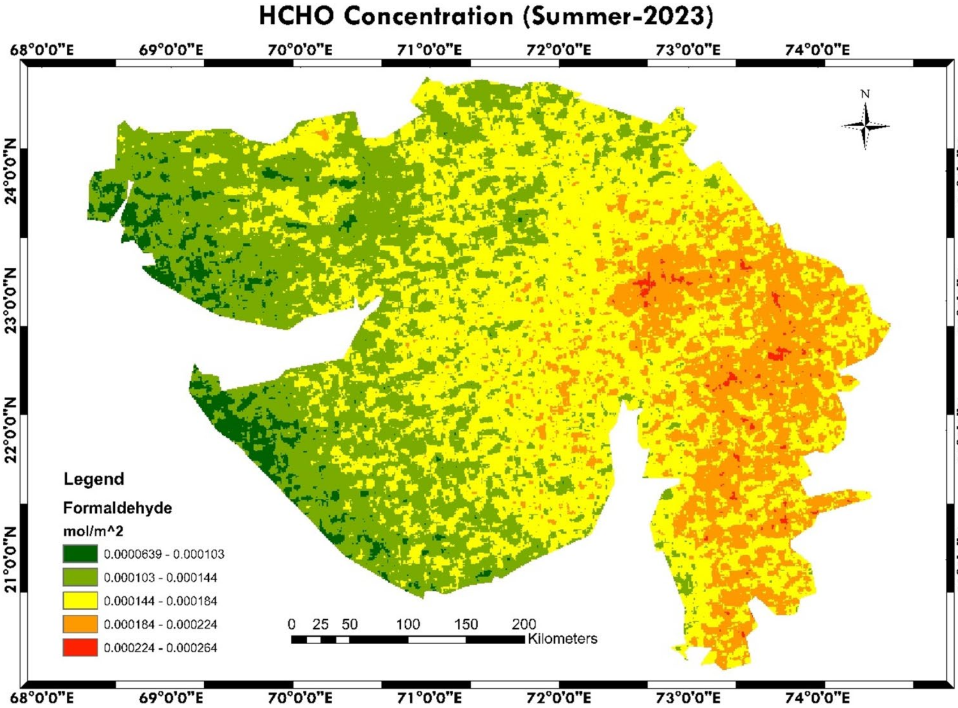


(a)



(b)

Fig. 11 Concentration of Formaldehyde in various seasons over Gujarat (**a**) Winter 2022, (**b**) Summer 2023, (**c**) Monsoon 2023, and (**d**) Yearly graph of HCOH concentration over Gujarat



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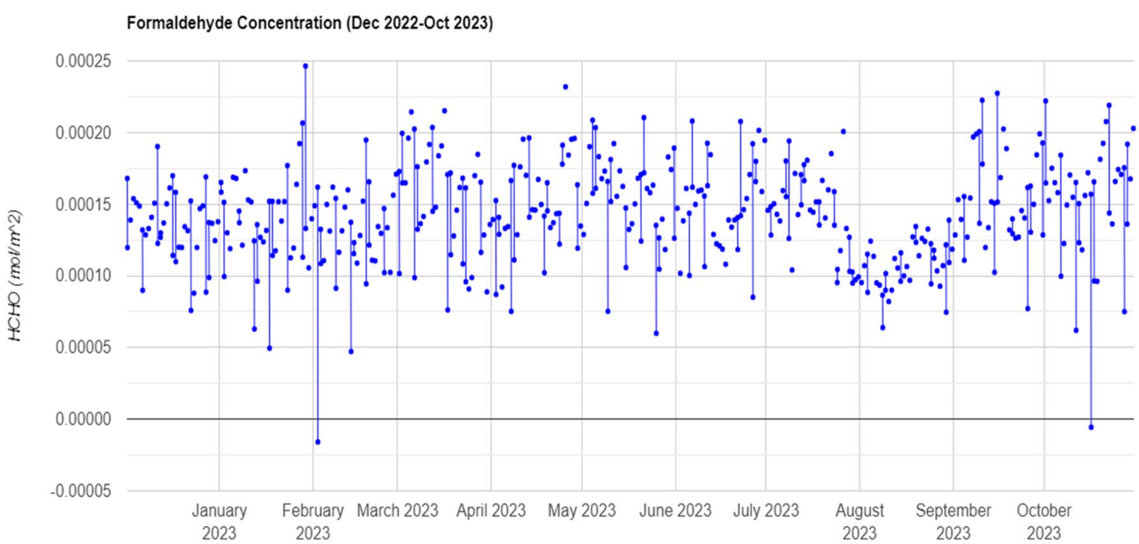

(d)

Fig. 11 (continued)

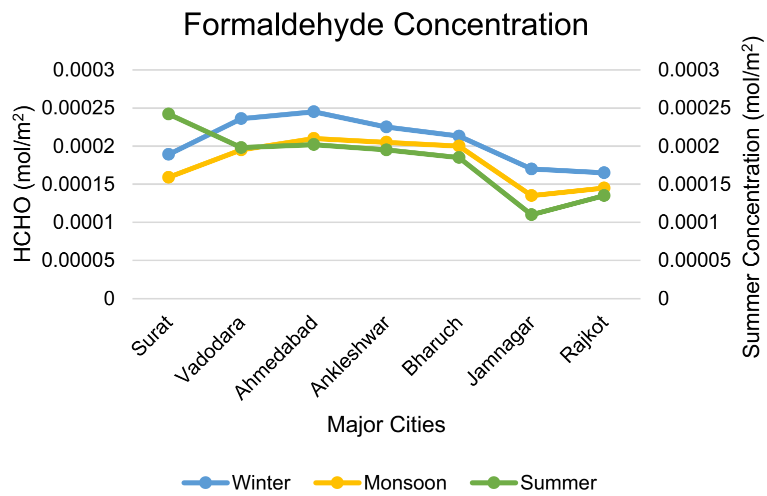

Fig. 12 Formaldehyde concentration in major cities of Gujarat

controlling and mitigating air pollution, ultimately working towards a healthier and more sustainable environment in the region. The seasonal changes in the concentration of various pollutants after the pandemic, for the year are analyzed thoroughly, the same study can be done for upcoming years which would help in understanding the changes through a trend line and hence predict the changes accordingly for the near future. Following this, a spatiotemporal analysis using various technologies in collaboration with recent advanced techniques like machine learning and artificial intelligence can be used to increase the accuracy of the same.

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Data Availability The data supporting the results of this paper are available on reasonable request.

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