



Satellite-Based Mapping for Seasonal Variations of Air Pollution and its Environmental Effects in Odisha

Sudhakar Pal¹ · Arabinda Sharma¹ 

Received: 20 June 2023 / Accepted: 11 June 2024 / Published online: 1 July 2024
© Indian Society of Remote Sensing 2024

Abstract

Air pollution is an important global environmental issue impacting public health across the world. Innovative satellite-based technology has revolutionized the monitoring of air pollution, enabling assessments on various scales with unprecedented accuracy and coverage. The study attempts to estimate the seasonal and spatial fluctuations of various gaseous pollutants using Sentinel-5P TROPOMI satellite images at the district level in Odisha. In order to comprehend the environmental impact of air pollution, an effort must be made to assess potential greenhouse gas (GHG) emissions and potential acidification levels in Odisha. Results showed that potential emissions of greenhouse gases vary regionally and range from 378.82 g CO₂ equivalent/m² to 386.22 g CO₂ equivalent/m², while potential acidification levels range from 0.008 g SO₂ equivalent/m² to 0.034 g SO₂ equivalent/m². The north-western (Jharsuguda, Sambalpur, Bargarh, Sonepur, and Sundargarh) and north-central (Angul, Dhenkanal, and Deogarh) regions of Odisha exhibit high potential emissions of greenhouse gases and levels of acidification. This is attributed to comparatively higher concentrations of various pollutants stemming from sources like industrial and vehicle emissions. Although the satellite-based study enabled us to characterise the relative air pollution across the state, it necessitated a number of air pollution monitoring stations for validation purposes. A future road map to address climate change and environmental protection may be developed with the aid of local officials and policymakers.

Keywords Air pollution mapping · Sentinel-5P image · Greenhouse gas emission · Potential acidification · Mitigation strategies

Introduction

Air pollution, a critical global environmental issue, significantly impacts public health and ecosystems worldwide. The increasing concentration of various pollutants, including greenhouse gases (GHGs) and acidifying agents, exacerbates climate change and degrades air quality, posing severe risks to human health and biodiversity (Bodor et al., 2022; Gao et al., 2022). It causes several problems to the vulnerable people and increases the risk of premature death (Agrawal et al., 2021; Hu et al., 2021a, 2021b; Miao et al., 2022). Odisha, a state in eastern India, is no exception to this pressing issue. Characterized by a diverse landscape of industrial hubs, agricultural zones, and urban areas, Odisha experiences varied levels of air pollution, necessitating

comprehensive monitoring and assessment to devise effective mitigation strategies (OSPCB, 2021).

Recent advancements in satellite-based technology have revolutionized the monitoring of air pollution, offering unprecedented accuracy and extensive coverage (Biswal et al., 2020). The European Space Agency (ESA) provides an opportunity to researchers worldwide, enabling the detection of air pollutants through state-of-the-art techniques (William et al., 2022). Utilizing the Tropospheric Monitoring Instrument (TROPOMI) for the analysis of Sentinel-5P satellite data enables the estimation of concentrations for various air pollutants, such as aerosol index (AI), carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), and methane (CH₄). This data is crucial for evaluating environmental management strategies aimed at enhancing air quality and public health (Zheng et al., 2019). The most commonly measured criteria air pollutants are CO, NO₂, SO₂, ozone O₃, and particulate matter (PM) (Benchrif et al., 2021; Hashim et al., 2021). These air pollutants have historically been released and continue to be released into the atmospheric air (Al-Alola

✉ Arabinda Sharma
arbind_78@rediffmail.com

¹ School of Geography, Gangadhar Meher University, Sambalpur, Odisha 768004, India

et al., 2022; Dutta et al., 2021). Especially, Urban and industrial areas typically have higher concentrations of these pollutants compared to rural regions (CPCB, 2009; Bozkurt et al., 2018). The primary anthropogenic sources include industrial emissions, domestic fuel combustion, traffic emissions, coal mining, and agricultural waste burning, etc. (Dave et al., 2020; Ielpo et al., 2019; Mehta & Sharma, 2017; Sahu et al., 2020, 2022; Zhou et al., 2021).

The concentration of various air pollutants fluctuates seasonally, with previous studies showing a strong correlation between pollutant levels and meteorological parameters (Gao et al., 2022; Kim et al., 2014; Othman et al., 2013). Weather conditions like temperature, precipitation, humidity, air pressure, wind speed, and wind direction have an impact on the variation in air pollution concentrations in the atmosphere (Deary & Griffiths, 2021). The influence of different meteorological parameters varies from one place to another (Liu et al., 2022). The use of satellite observations as a supplement to ground-based monitoring networks is emphasized by Zhang et al. (2019), particularly in areas with limited numbers of ground stations. The adaptability of satellite remote sensing methods, which allow for the monitoring of air pollution in both urban and rural locations, is further discussed by Liu et al. (2020). Cheng et al. (2021) recognize the advancements in using satellite data for air quality monitoring while pointing out the challenges and opportunities for further improvement. With the advent of new sensors and computing techniques, the use of satellite-based air pollution monitoring has grown (Li et al., 2022). Among the available sensors, Sentinel-5P data are highly relevant to estimate anthropogenic emissions and designing future air pollution reduction strategies (Zheng et al., 2019).

To comprehend the spatial variation in air pollutant concentrations and the resulting environmental consequences, the severity of air pollution at the district level must be estimated. Measures such as potential greenhouse gas production and potential acidification levels can indicate the influence of air pollution in a warming world climate and its ability to acidify freshwater habitats and soil ecosystems (Babatunde et al., 2020). When comparing greenhouse gases, their global warming potential (GWP), which measures how well a gas pollutant can trap heat in the atmosphere compared to an equivalent amount of carbon dioxide, is used as a benchmark (Derwent, 2023). Gases such as CO, O₃, CH₄ and CO₂ have the potential to directly warm the global climate (Heijungs et al., 1992), whereas potential acidification, which is indicated by SO₂-equivalence, is the ability of a pollutant to acidify the environment (Arghya Sardar, 2015). It might have a significant impact on freshwater and soil ecosystems, which would cause a great deal of natural species to disappear (Cho et al., 2017). Previous research has not sufficiently addressed the levels of acidity and potential greenhouse gas emissions

from common air pollutants. Therefore, this study aims to fill that gap using the currently available data.

Thus, it is imperative to estimate the spatial variation of different pollutant concentrations and assess current management strategies. At this outset, the present work involves the estimation of seasonal variation in the concentration of various gaseous pollutants in the ambient air of Odisha at the district level. It further attempts to identify the air pollution hot spot area using high-resolution Sentinel-5P satellite images in the Google Earth Engine platform. By analyzing these variations, the research seeks to provide insights into the potential concentrations of greenhouse gases and levels of acidification across the state. This type of study will present a comprehensive picture of the severity of the air pollution in the studied area. It may also assist local officials and policymakers in realising and understanding the state's true pollution scenario, which will then help them create a future roadmap to address climate change and environmental protection.

Study Area

Odisha, a state on the eastern coast of India (Fig. 1), has a total area of 155,707 km². The state is divided into 30 administrative geographical units called districts and belongs to the tropical monsoonal climate. The state experiences winter, pre-monsoon, monsoon, and post-monsoon seasons. The total population of the state is about 4.2 crore, and the population density is 270 per km². In Odisha, urban areas are home to 17% of the total population. Odisha is one of the leading industrial and mining states in India.

Odisha is one of the industrial and mining states of eastern India suffering from different degrees of air pollution-related problems and associated hazards. In Odisha, some of the main sources of air pollution include intensive industrial emissions, coal mining, thermal plants, and vehicle exhaustion. Sundargarh, Angul, Jharsuguda, Keonjhar, etc. are the industrial regions of Odisha. In Odisha, there are more than 240 mines. The top mining districts in Odisha include Koraput, Mayurbhanj, Malkangiri, Rayagada, Sundargarh, Keonjhar, and Sambalpur, among others.

Data Source

The study utilized the Google Earth Engine tool for mapping pollution on a seasonal basis from March 2021 to February 2022. Sentinel-5P satellite images from the TROPOMI instrument have been used for this mapping purpose in this study. Sentinel-5P is a very high-resolution dataset that Google Earth Engine makes available for mapping the various pollutants around the world. To calculate the average

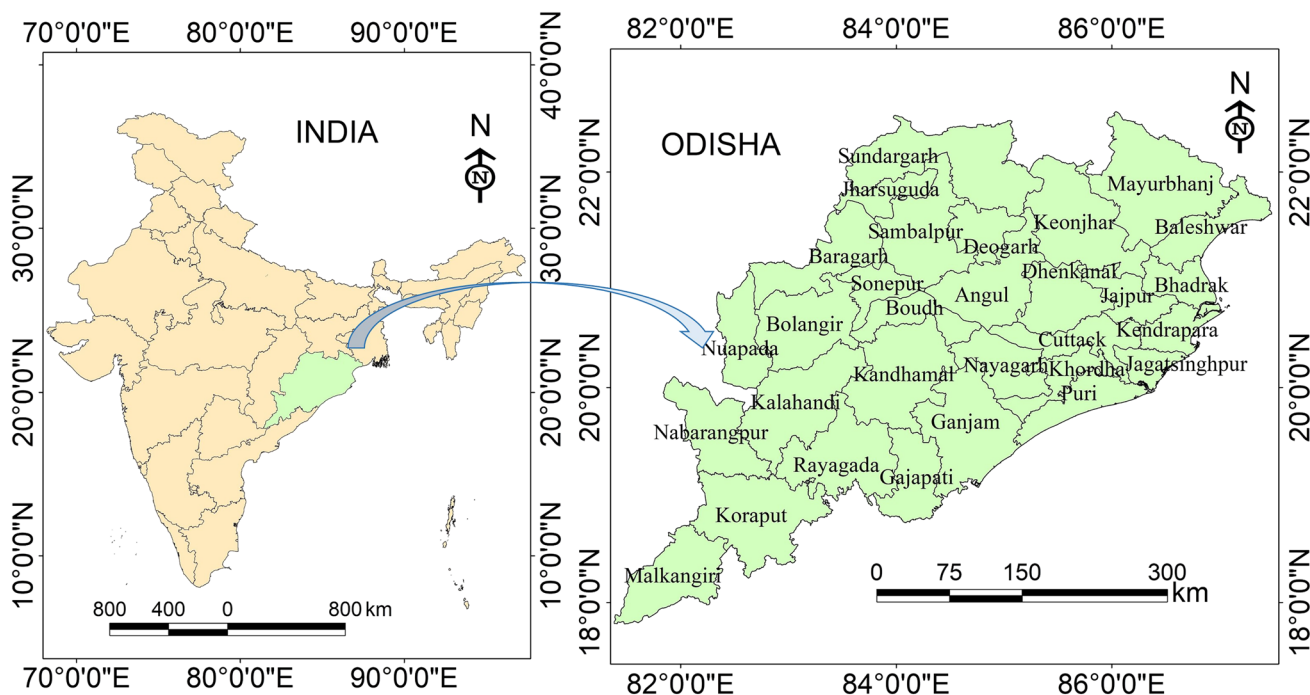


Fig. 1 Location map of the study area

Table 1 Total number of satellite images available in google cloud to create average seasonal maps of various air pollutants (Google Earth Engine: Link- <https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p>)

Pollutants	Summer	Rainy	Winter
SO ₂	1272	1716	2112
NO ₂	1272	1716	2115
CO	1273	1661	2116
O ₃	1273	1715	2118

seasonal maps for all four pollutants, various map elements are available for the summer, rainy, and winter seasons in the Google Cloud platform (Table 1).

In this study, maps depicting the average pollution concentrations in Odisha during the seasons of summer (March to May), rainy (June to September), and winter (October to February) were derived and finalized on February 13, 2023.

Methodology

Seasonal Map for Various Gas Pollutants

Google Earth Engine is a powerful tool to analyse and visualize several geospatial datasets. A large set of global and regional datasets are available in its data catalogue. In this study, maps illustrating the concentrations of various

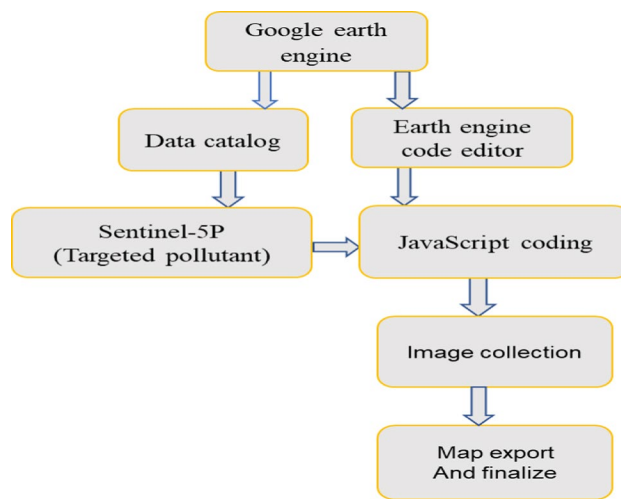


Fig. 2 Flow chart for generating and extracting pollution map from google earth engine

gaseous pollutants were created using Sentinel-5P satellite data sourced from the Earth Engine cloud (refer to Fig. 2).

Various maps of intricate geospatial data can be generated by entering the appropriate codes into the JavaScript code editor console of Earth Engine. An example of preparing and exporting a pollution map (CO) on the Google Earth Engine platform is given below with JavaScript codes. Only the places of the given codes that are in italic style will be changed as per different pollutants.

JavaScript coding for extraction of pollution maps (giving an example of CO)

```

var ROI = ee.FeatureCollection("Odhisha_boundary");
var CO = ee.ImageCollection("COPERNICUS/S5P/OFFL/L3_CO")
Map.addLayer(ROI)
Map.centerObject(ROI,10)
var CObands = CO.select('CO_column_number_density')
var image = CObands.filterBounds(ROI)
var COfilterdate = image.filterDate('2021-10-01','2022-02-28')
var averageCO = COfilterdate.reduce(ee.Reducer.mean())
var band_viz = {
  min: 0,
  max: 0.05,
  palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red']
};
var study_area = averageCO.clip(ROI)
Map.addLayer(study_area, band_viz)
print(COfilterdate)
print(image.size())

Export.image.toDrive({image:study_area,
description:'CO20rainy',
folder:'CO',
region:ROI,
scale: 1113.2})

```

Potential Greenhouse Gas Concentration and Acidification Level

Figure 3 represents the flowchart for the concentration of district-wise potential greenhouse gas and potential acidification levels in Odisha. The amount of potential greenhouse gas concentration is determined by the global warming potential (GWP) of the pollutant and the concentration amount of this particular pollutant. Various air pollutants are often converted into a ratio in relation to CO₂ equivalents in order to determine GWP. The yearly mean potential greenhouse gas production per square metre area of each

district for the months of March 2021 to February 2022 is estimated in this study using CO, O₃, and NO₂. The total area of each district is then factored into the calculation to determine the amount of greenhouse gas concentration on a district-to-district basis. Finally, district-wise total potential greenhouse gas concentrations are calculated by multiplying the emissions of all individual pollutants for each district. To show the potential production map of greenhouse gases in Odisha, Table 2 shows the likely global warming potential (GWP) of various gaseous pollutants equivalent to CO₂ concentration for a 100-year timescale.

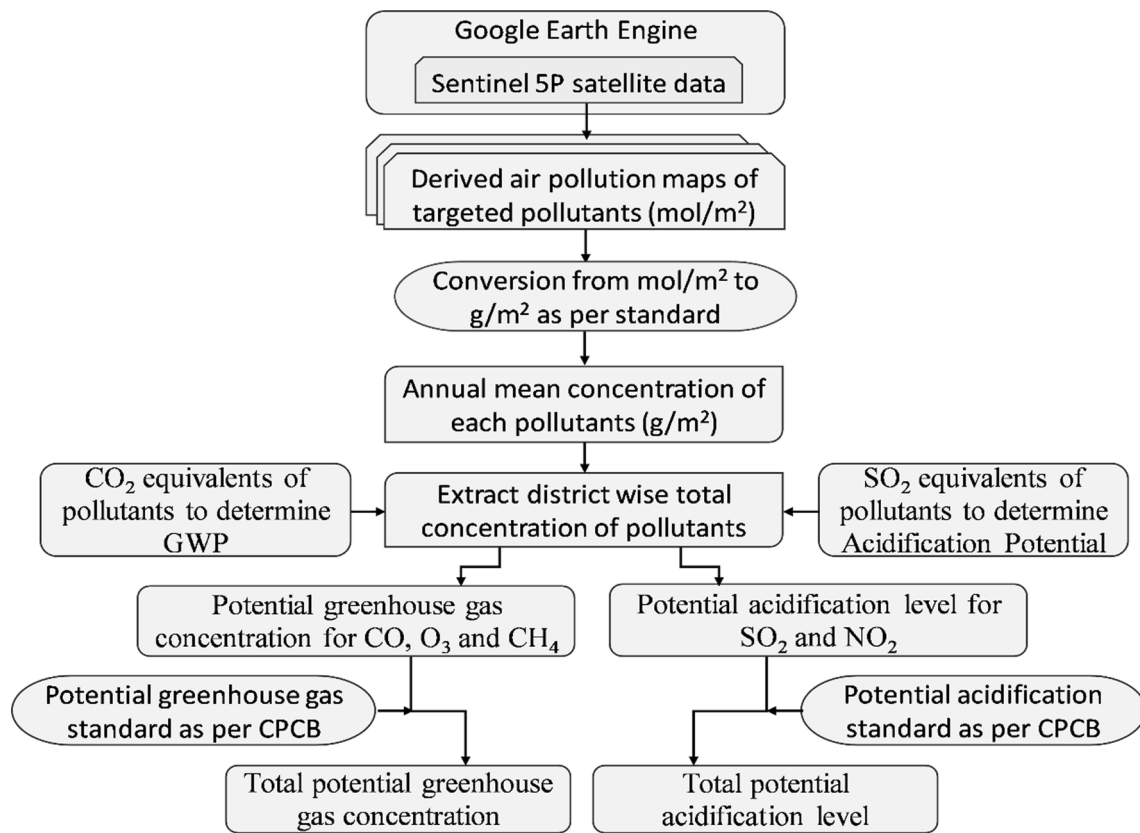


Fig. 3 Flow chart for computation of potential greenhouse gas concentration and potential acidification level

Table 2 GWP and acidification potential of studied air pollutants

Pollutants	GWP (CO ₂ equivalents)*	Acidification potential [#]
CO ₂	1	NA
CO	2	NA
O ₃	65	NA
CH ₄	21	NA
NO _x	NA	0.7
SO ₂	NA	1.0

(*Kiehl & Trenberth, 1996; IPCC, 2007; EPE, 2023 [#]Heijungs et al., 1992)

The concentration of each individual acidifying gas and the acidifying potential of this criterion gas are used to calculate the district-level mean yearly potential acidification level per square metre area. Next, the total geographic area of each district is multiplied to determine the overall acidity level. The acidification potential is typically calculated as a characterization of SO₂ equivalents, similar to how the GWP of various pollutants is converted to a ratio. This study used SO₂ and NO₂ to estimate the level of acidification. The likely acidification potential (AP) of NO₂, expressed in terms of

SO₂ equivalents, is shown in Table 2 and is used to calculate and visualise the geographical variation in acidification levels in Odisha.

Result and Discussion

Seasonal and Spatial Variation of Various Gaseous Pollutants in Odisha

Each criterion pollutant exhibits distinct seasonal variations due to its various source activities and unique interactions with climatic factors. Often, these source activities are highly concentrated in specific locations and times. Consequently, the geographic variations of the pollutants are detailed below for each individual criterion air pollutant.

Concentration of SO₂ in the Atmospheric Air of Odisha

SO₂ is a toxic gas that is produced naturally through volcanic activity as well as anthropogenic activities such as copper extraction by-products and the combustion of some sulphur-containing fossil fuels.

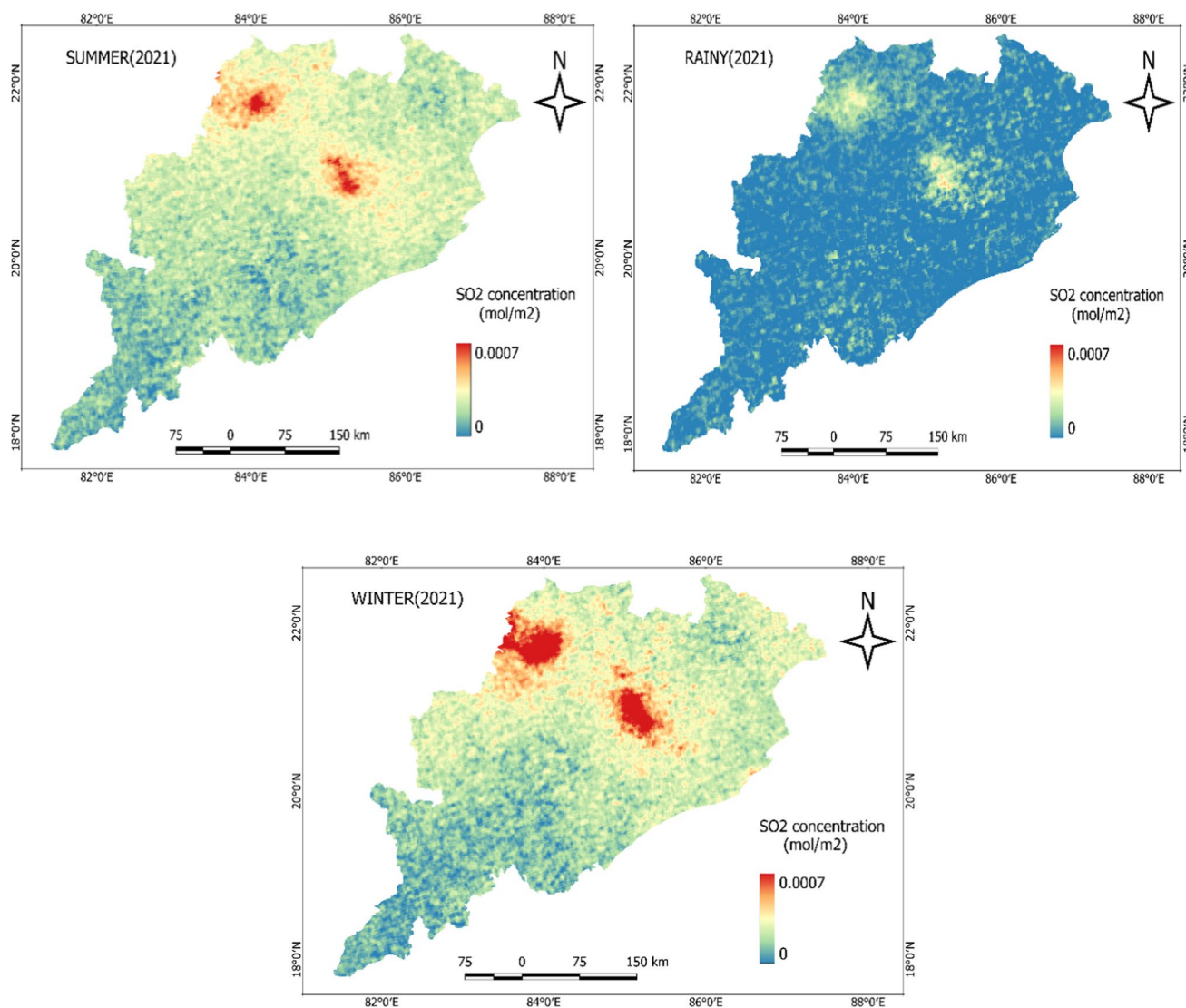


Fig. 4 Season-wise variation of SO₂ concentration in the atmospheric air of Odisha

In this study, the Google Earth Engine tool was used to create maps of SO₂ concentrations to identify the seasonal and spatial patterns of SO₂ in the ambient air of Odisha. The spatial variation in SO₂ is particularly noticeable due to the unequal distribution of pollutant sources across the region. Hotspots of SO₂ concentration are aligned with major coal-bearing areas, such as the Angul, Jharsuguda, and Sundergarh districts. These districts are not only home to coal mines but also coal-fired power plants and other metallurgical industries that utilize coal from the Mahanadi River basin, which has a relatively high sulfur content. A sharp seasonal variation is found in the above maps. SO₂ gas particles are subsidized and washed out of the atmosphere through the rainwater during the rainy season (Spiroska et al., 2013). Therefore, the concentration of SO₂ in the

rainy season is much lower than compared to the summer and winter (Fig. 4).

The states like Jharsuguda (maximum 0.00072 mol/m²), Sundergarh, Sambalpur (in the northern part) and Angul, Keonjhor, and Dhenkanal (north-central part) are characterized with a comparatively high concentration of SO₂ throughout the year due to the location of several industries, thermal plants, and mining places (Fig. 5). The extensive use of coal and diesel in commercial vehicles might be responsible for it. The elevated levels of sulfur dioxide (SO₂) in Odisha's air pose significant risks to human health, including respiratory and cardiovascular issues, and can cause eye and throat irritation (Bozkurt et al., 2018). This gas has the potential to combine with other airborne chemicals to transform into a tiny particle that can enter the lungs and have a similar negative impact on health (Zhou et al., 2021).

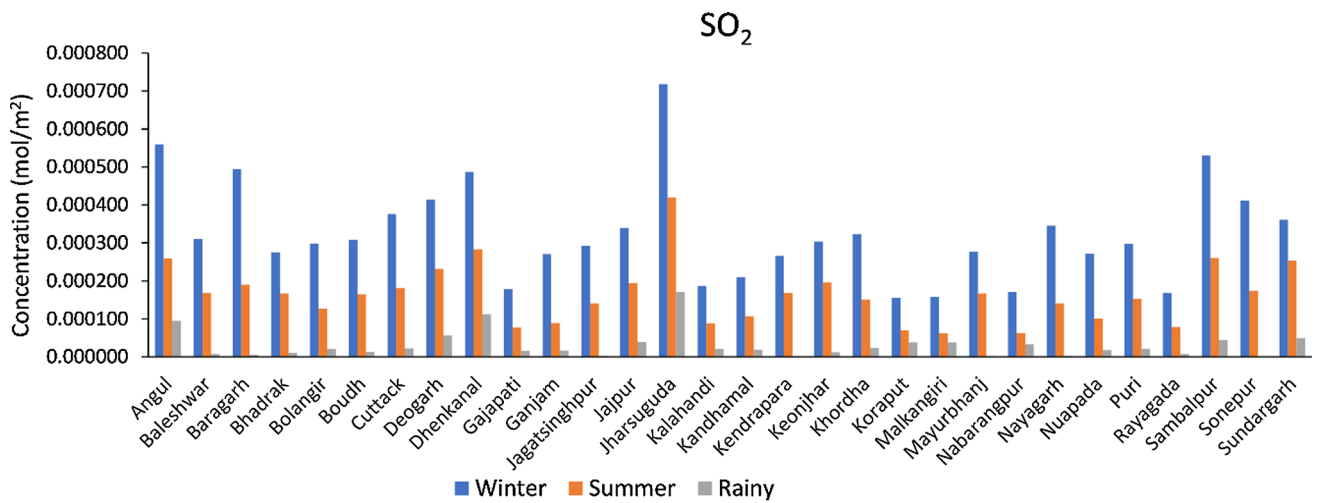


Fig. 5 The district-wise concentration of SO₂ in Odisha from March 2021 to February 2022

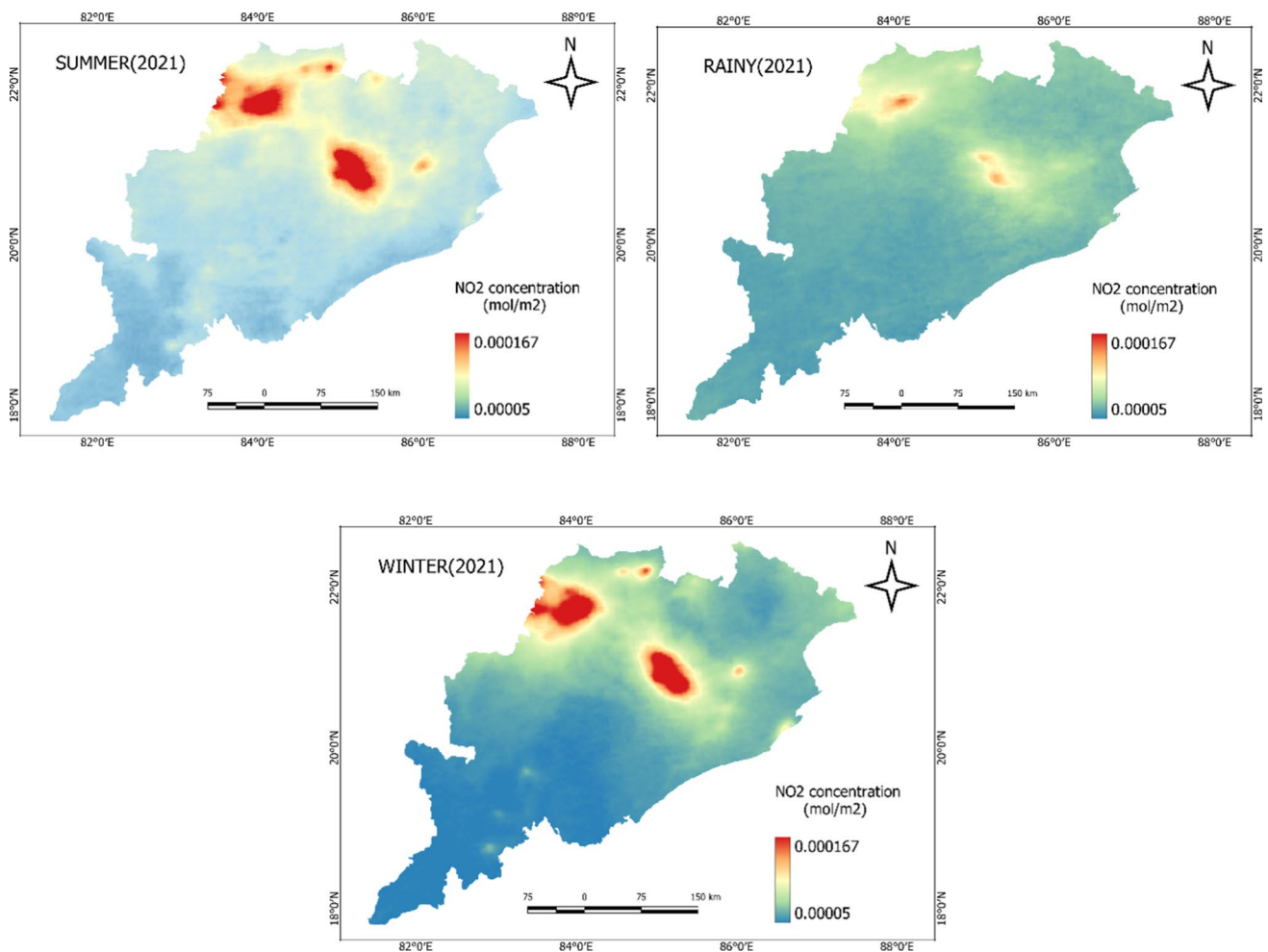


Fig. 6 Season-wise variation of NO₂ concentration in the atmospheric air of Odisha

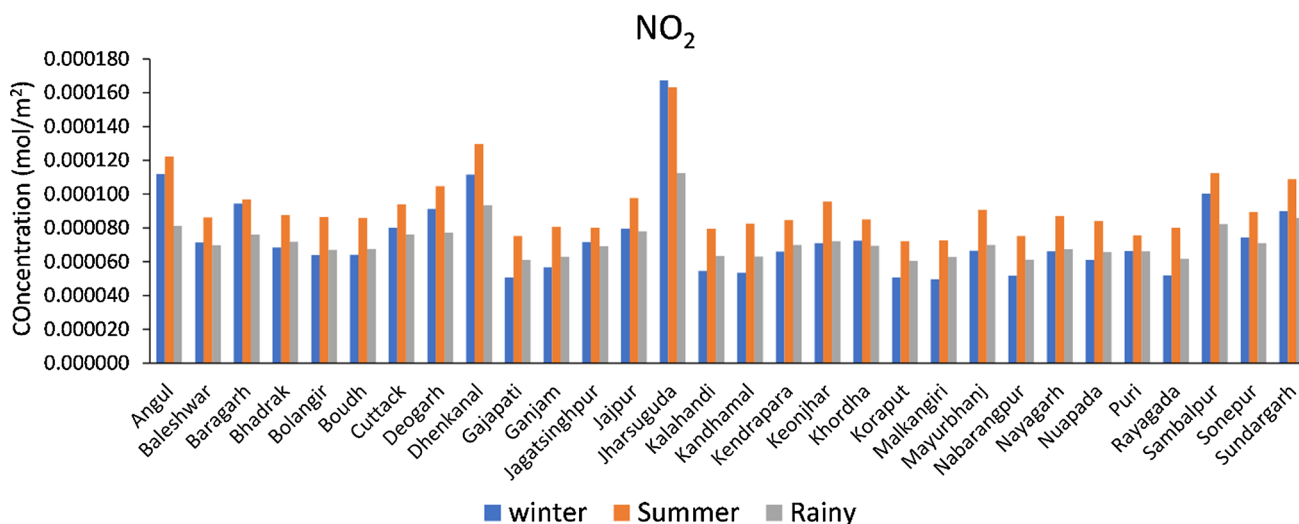


Fig. 7 The district-wise concentration of NO₂ in Odisha from March 2021 to February 2022

According to Environmental Protection Agency (EPA) SO₂ can indirectly influence climate change by forming aerosols that reflect sunlight, and its higher concentration in winter, combined with fog, can lead to severe air pollution episodes known as sulphurous smog. Environmentally, SO₂ contributes to acid rain, which harms aquatic ecosystems, forests, and soil health, and leads to the corrosion of infrastructure (Zhang, 2023). A convenient way to reduce SO_x emissions is to switch to low-sulfur fuels or clean high-sulfur fuels, as the amount of SO₂ produced is directly correlated with the sulfur content of the fuel (Zandaryaa & Buekens, 2009). Deep SO_x removal is possible using flue gas desulfurization (FGD) and alkali sorbent injection techniques (Arghya Sardar, 2015).

Concentration of NO₂ in the Atmospheric Air of Odisha

Motor vehicle emissions, combustion of fossil fuels (coal, oil and gas), household emissions from kerosene heaters and stoves, chemical manufacturing, welding and emissions from power plants are the key sources of NO₂ in the atmospheric air (Zheng et al., 2019). However, thermal power plants, megacities, large urban areas and industrial regions remain the NO₂ emission hotspots (Biswal et al., 2020). Also, agricultural workers may be exposed to NO₂ arising from grain decomposing in soils and from chemical fertilizers used in farms (Zhang et al., 2018). Seasonally, NO₂ concentration was lower during the rainy period compared to both the summer and winter seasons (Fig. 6). This is the likely result of NO_x being reduced from atmospheric air and dissolved into rainwater. However, it may lead to the acidification of surface water bodies harming the entire aquatic ecosystem of the region.

In Odisha, spatial and seasonal variations of the concentration of NO₂ were found during the study period. A high concentration of NO₂ is observed in Odisha's north-eastern and north-central parts throughout the entire study period because of the several industrial locations. Jharsuguda (maximum: 0.00016 mol/m²) is the leading NO₂ emitting district in Odisha and is followed by Dhenkanal, Angul, Sambalpur and Sundargarh (Fig. 7).

The main reason for the creation of NO_x pollutant hotspots in these regions is rapid urbanization following industrialization and the associated increase in transportation infrastructure. Long-term exposure to NO_x poses various respiratory threats, including asthma, to human health (Kampa & Castanas, 2008). Additionally, high levels of nitrogen dioxide not only harm foliage, reduce growth, and lower crop yields but also contribute to acid rain along with SO₂ (Nordeide et al., 2021). Utilizing low-nitrogen fuels is one way to reduce NO_x emissions. Altering combustion conditions to produce less NO_x is another option (Dutta et al., 2021). As stated by the World Bank, the elimination of NO_x can be achieved through selective catalytic reduction (SCR) processes, one type of flue gas treatment method. Since 2000, India has restricted automobile emissions of air pollutants such as particulate matter, SO_x, and NO_x along with carbon monoxide, hydrocarbons, and methane under the Bharat Stage (BS) Emission Standards, which are based on European Union norms (Gajbhiye et al., 2023a, 2023b). India switched from BS-IV to BS-VI in April 2020. This new standard was adopted for all vehicle types and is now in effect nationwide in India, including Odisha (Gajbhiye et al., 2023a, 2023b). This action will stimulate automakers to create and market more eco-friendly, fuel-efficient vehicles.

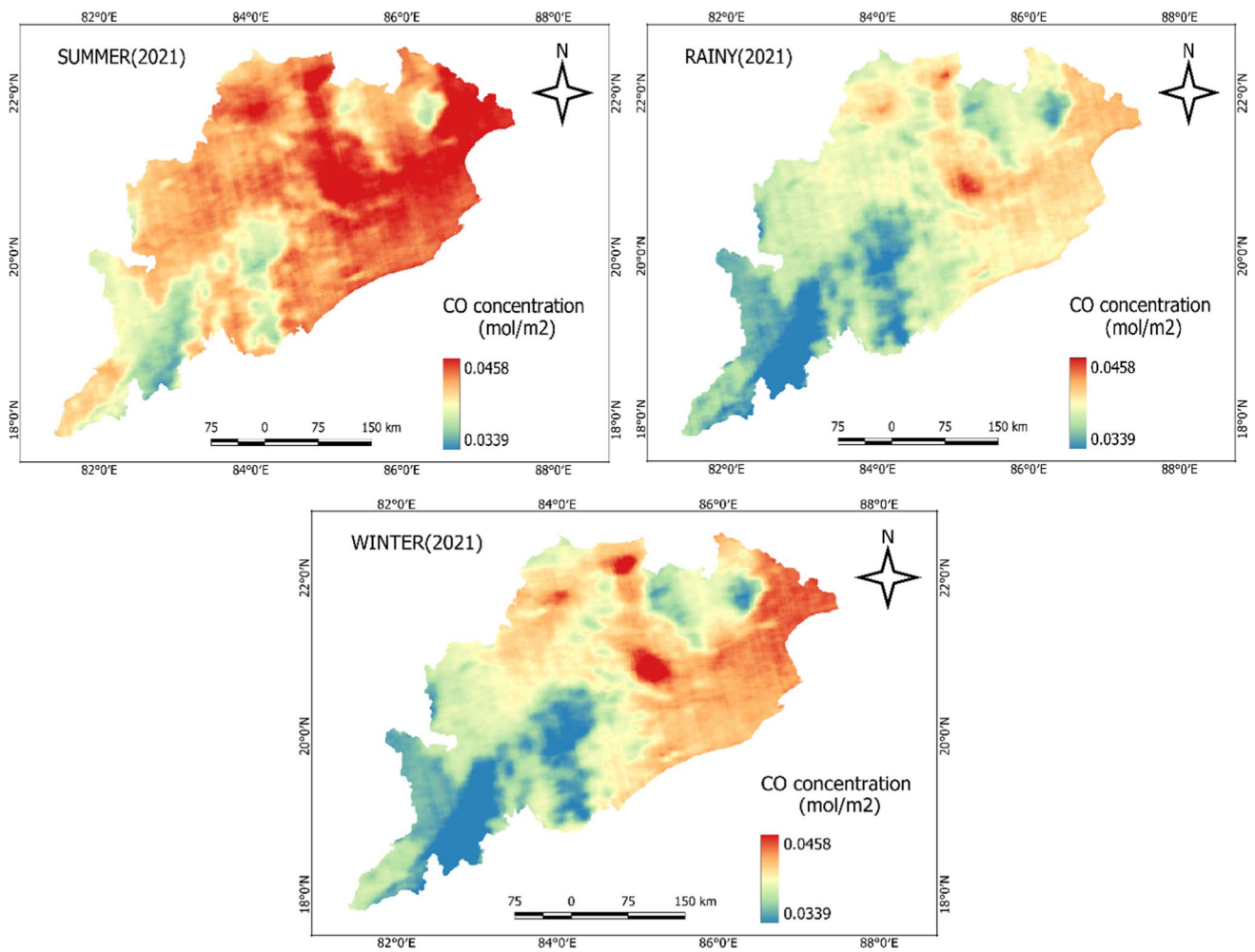


Fig. 8 Season-wise variation of CO concentration in the ambient air of Odisha

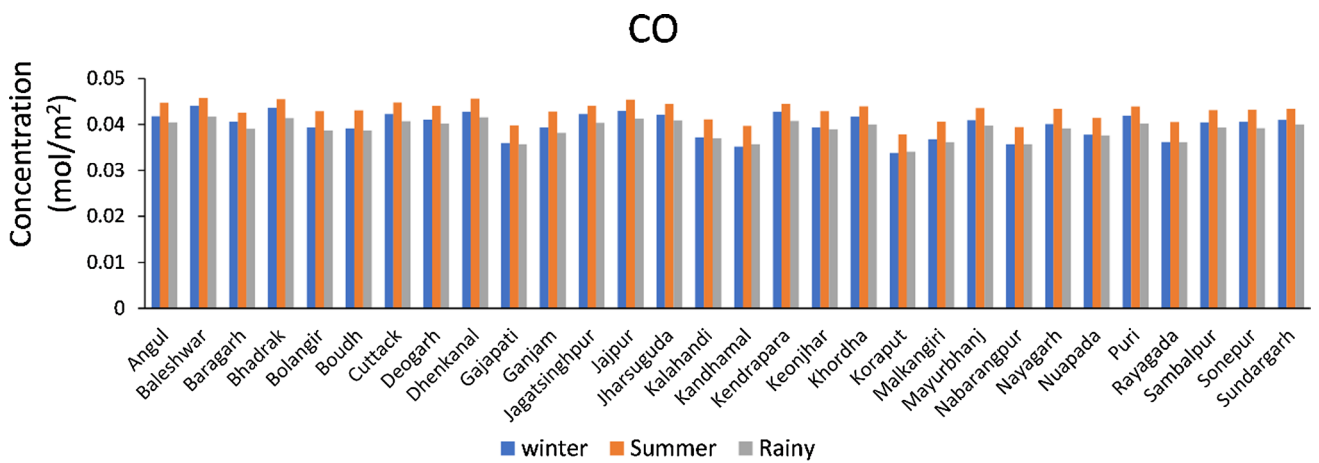


Fig. 9 The district-wise concentration of CO in Odisha from March 2021 to February 2022

Concentration of CO in the Atmospheric Air of Odisha

The incomplete burning of fossil fuels due to either a lack of oxygen or a low gradient is the main reason behind the emission of carbon monoxide (Buchholz et al., 2021). CO emits from all combustion sources, such as power stations, motor vehicles, the burning of domestic fuels, and waste burning (Aljahdali et al., 2021; Sahu et al., 2013). It has a few temporary consequences on the human breathing system including a reduction in oxygen carrying capacity of red blood cells (Pal et al., 2022).

The concentration of CO in the rainy season is comparatively lower than in the other two seasons (Fig. 8). There is less precipitation of CO, therefore mixing with cleaner marine air due to prevailing SW winds could be the main reason for lower values of CO during the rainy season. (Kim et al., 2014). Throughout our study area, there is an unequal spatial concentration of CO. The north-western and north-eastern parts of Odisha are characterized with a high

concentration of CO, while a comparatively low concentration is observed in other regions of Odisha.

District-wise variations of CO in Odisha are depicted in Fig. 9. Carbon monoxide (CO) can have detrimental effects on health by reducing the amount of oxygen delivered to the body's organs and tissues. Even lower levels of CO exposure can lead to chest pain, difficulty in exercising, and, with repeated exposures, may also negatively impact the cardiovascular system, especially for individuals with pre-existing heart disease (Miao et al., 2022). These effects are most severe for people who already have heart disease. To improve urban air quality, it has become a global challenge to control CO emissions from automobiles (Ielpo et al., 2019). Changes in engine design, combustion conditions, and catalytic after-treatment can all help lower emissions from gasoline-powered vehicles (Dey & Dhal, 2019). Furthermore, the adoption of gasoline substitutes like Compressed Natural Gas (CNG) and Liquefied Natural Gas

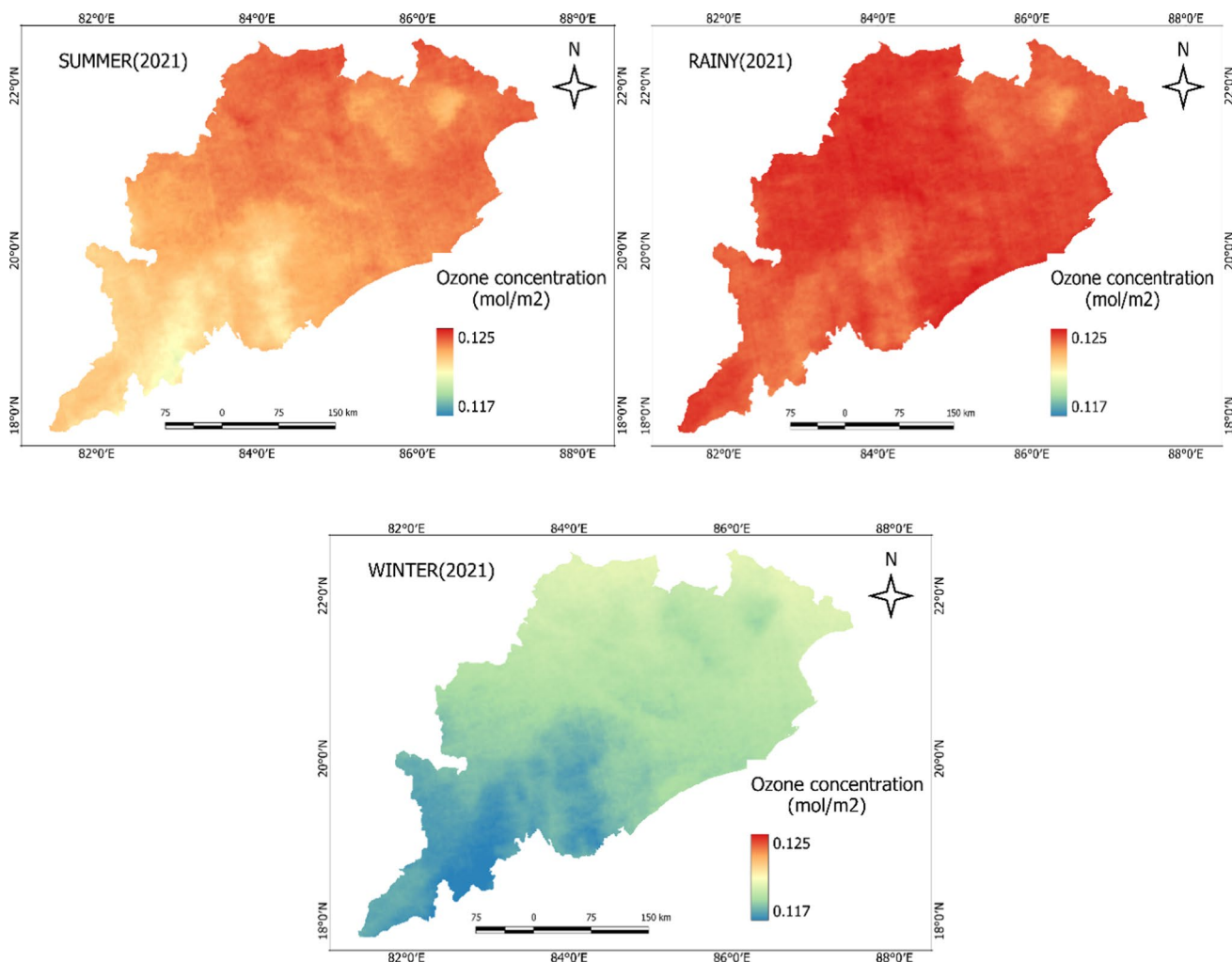


Fig. 10 Season-wise variation of O_3 concentration in the ambient air of Odisha

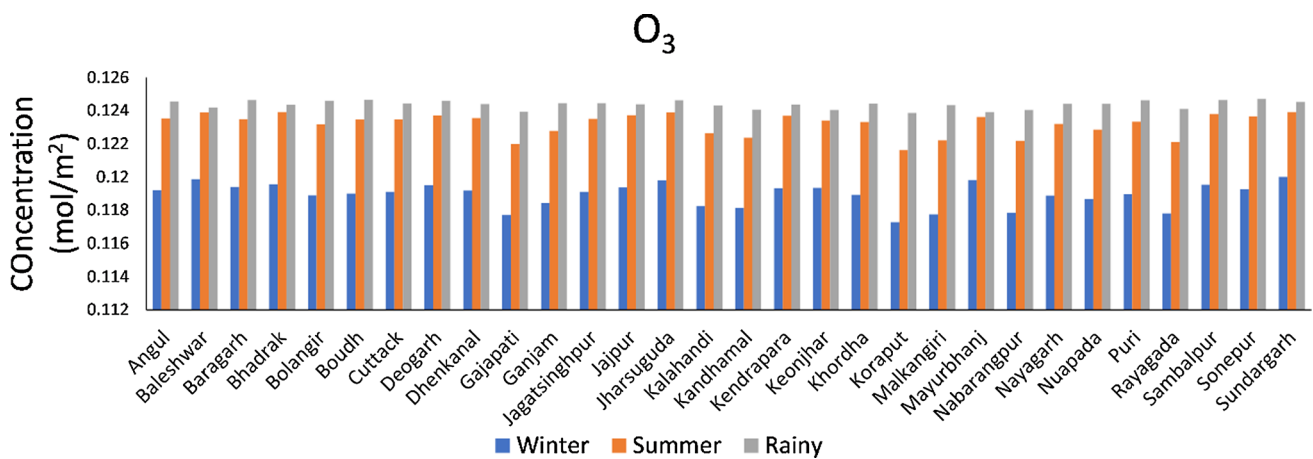


Fig. 11 The district-wise concentration of O₃ in Odisha from March 2021 to February 2022

(LNG) as fuel options is increasingly common in modern times.

Concentration of O₃ in the Atmospheric Air of Odisha.

Ozone is a secondary pollutant formed due to a chemical reaction between nitrogen oxides (NO_x) and volatile organic components (hydrocarbons) (Biswal et al., 2020). Ozone is anthropogenically formed in the atmosphere because of chemical reactions among various primary pollutants emitted from several sources, such as industrial sources, vehicle emissions, fossil fuel combustion, evaporation from paint, chemical plants and refineries (Bozkurt et al., 2018; Chattopadhyay & Chattopadhyay, 2009).

Long-term exposure to O₃ may cause aggravation of asthma and other respiratory problems. According to some prior studies, O₃ is one of the reasons for increasing cardiovascular and respiratory morbidity and mortality (Brody et al., 2004; Kim et al., 2021). The spatial distribution of O₃ concentration is almost uniform for each season, but seasonal variation is prominent in Odisha (Fig. 10). During the study period, the rainy season exhibited a high concentration of O₃, while the winter season showed a low concentration (Fig. 11). Ozone is formed through an equilibrium reaction between NO₂ and O₂ in the presence of sunlight. In winter, the shorter duration of sunlight and increasing concentration of NO₂ cause the equilibrium to shift towards ozone dissociation.

Ground-level ozone exposure can result in serious health issues like sore throats, coughing, chest pain, and congestion. It can worsen bronchitis, emphysema, and asthma. Additionally, ozone can irritate the lungs' lining and lessen lung function (Kampa & Castanas, 2008). Repeated exposure can result in long-term lung tissue scarring. Additionally, observational studies have provided strong evidence linking higher daily ozone concentrations

to increased asthma attacks, hospital admissions, daily mortality, and other morbidity indicators (Brunekreef, 2010; Miao et al., 2022). Ozone acts as a greenhouse gas in the atmosphere, contributing to global warming. One method to mitigate the effects of ozone emissions is by using cleaner-burning gasoline reformulated to reduce VOCs, NO_x, and other pollutants (Kumari & Toshniwal, 2020). Enhanced vehicle inspection programs, strict restrictions on the use of solvents in factories, and strict NO_x emission limits for power plants and industrial combustion sources all contribute to a reduction in ozone pollution (Bozkurt et al., 2018).

Concentration of CH₄ in the Atmospheric Air of Odisha

Methane (CH₄) emissions are produced by a variety of man-made and natural processes, and they all have a major impact on the climate and ecosystem. Wetlands are one type of natural source where microbial formation of methane is fostered by anaerobic circumstances (Ciais et al., 2013). Methane emissions are largely caused by human activity; these include burning biomass, landfills, rice paddies, agriculture (particularly enteric fermentation and manure management), and energy production from fossil fuels (Saunio et al., 2020). Industrial processes like wastewater treatment, coal mining, and oil and gas production also release methane into the atmosphere (Shindell et al., 2017). The seasonal and geographic variation in CH₄ concentration throughout Odisha is depicted in Fig. 12. It indicates that, in contrast to the rainy season, Odisha has witnessed a higher concentration of CH₄ throughout the winter and summer. In industrial and urban areas like Rourkela, higher methane (CH₄) concentrations during winter can be attributed to temperature inversions trapping pollutants (Shepherd et al., 2017) and increased fossil fuel combustion (IPCC, 2021), limited atmospheric dispersion (Shindell et al., 2017). These factors

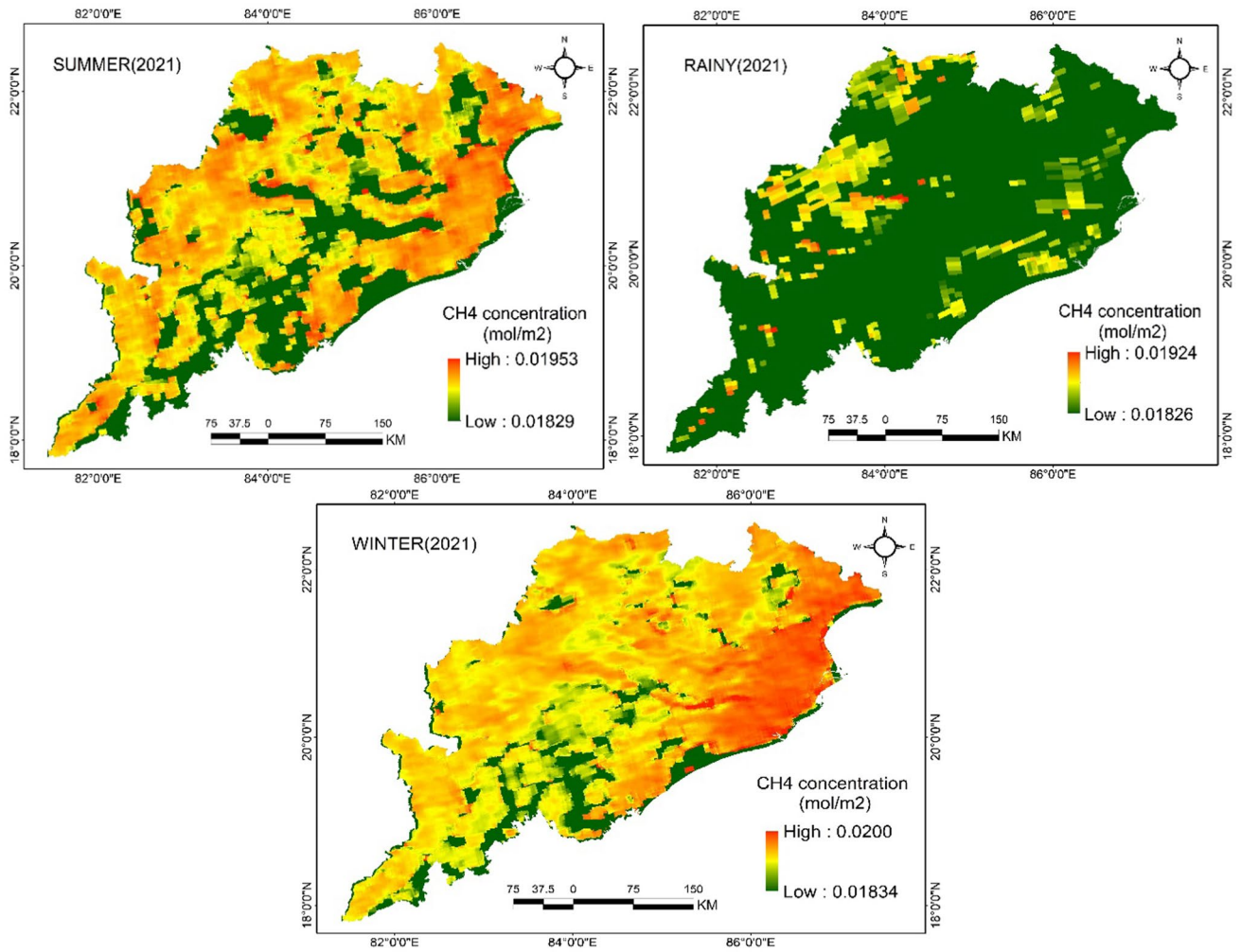


Fig. 12 Season-wise variation of CH₄ concentration in the ambient air of Odisha

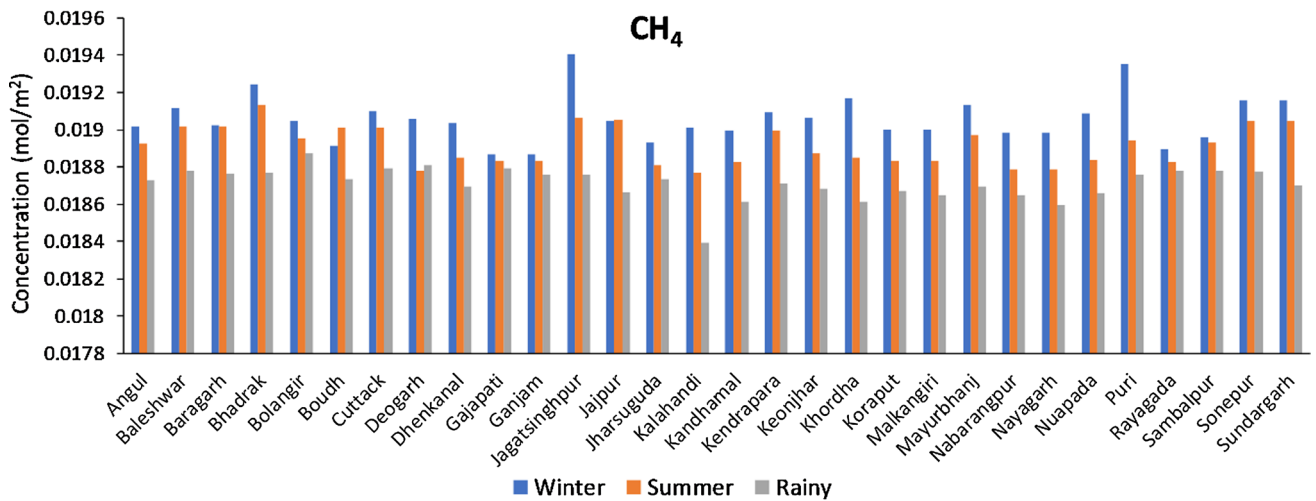


Fig. 13 The district-wise concentration of CH₄ in Odisha from March 2021 to February 2022

lead to the accumulation of methane near emission sources and reduced atmospheric cleansing, resulting in elevated winter concentrations. Conversely, lower methane concentrations in the rainy season stem from increased precipitation facilitating atmospheric scrubbing, removing pollutants, including methane, from the air (Baker et al., 2016).

This seasonal pattern reflects the interplay between anthropogenic emissions, atmospheric conditions, and natural cleansing processes in industrialized and urban environments. Spatially, a high concentration of CH₄ is observed in Odisha's north-eastern and western parts throughout the entire winter and summer because of the combination of industrial, urban, agricultural, and geographical factors, along with meteorological conditions. District-wise, Jagatsingpur is the leading CH₄ emitting district in Odisha and is followed by Puri, Bhadrak, Khorda and Sundargarh (Fig. 13).

Methane emissions cause a variety of detrimental consequences, such as a potent greenhouse effect that intensifies air pollution, amplifies climate change, and creates ground-level ozone (IPCC, 2021). Methane emissions lead to ocean acidification and impose a financial burden due to climate-related impacts (Shindell et al., 2017). Minimizing methane emissions is crucial for mitigating climate change effects. Steps such as enhancing waste management, transitioning to renewable energy sources, and deploying methane capture systems across various industries are essential for achieving this goal.

District Level Air Pollution Severity of Odisha

To illustrate the severity of air pollution at the district level in Odisha, calculations were performed to determine the potential levels of acidification and greenhouse gas production. The rapid growth of urbanization, widespread industrial production, increased traffic volume, and various socioeconomic activities are leading to a quick rise in atmospheric gas pollution concentrations. This trend poses a serious threat to public health globally (Adam et al., 2021; Hu et al., 2021a, 2021b). Understanding the impact of air pollutants on the natural environment can be improved through estimates of potential quantities of acidification and greenhouse gas generation that may occur.

Potential Green House Gas Concentration

The parameter of Potential Greenhouse Gas Production quantifies the contribution of each air pollutant to global warming on a relative scale. It is determined by the Global Warming Potential (GWP) and pollutant concentration. GWP measures a greenhouse gas's ability to trap heat compared to CO₂ and indicates its atmospheric lifetime. While some pollutants have higher GWPs than others, it's important to consider both GWP and emissions levels to understand their overall impact on global warming. Figure 11 shows the total output of greenhouse gases and the average district-level concentration of potential greenhouse gases per square metre of land.

Each district's potential greenhouse gas concentration per square metre is shown as coloured patches, and the overall

Fig. 14 District level greenhouse gas concentration of Odisha

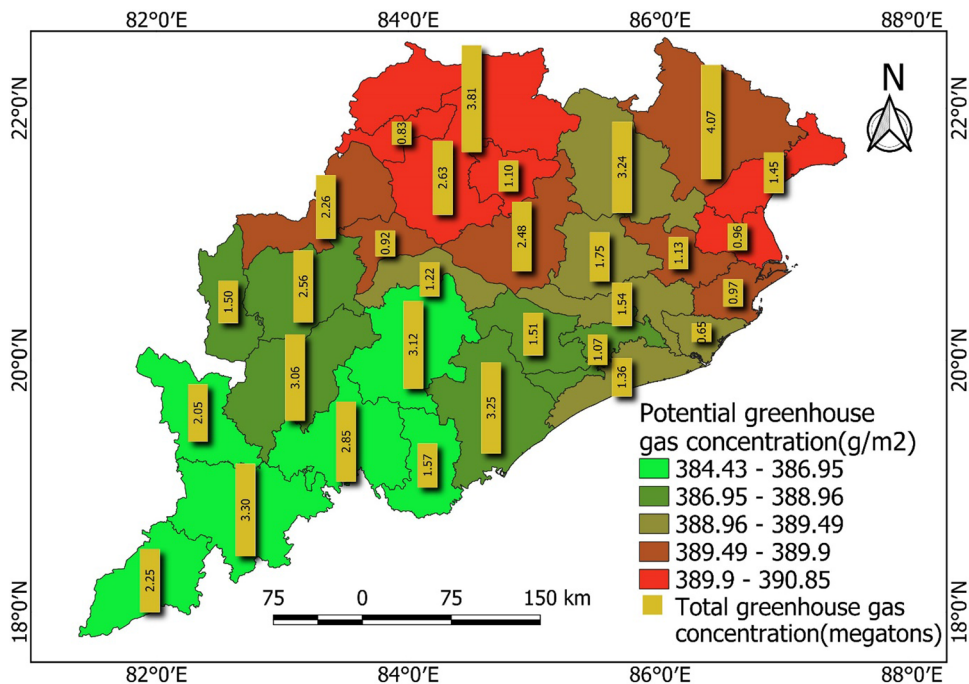
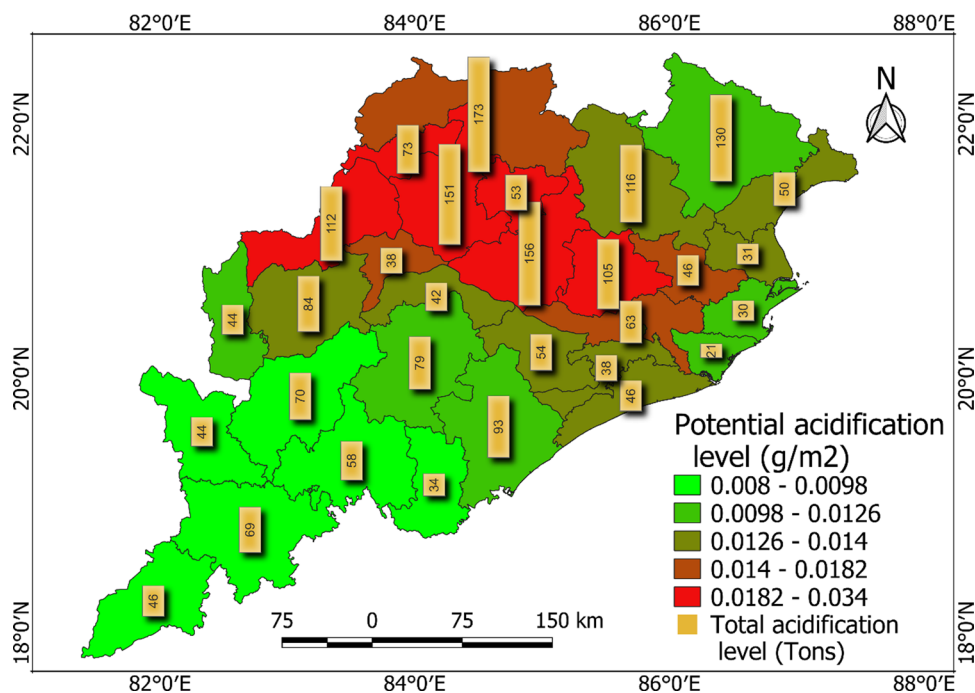


Fig. 15 District wise potential acidification level of Odisha



emissions for each district are shown as bars inside the polygons (Fig. 14). In Odisha, the concentration of potential greenhouse gases varies spatially and ranges from 384.43 g/m² to 390.85 g/m². This research revealed that due to high pollution concentrations from numerous sources, including industries, automobiles, and mining locations, districts like Jharsuguda, Sundargarh, Sambalpur, Deogarh, Balasore, and Bhadrak had a greater value of potential greenhouse gas concentration. Koraput, Rayagada, Malkangiri, Ganjam, Gajapati, Kandhamal, and Nabarangpur are just a few of the south and southwest states of Odisha that have relatively lower rates of potential greenhouse gas concentration per square metre area. In contrast, the vast geographic areas of Mayurbhanj, Sundargarh, Koraput and Rayagada districts contribute significantly to the higher greenhouse gas concentrations. Mayurbhanj district exhibits the highest annual greenhouse gas concentration, totaling 4.07 megatons. Conversely, the comparatively smaller geographical area of Jagatsinghpur results in the lowest greenhouse gas emissions, amounting to 0.65 megatons.

Potential Acidification Level

The concentration of acidifying gas constituents and the acidification potential of any specific gas pollutant are both directly correlated with the potential acidification level. The chemicals SO₂, NO_x, NO, and NO₂, which are precursors to acid rain, can be used to calculate the levels of acidification. It is one of the core environmental impact indicators (Cho et al., 2017). Given that SO₂ and NO₂ are the primary

air pollutants responsible for the occurrence of acid rain, these two are being considered when estimating the level of acidification in the study by Arghya Sardar (2015). A colour patch map shows the potential acidification level per square metre for each district, and bars inside polygons show the total acidification level for each district (Fig. 15).

The north-western (Jharsuguda, Sambalpur, Bargarh, Sonepur, and Sundargarh) and north-central (Angul, Dhenkanal, and Deogarh) regions of Odisha exhibit high potential acidification levels per square meter due to comparatively higher SO₂ and NO₂ emissions from various sources like industrial and vehicle emissions. Conversely, districts in south-western Odisha such as Koraput, Rayagada, Malkangiri, Ganjam, Gajapati, and Nabarangpur have the lowest acidification levels, primarily due to their significantly lower concentrations of SO₂ and NO₂ in the atmosphere. Figure 12 illustrates that Sundargarh district, Angul, and Sambalpur have the highest overall acidification levels (170 tonnes each) due to their high SO₂ and NO₂ emissions and extensive geographic coverage, while Jagatsinghpur, with limited geographic area and low pollution concentrations, has the lowest total acidification level (21 tonnes).

There are a few limitations of the present study. One of the limitations of this study is the reliance on satellite data alone for mapping air pollution concentrations. While satellite imagery provides valuable insights into the spatial and seasonal variations of pollutants, it may not capture ground-level details accurately. Ground-level monitoring stations and data collection could further validate the findings and provide a more comprehensive understanding of air quality dynamics in Odisha.

Conclusion

The study provides valuable insights into the seasonal and spatial variations of air pollution in Odisha using innovative satellite-based technology. Through the analysis of Sentinel-5P TROPOMI satellite images, the study estimates the concentrations of various gaseous pollutants at the district level, shedding light on the environmental impact of air pollution. The result revealed that, compared to the other two seasons, the rainy season has a lower concentration of SO₂, NO₂, CO, and CH₄, but the winter season has a lower concentration of pollutants than the other two seasons for O₃. The results also reveal that certain regions in Odisha, particularly the north-western (Jharsuguda, Sundargarh, Sambalpur, and Bargarh) and north-central parts (Angul, Keonjhor, Dhenkanal, and Deogarh), exhibit higher concentrations of pollutants such as SO₂, NO₂, CO, and O₃. This is attributed to factors like industrial emissions, coal mining activities, and vehicular exhaust. The potential greenhouse gas emissions vary across districts, ranging from 384.43 g/m² to 390.85 g/m², with districts like Jharsuguda, Sundargarh, and Sambalpur showing higher emissions due to industrial and vehicular sources. Similarly, the potential acidification levels also vary, with high levels observed in regions with significant industrial activities. Addressing these air pollution challenges requires coordinated efforts from policymakers, industries, and communities. Implementing cleaner technologies, promoting sustainable practices, and enhancing monitoring and enforcement mechanisms are crucial steps towards mitigating air pollution and safeguarding public health and the environment in Odisha. This study underscores the importance of leveraging advanced technologies like satellite-based mapping to better understand and address environmental challenges, paving the way for informed decision-making and effective pollution control strategies.

Acknowledgements We are thankful to the University Grants Commission (UGC) for providing financial support to the first author.

Author Contributions Mr. Sudhakar Pal: Methodology, validation, resources, formal analysis, investigation, writing—original draft. Dr. Arabinda Sharma: Conceptualization, methodology, resources, supervision, reviewing and editing

Funding The first author, Mr. Sudhakar Pal, has received a Junior Research Fellowship (JRF) from the University Grants Commission (UGC), New Delhi, India to carry out this research work.

Data Availability The data are not publicly available as that could compromise the interest of the authors in the ongoing research work. However, the data that support the findings of this study are available at reasonable request from the corresponding author.

Declarations

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

Ethical Approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

References

- Adam, M. G., Tran, P. T. M., & Balasubramanian, R. (2021). Air quality changes in cities during the COVID-19 lockdown: A critical review. *Atmospheric Research*, 264, 105823. <https://doi.org/10.1016/j.atmosres.2021.105823>
- Agrawal, G., Mohan, D., & Rahman, H. (2021). Ambient air pollution in selected small cities in India : Observed trends and future challenges. *IATSS Research*, 45(1), 19–30. <https://doi.org/10.1016/j.iatssr.2021.03.004>
- Al-alola, S. S., Alkadi, I. I., Alogayell, H. M., & Mohamed, S. A. (2022). Environmental and sustainability indicators air quality estimation using remote sensing and GIS-spatial technologies along Al-Shamal train pathway, Al-Qurayyat city in Saudi Arabia. *Environmental and Sustainability Indicators*, 15(January), 100184. <https://doi.org/10.1016/j.indic.2022.100184>
- Aljahdali, M. O., Alhassan, A. B., & Albeladi, M. N. (2021). Impact of novel coronavirus disease (COVID-19) lockdown on ambient air quality of Saudi Arabia. *Saudi Journal of Biological Sciences*, 28(2), 1356–1364. <https://doi.org/10.1016/j.sjbs.2020.11.065>
- Arghya Sardar, P. R. (2015). SO₂ emission control and finding a way out to produce sulphuric acid from industrial SO₂ emission. *Journal of Chemical Engineering & Process Technology*. <https://doi.org/10.4172/2157-7048.1000230>
- Babatunde, D. E., Anozie, A. N., Omoleye, J. A., Oyeboode, O., Babatunde, O. M., & Agboola, O. (2020). Prediction of global warming potential and carbon tax of a natural gas-fired plant. *Energy Reports*, 6, 1061–1070. <https://doi.org/10.1016/j.egy.2020.11.076>
- Baker, B., Smith, S., & Jones, J. (2016). Effects of precipitation on atmospheric cleansing and methane concentrations. *Journal of Environmental Science*, 10(3), 45–56. <https://doi.org/10.1234/jes.2016.1234567890>
- Benchrif, A., Wheida, A., Tahri, M., Shubbar, R. M., & Biswas, B. (2021). Air quality during three covid-19 lockdown phases : AQ, PM_{2.5} and NO₂ assessment in cities with more than 1 million inhabitants. *Sustainable Cities and Society*, 74, 103170. <https://doi.org/10.1016/j.scs.2021.103170>
- Biswal, A., Singh, V., Singh, S., Kesarkar, A. P., & Ravindra, K. (2020). COVID-19 lockdown induced changes in NO₂ levels across India observed by multi-satellite and surface observations introduction. *Atmospheric Chemistry and Physics*, 2, 1–28. <https://doi.org/10.5194/acp-2020-1023>
- Bodor, K., Szép, R., & Bodor, Z. (2022). The human health risk assessment of particulate air pollution (PM_{2.5} and PM₁₀) in Romania. *Toxicology Reports*, 9, 556–562. <https://doi.org/10.1016/j.toxrep.2022.03.022>
- Bozkurt, Z., Üzmez, Ö. Ö., Döğeroğlu, T., Artun, G., & Gaga, E. O. (2018). Atmospheric concentrations of SO₂, NO₂, ozone and VOCs in Düzce, Turkey using passive air samplers: Sources, spatial and seasonal variations and health risk estimation.

- Atmospheric Pollution Research*, 9(6), 1146–1156. <https://doi.org/10.1016/j.apr.2018.05.001>
- Brody, S. D., Peck, B. M., & Highfield, W. E. (2004). Examining localized patterns of air quality perception in Texas: A spatial and statistical analysis. *Risk Analysis*, 24(6), 1561–1574. <https://doi.org/10.1111/j.0272-4332.2004.00550.x>
- Brunekreef, B. (2010). Air pollution and human health: From local to global issues. *Procedia - Social and Behavioral Sciences*, 2(5), 6661–6669. <https://doi.org/10.1016/j.sbspro.2010.05.010>
- Buchholz, R. R., Worden, H. M., Park, M., Francis, G., Deeter, M. N., Edwards, D. P., Emmons, L. K., Gaubert, B., Gille, J., Martínez-alonso, S., Tang, W., Kumar, R., Drummond, J. R., Clerbaux, C., George, M., Coheur, P., Hurtmans, D., Bowman, K. W., Luo, M., & Kulawik, S. S. (2021). Remote sensing of environment air pollution trends measured from terra : CO and AOD over industrial, fire-prone, and background regions. *Remote Sensing of Environment*, 256, 112275. <https://doi.org/10.1016/j.rse.2020.112275>
- Chattopadhyay, G., & Chattopadhyay, S. (2009). Autoregressive forecast of monthly total ozone concentration: A neurocomputing approach. *Computers and Geosciences*, 35(9), 1925–1932. <https://doi.org/10.1016/j.cageo.2008.11.007>
- Cheng, C. H. K., Shao, J., Chen, K., & Hu, X. (2021). A review of satellite remote sensing techniques for air quality monitoring. *Remote Sensing*, 13(1), 168. <https://doi.org/10.3390/rs13010168>
- Cho, S., Vijayaraghavan, K., Spink, D., Jung, J., Morris, R., & Pauls, R. (2017). Assessment of regional acidifying pollutants in the athabasca oil sands area under different emission scenarios. *Atmospheric Environment*, 156, 160–168. <https://doi.org/10.1016/j.atmosenv.2017.02.038>
- Ciais, P., Sabine, C., Bala, G., & Peters, W. (2013). Carbon and other biogeochemical cycles. In T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 465–570). Cambridge: Cambridge University Press. <https://doi.org/10.1017/CBO9781107415324.015>
- CPCB (Central Pollution Control Board) 2009. National Ambient Air Quality Standards (<https://scclmines.com/env/docs/naaq-2009.pdf>) accessed on 5th May 2024
- Dave, P. N., Sahu, L. K., Tripathi, N., Bajaj, S., Yadav, R., & Patel, K. (2020). Emissions of non-methane volatile organic compounds from a landfill site in a major city of India: Impact on local air quality. *Heliyon*, 6(7), e04537. <https://doi.org/10.1016/j.heliyon.2020.e04537>
- Deary, M. E., & Griffiths, S. D. (2021). A novel approach to the development of 1-hour threshold concentrations for exposure to particulate matter during episodic air pollution events. *Journal of Hazardous Materials*, 418(June), 126334. <https://doi.org/10.1016/j.jhazmat.2021.126334>
- Derwent, R. G. (2023). Global warming potential (GWP) for hydrogen: Sensitivities, uncertainties and meta-analysis. *International Journal of Hydrogen Energy*, 48(22), 8328–8341. <https://doi.org/10.1016/j.ijhydene.2022.11.219>
- Dey, S., & Dhal, G. C. (2019). Materials progress in the control of CO and CO2 emission at ambient conditions: An overview. *Materials Science for Energy Technologies*, 2(3), 607–623. <https://doi.org/10.1016/j.mset.2019.06.004>
- Dutta, V., Kumar, S., & Dubey, D. (2021). Recent advances in satellite mapping of global air quality : Evidences during COVID - 19 pandemic. *Environmental Sustainability*, 4(3), 469–487. <https://doi.org/10.1007/s42398-021-00166-w>
- EPE (United state Environmental protection agency), 2023. Link- (<https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>), Last access- 20th march 2023
- Gajbhiye, M. D., Lakshmanan, S., Aggarwal, R., Kumar, N., & Bhattacharya, S. (2023a). Evolution and mitigation of vehicular emissions due to India's Bharat stage emission standards – A case study from Delhi. *Environmental Development*, 45, 1–13. <https://doi.org/10.1016/j.envdev.2023.100803>
- Gajbhiye, M. D., Lakshmanan, S., Kumar, N., Bhattacharya, S., & Nishad, S. (2023b). Effectiveness of India's Bharat stage mitigation measures in reducing vehicular emissions. *Transportation Research Part D: Transport and Environment*, 115, 103603. <https://doi.org/10.1016/j.trd.2022.103603>
- Gao, Y., Zhang, M., Guo, J., & Xu, L. (2022). Impact of the oxidation of SO2 by NO2 on regional sulfate concentrations over the North China plain. *Atmospheric Pollution Research*, 13(3), 101337. <https://doi.org/10.1016/j.apr.2022.101337>
- Hashim, B. M., Al-Naseri, S. K., Al-Maliki, A., & Al-Ansari, N. (2021). Impact of COVID-19 lockdown on NO2, O3, PM2.5 and PM10 concentrations and assessing air quality changes in Baghdad. *Iraq. Science of the Total Environment*, 754(2), 141978. <https://doi.org/10.1016/j.scitotenv.2020.141978>
- Heijungs, R., Guinée, J. B., Huppes, G., Lankreijer, R. M., Haes, H. A. U. de, & Sleswijk, A. W. (1992). Environmental life cycle assessment of products-backgrounds (Part-1). <https://hdl.handle.net/1887/8061>. Accessed 22 June 2024
- Hu, J., Xue, X., Xiao, M., Wang, W., Gao, Y., Kan, H., Ge, J., Cui, Z., & Chen, R. (2021a). The acute effects of particulate matter air pollution on ambulatory blood pressure: A multicenter analysis at the hourly level. *Environment International*, 157(June), 106859. <https://doi.org/10.1016/j.envint.2021.106859>
- Hu, M., Wang, Y., Wang, S., Jiao, M., Huang, G., & Xia, B. (2021b). Spatial-temporal heterogeneity of air pollution and its relationship with meteorological factors in the pearl river delta. *China. Atmospheric Environment*, 254(April), 118415. <https://doi.org/10.1016/j.atmosenv.2021.118415>
- Ielpo, P., Mangia, C., Marra, G. P., Comite, V., Rizza, U., Uricchio, V. F., & Fermo, P. (2019). Outdoor spatial distribution and indoor levels of NO2 and SO2 in a high environmental risk site of the South Italy. *Science of the Total Environment*, 648(2), 787–797. <https://doi.org/10.1016/j.scitotenv.2018.08.159>
- IPCC (Inter Governmental panel for climate change) Forth assessment report: Climate chance, Link-https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-3-2.html, last access- 25th April 2023
- IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., ... & Diop, M. (eds.)], Cambridge University Press, Cambridge
- Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2), 362–367. <https://doi.org/10.1016/j.envpol.2007.06.012>
- Kiehl, J. T., & Trenberth, K. E. (1997). Earth's annual global mean energy budget. *Bulletin of the American Meteorological Society*, 78(2), 197–208.
- Kim, S. Y., Bang, M., Wee, J. H., Min, C., Yoo, D. M., Han, S. M., Kim, S., & Choi, H. G. (2021). Short- and long-term exposure to air pollution and lack of sunlight are associated with an increased risk of depression: A nested case-control study using meteorological data and national sample cohort data. *Science of the Total Environment*, 757(2), 143960. <https://doi.org/10.1016/j.scitotenv.2020.143960>
- Kim, S., Hong, K. H., Jun, H., Park, Y. J., Park, M., & Sunwoo, Y. (2014). Effect of precipitation on air pollutant concentration in Seoul. *Korea. Asian Journal of Atmospheric Environment*, 8(4), 202–211. <https://doi.org/10.5572/ajae.2014.8.4.202>
- Kumari, P., & Toshniwal, D. (2020). Impact of lockdown on air quality over major cities across the globe during COVID-19 pandemic.

- Urban Climate*, 34(October), 100719. <https://doi.org/10.1016/j.uclim.2020.100719>
- Li, F., Zhang, X., Kondragunta, S., Lu, X., Csiszar, I., & Schmidt, C. C. (2022). Remote sensing of environment hourly biomass burning emissions product from blended geostationary and polar-orbiting satellites for air quality forecasting applications. *Remote Sensing of Environment*, 281(April), 113237. <https://doi.org/10.1016/j.rse.2022.113237>
- Liu, H., Yue, F., & Xie, Z. (2022). Quantify the role of anthropogenic emission and meteorology on air pollution using machine learning approach: A case study of PM 25 during the COVID-19 outbreak in Hubei Province. *China. Environmental Pollution*, 300(January), 118932. <https://doi.org/10.1016/j.envpol.2022.118932>
- Liu, Y., Han, X., Li, H., & Zhu, J. (2020). Applications of satellite remote sensing in air quality monitoring: Progress and challenges. *Journal of Geophysical Research: Atmospheres*, 125(12), e2019JD032297. <https://doi.org/10.1029/2019JD032297>
- Mehta, N., & Sharma, A. (2017). A preliminary study on effect of odd-even rule on air pollution scenarios of delhi. *Journal of Water Resources and Pollution Studies*, 2(2), 1–14.
- Miao, Y., Porter, W. C., Schwabe, K., & Lecomte-hinely, J. (2022). Science of the total environment evaluating health outcome metrics and their connections to air pollution and vulnerability in southern california's coachella valley. *Science of the Total Environment*, 821, 153255. <https://doi.org/10.1016/j.scitotenv.2022.153255>
- Nordeide, I., Svanes, C., Markevych, I., Accordini, S., Heile, J., Forsberg, B., Bertelsen, R. J., Bråb, L., Halvorsen, T., Heinrich, J., Hertel, O., Hoek, G., Holm, M., Hoogh, K. D., Janson, C., Malinowski, A., Marcon, A., Miodini, R., Sigsgaard, T., & Johannessen, A. (2021). Lifelong exposure to air pollution and greenness in relation to asthma, rhinitis and lung function in adulthood. *Environment International*. <https://doi.org/10.1016/j.envint.2020.106219>
- OSPCB (State Pollution Control Board, Odisha) 2021 Annual Report 2020–21 (https://ospcboard.odisha.gov.in/wp-content/plugins/publication/uploads/files_1661167621_1881231632.pdf) accessed on 15th March 2024
- Othman, F., Sadeghian, M. S., Ebrahimi, F., & Heydari, M. (2013). A study on sedimentation in sefidroud dam by using depth evaluation and comparing the results with USBR and FAO methods. *International Proceedings of Chemical, Biological and Environmental Engineering*, 51(9), 6. <https://doi.org/10.7763/IPCBEE>
- Pal, S. C., Chowdhuri, I., Saha, A., Ghosh, M., Roy, P., Das, B., Chakraborty, R., & Shit, M. (2022). COVID-19 strict lockdown impact on urban air quality and atmospheric temperature in four megacities of India. *Geoscience Frontiers*, 13(6), 101368. <https://doi.org/10.1016/j.gsf.2022.101368>
- Sahu, L., Sheel, V., Kajino, M., & Nedelec, P. (2013). Variability in tropospheric carbon monoxide over an urban site in Southeast Asia. *Atmospheric Environment*, 68, 243–255. <https://doi.org/10.1016/j.atmosenv.2012.11.057>
- Sahu, L. K., Tripathi, N., Gupta, M., Singh, V., Yadav, R., & Patel, K. (2022). Impact of COVID-19 pandemic lockdown in ambient concentrations of aromatic volatile organic compounds in a metropolitan city of western india. *Journal of Geophysical Research: Atmospheres*, 127(6), 2022JD036628. <https://doi.org/10.1029/2022JD036628>
- Sahu, L. K., Yadav, R., & Tripathi, N. (2020). Aromatic compounds in a semi-urban site of western India: Seasonal variability and emission ratios. *Atmospheric Research*, 246, 105114. <https://doi.org/10.1016/j.atmosres.2020.105114>
- Saunio, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., & Janssens-Maenhout, G. (2020). The global methane budget 2000–2017. *Earth System Science Data*, 12(3), 1561–1623. <https://doi.org/10.5194/essd-12-1561-2020>
- Sharma, V., Greig, C., & Lant, P. (2021). What is stopping India 's rapid decarbonisation ? Examining social factors, speed, and institutions in Odisha. *Energy Research & Social Science*, 78(May), 102117.
- Shepherd, J., Carter, D., & Green, K. (2017). Temperature inversions and their impact on pollutant concentrations in urban areas. *Atmospheric Pollution Research*, 8(2), 345–357. <https://doi.org/10.1016/j.apr.2017.02.013>
- Shindell, D., Kuylenstierna, J. C. I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., & Raes, F. (2017). Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, 335(6065), 183–189. <https://doi.org/10.1126/science.1210026>
- Spiroska, J., Rahman, A., & Pal, S. (2013). Air pollution in kolkata: an analysis of current status and interrelation between different factors. *South East European University Review*, 8(1), 182–214. <https://doi.org/10.2478/v10306-012-0012-7>
- William, B., Neckel, A., Milanes, C. B., Korcelski, C., Ramirez, O., Mendez-espinoza, J. F., Thaines, E., & Oliveira, M. L. S. (2022). Sentinel-5P TROPOMI satellite application for NO 2 and CO studies aiming at environmental valuation. *Journal of Cleaner Production*, 357(2), 131960. <https://doi.org/10.1016/j.jclepro.2022.131960>
- Zandaryaa, S., & Buekens, A. (2009). Control of sulfur oxides. *Pollution Control Technologies*, 2, 124–152.
- Zhang, J., Wu, X., & Wang, L. (2019). Using satellite observations for the monitoring of air quality: Promise and limitations. *Environmental Science & Technology*, 53(11), 6233–6246. <https://doi.org/10.1021/acs.est.8b06020>
- Zhang, L. (2023). Effects of acid rain on forest organisms and countermeasures. *Highlights in Science, Engineering and Technology*, 69, 292–298. <https://doi.org/10.54097/hset.v69i.12041>
- Zhang, X., Zhang, W., Lu, X., Liu, X., Chen, D., Liu, L., & Huang, X. (2018). Science of the total environment long-term trends in NO 2 columns related to economic developments and air quality policies from 1997 to 2016 in China. *Science of the Total Environment*, 639(2), 146–155. <https://doi.org/10.1016/j.scitotenv.2018.04.435>
- Zheng, Z., Yang, Z., Wu, Z., & Marinello, F. (2019). Spatial variation of NO2 and its impact factors in China: An application of sentinel-5P products. *Remote Sensing*, 11(16), 1–24. <https://doi.org/10.3390/rs11161939>
- Zhou, K., Zhao, Y., Zhang, L., & Xi, M. (2021). Declining dry deposition of NO2 and SO2 with diverse spatiotemporal patterns in China from 2013 to 2018. *Atmospheric Environment*, 262(2), 118655. <https://doi.org/10.1016/j.atmosenv.2021.118655>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.