PRINT ISSN 1119-8362
Electronic ISSN 2659-1502

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 27 (12) 2715-2722 December 2023

Monitoring and Mapping of Atmospheric Concentration of Carbon Monoxide, Sulphur Dioxide, and Nitrogen Dioxide from 2019 - 2022 in Benin City, Southern Nigeria

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ABSTRACT: This study presents a comprehensive monitoring and mapping assessment of the atmospheric concentrations of carbon monoxide (CO), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2) from 2019 - 2022 in Benin City, Southern Nigeria using Google Earth Engine (GEE) and Sentinel 5P (S5P) TROPOMI satellite data. To extract the pollution map, all satellite datasets were imported into GEE, and pollutant results were obtained through JavaScript coding. The spatial map showed that the highest annual concentration of CO was recorded in 2020 as 0.0554 mol/m^2, the highest annual concentration of SO_2 was recorded in 2020 as 0.0000866 mol/m^2, and the highest annual concentration of NO_2 was recorded in 2021 as 0.0000797 mol/m^2. For CO, a paired sample t-test revealed that there was a significant difference in 2019 compared to 2020, but not in 2020 compared to 2021. The years 2021 and 2022 did not significantly differ from one another either. There was no significant difference in SO_2 across the years. For NO_2, there was a significant difference between 2019 and 2020, and also a significant difference between 2020 and 2021, but no significant difference between 2021 and 2022. This study finds that the COVID-19 lockdown protocol was loosely implemented in Benin City, as the results from this study did not effectively correlate with those of other studies. The study also finds the efficacy of S5P in monitoring and mapping the concentrations of CO, SO_2, and NO_2 in Benin City, laying the groundwork for future research using Sentinel 5P.

DOI: https://dx.doi.org/10.4314/jasem.v27i12.7

Cite this paper as: OKODUWA, K. A; AMAECHI, C. F. (2023). Monitoring and Mapping of Atmospheric Concentration of Carbon Monoxide (CO), Sulphur Dioxide (SO_2), and Nitrogen Dioxide (NO_2) from 2019 - 2022 in Benin City, Southern Nigeria. *J. Appl. Sci. Environ. Manage.* 27 (12) 2715-2722

Dates: Received: 12 November 2023; Revised: 10 December 2023; Accepted: 15 December 2023 Published: 30 December 2023

Keywords: Air quality; Google Earth Engine; Carbon Monoxide; Sulphur Dioxide; Nitrogen Dioxide

The debate on elevated atmospheric concentrations of air pollutants at the local, regional, and global scales is one that cannot be overemphasized. Air pollution requires detailed quantitative measurements on the ground (point-based) but also robust spatial mapping to detect the most affected areas over time and help decision-makers find sustainable solutions to improve air quality and public health (Vîrghileanu *et al*., 2020). In the 2019 Health Effects Institute evaluation of global air quality, Nigeria rated first in Africa and fourth globally for air pollution, with 1500 air-related fatalities per million population (Health Effects Institute, 2019). Ground based measuring stations for pollutants are one of the most reliable means of determining pollution levels in any region (Kazemi *et al*., 2023). However, since pollution travels far in the atmosphere, ground measurements become limited to the area around the stations (Batur *et al*., 2022). The absence of a physical ground-based monitoring system in Benin City, Nigeria, hinders the ability to perform air quality monitoring in a large area. Hence, researchers often use portable hand-held meters to collect air quality readings at different points, which can be time-consuming. Even if it becomes available in the future, these ground-based monitoring stations and instruments have certain limitations, such as higher maintenance costs and data point collections limited to small areas (Amanollahi *et al*., 2013). To proffer solution to this, there has been increased use of earth observation datasets for the monitoring of atmospheric pollutants (Maurya *et al*., 2022). For instance, S5P allows for the independent monitoring of criteria air pollutants such as CO, SO_2, and NO_2 over a period of time and at a greater regional extent.

S5P is a single satellite mission (Lorente *et al*., 2019). A passive sun backscatter imaging spectrometer included in S5P, the TROPOspheric Monitoring Instrument, or TROPOMI, is capable of acquiring 8-

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band imagery, spanning a variety of spectral domains from UV and visible to near-infrared (NIR) and shortwave infrared (SWIR) (Ialongo *et al*., 2019). With a higher spatial resolution of 7×3.5 km^2 (along and across tracks) than its predecessors, it presents a new opportunity for air quality research and is appropriate for monitoring atmospheric pollution. Studies have been conducted to monitor air quality throughout Nigeria (Ukpebor *et al*., 2021; Abulude *et al*., 2022; Ezeonyejiaku *et al*., 2022) and none has yet fully utilized the benefits of the Sentinel-5P TROPOMI to monitor the annual atmospheric pollutants in Benin City and other major cities in Nigeria. A review of the literature reveals that few studies have explored the effectiveness of S5P for air pollution monitoring during the COVID-19 period in cities outside Nigeria (Behera *et al*., 2022; Kazemi *et al*., 2023; Muniraj *et al*., 2023). It is against this drawback that this study was carried out to achieve comprehensive monitoring and mapping assessment of the atmospheric concentrations of CO, SO_2, and NO_2 from 2019 to 2022 in Benin City, Southern Nigeria.

MATERIALS AND METHODS

Study Area: Edo State's capital and largest city is Benin City, which is located in southern Nigeria. It comprises Oredo, Ikpoba-Okha, Ovia North East, and Egor local government areas (LGA) (Amedu *et al*., 2020) and is located at an altitude of 77.8 m above sea level (Ogunbodede and Balogun, 2013). It is located between the latitudes of 6º 19'N and 6º 21'N and the longitudes of 5º 34'E and 5º 44'E. Benin City's wet season lasts from March/April to October while wet season last from November to January (Balogun and Orimoogunje, 2015). As a node city, the municipality has risen swiftly, connecting numerous cities in the west with cities in eastern Nigeria and others from the south to the north of the country. It is a commercial hub due to rural-urban migration and its cultural, social, economic, and political benefits (Ayo-Odifiri *et al*., 2021).

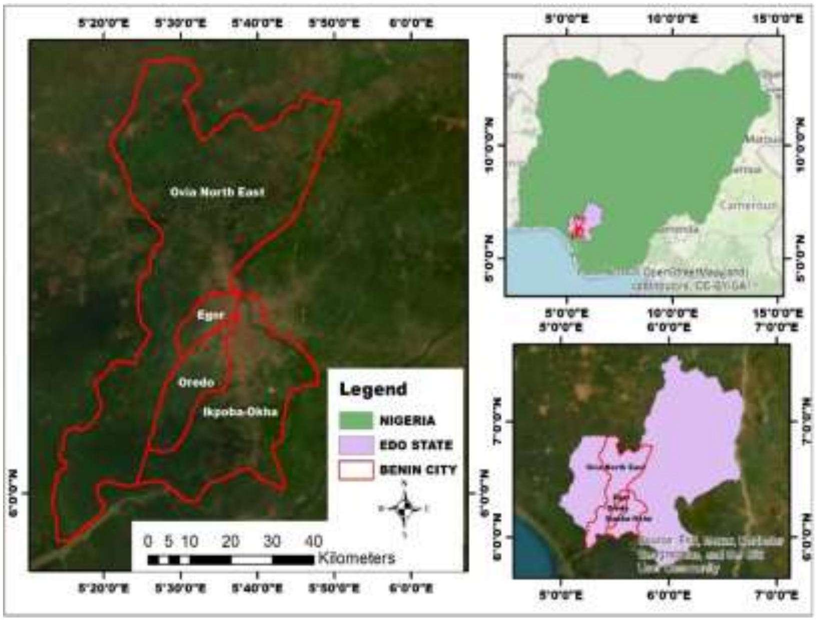

Fig. 1. Map of Benin City
Source: Researcher Field Work, 2023

Data Source and Preprocessing: GEE and S5P satellite data were used in this study to evaluate annual concentrations of CO, SO_2, and NO_2 in Benin City from 2019 - 2022. The following processes were taken to extract the pollution maps (CO, SO_2, and NO_2): The initial step was to import all satellite datasets into GEE. Secondly, air pollutant results were obtained through JavaScript coding. Figure 2 presents the research methodology flow chart.

All datasets are given in Table 1. After applying the spatial filters, CO, SO_2, and NO_2, products for the study area were generated. The images were downloaded in Geotiff format and referenced to the World Geodetic System of 1984 (WGS 1984). The mean value derived from S5P for each month was analyzed with SPSS to determine the statistically significant differences across the different study periods for each air quality parameter. As earlier stated, limitations due to the absence of a ground-based monitoring system did not give the opportunity for result comparison. The study therefore relied completely on data obtained through S5P. However, results from Kazemi *et al*. (2023) and Vîrghileanu *et al*. (2020) have revealed a positive correlation between results obtained from S5P and results from ground-based monitoring stations.

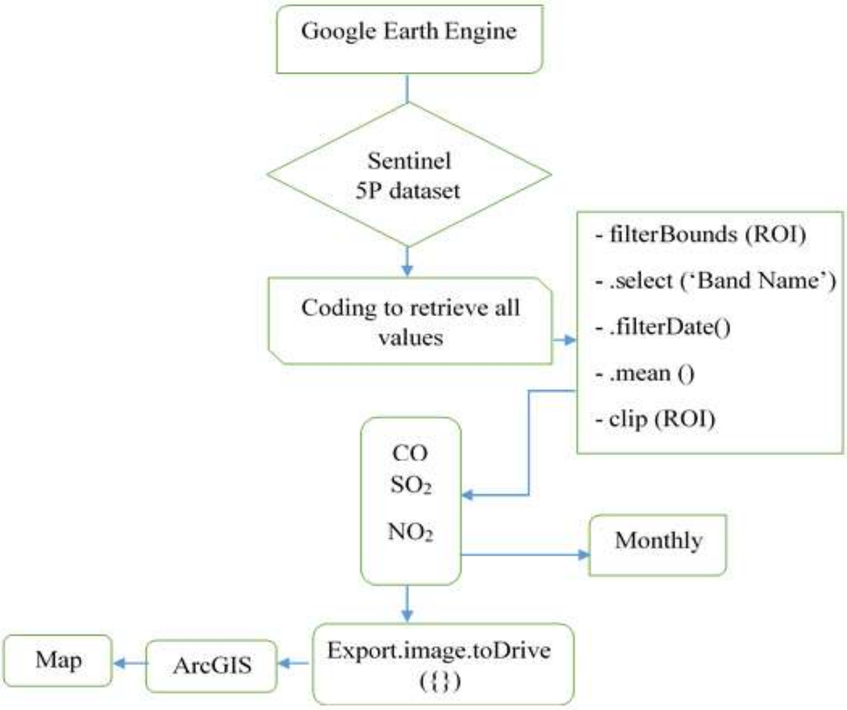

Fig. 2. Research Methodology Flowchart
Source: Researcher Field Work, 2023

Table 1. CO, SO_2, and NO_2 Dataset obtained from Sentinel 5P

Band Name	Dataset	Unit	Min	Max	Description
CO_column_number_density	OFFL/L3_CO	mol/m^2	-34.43	5.71	Vertically integrated CO column density.
SO_2_column_number_density	OFFL/L3_SO_2	mol/m^2	-0.4051	0.2079	SO_2 vertical column density at ground level, calculated using the DOAS technique.
NO_2_column_number_density	OFFL/L3_NO_2	mol/m^2	-0.00051	0.0192	Total vertical column of NO_2 (ratio of the slant column density of NO_2 and the total air mass factor).

Source: Researcher Field Work, 2023

RESULT AND DISCUSSION

Level of significant difference within each year: For CO, a paired sample t-test revealed that there was a statistically significant difference in 2019 compared to 2020, but not in 2020 compared to 2021. The years 2021 and 2022 did not significantly differ from one another either. There is no significant difference in SO_2 across the years. In 2019 and 2020, there was a significant difference in NO_2. Likewise, 2020 and 2021 exhibited a significant difference. However, no significant difference was observed between 2021 and 2022 (Table 2).

Table 2. Levels of significant difference

Parameters	Between 2019 and 2020	Between 2020 and 2021	Between 2021 and 2022
p-value of C0	$p < 0.05$ (0.003)	$p > 0.05$ (0.161)	$p > 0.05$ (0.452)
p-value of SO_2	$p> 0.05$ (0.401)	$p > 0.05$ (0.754)	$p> 0.05$ (0.145)
p-value NO_2	$p<0.05$ (0.049)	$p<0.05$ (0.003)	$p>0.05$ (0.510)

$p < 0.01$ = high significant difference; $p < 0.05$ = significantly difference; $p > 0.05$ = no significant difference; $p = 0$ represents no effect.
Source: Researcher Field Work, 2023

Monthly Distribution of Air Pollutants from 2019 - 2022: According to Tables 3, 4, and 5 for the year 2019, the month of February exhibited the most elevated concentration of CO (0.0724 mol/m^2). The month of

December displayed the highest concentration of SO_2 (0.0000282 mol/m^2). Similarly, the month of August experienced the highest concentration of NO_2 (0.00007 mol/m^2). In the subsequent year of 2020, February once again displayed the utmost concentration of CO (0.0796 mol/m^2). January, on the other hand, witnessed the highest concentration of SO_2 (0.0000478 mol/m^2), whereas February had the highest concentration of NO_2 (0.0000694 mol/m^2).

Table 3. Monthly mean concentration of CO from 2019 - 2022

Month	CO 2019	CO 2020	CO 2021	CO 2022
January	0.0653	0.0672	0.0633	0.0664
February	0.0724	0.0796	0.065	0.0668
March	0.0558	0.0641	0.0617	0.0596
April	0.0484	0.0504	0.0508	0.0502
May	0.042	0.0442	0.0415	0.0404
June	0.0403	0.0417	0.0414	0.0393
July	0.0431	0.0427	0.0474	0.0442
August	0.0417	0.0477	0.0476	0.0472
September	0.0376	0.0407	0.0385	0.0384
October	0.0367	0.0366	0.038	0.0365
November	0.0367	0.0474	0.045	0.0448
December	0.0516	0.0545	0.0527	0.0542
Mean	**0.047633**	**0.0514**	**0.0494**	**0.0490**

Source: Researcher Field Work, 2023

Table 4. Monthly Mean Concentration of SO_2 from 2019 - 2022

Month	SO_2 2019 (mol/m^2)	SO_2 2020 (mol/m^2)	SO_2 2021 (mol/m^2)	SO_2 2022 (mol/m^2)
January	0.0000148	0.0000478	-0.0000089	0.000048
February	-0.0000298	0.000013	0.0000156	1.20E-08
March	-0.0000488	-0.0000645	-0.000099	-0.0000591
April	-0.0000601	-0.0000498	-0.0000625	-0.0000599
May	-0.0000294	-0.0000297	-0.000045	-0.0000016
June	-0.0000514	-0.0000428	0.0000205	-0.0000063
July	-0.0000482	-0.0001165	-0.0000147	-0.0000201
August	0.0000164	0.0000275	-0.0000453	0.0000331
September	-0.0000685	0.0000028	-0.0000416	-0.0000333
October	-0.0000408	-0.0000161	-0.0000209	0.0000144
November	0.000012	0.0000083	0.0000265	0.0000032
December	0.0000282	0.0000185	0.000019	0.0000112
Mean	**-0.0000255**	**-0.0000167**	**-0.0000214**	**-0.0000059**

Source: Researcher Field Work, 2023

Table 5. Monthly Mean Concentration of NO_2 from 2019 - 2022

Month	NO_2 2019 (mol/m^2)	NO_2 2020 (mol/m^2)	NO_2 2021 (mol/m^2)	NO_2 2022 (mol/m^2)
January	0.0000626	0.0000668	0.000062	0.0000746
February	0.0000654	0.0000694	0.0000699	0.0000755
March	0.0000619	0.0000586	0.0000662	0.0000699
April	0.0000536	0.0000513	0.0000616	0.0000617
May	0.0000518	0.0000505	0.0000531	0.000056
June	0.0000468	0.0000534	0.0000602	0.000054
July	0.0000478	0.0000466	0.0000521	0.0000482
August	0.0000432	0.0000493	0.0000505	0.0000498
September	0.0000458	0.0000485	0.0000549	0.000052
October	0.0000413	0.0000495	0.000059	0.0000549
November	0.0000466	0.0000547	0.0000598	0.0000605
December	0.000055	0.0000605	0.0000721	0.0000766
Mean	**0.0000522**	**0.0000549**	**0.0000601**	**0.0000611**

Source: Researcher Field Work, 2023

In the year 2021, February exhibited the highest concentration of CO (0.065 mol/m^2). November recorded the highest concentration of SO_2 (0.0000265 mol/m^2), while December registered the highest concentration of NO_2 (0.0000721 mol/m^2). In the year 2022, February presented the most elevated concentration of CO (0.0668 mol/m^2). Lastly, January exhibited the highest concentration of SO_2 (0.000048 mol/m^2), whereas December experienced the highest concentration of NO_2 (0.0000766 mol/m^2).

Spatial trend of CO in 2019, 2020, 2021, and 2022: Figure 3 shows that 2019 had a maximum and minimum annual concentration of 0.0516 and 0.0482 mol/m^2 respectively. The highest annual concentration of CO was recorded in 2020 as 0.0554 mol/m^2; while 2021 had a maximum and minimum annual concentration value of 0.0525 and 0.0487 mol/m^2. On the other hand the year 2022 recorded 0.052 and 0.0479 mol/m^2 as its maximum and minimum annual concentration. Spatial mapping revealed that the most polluted areas were in the Benin City metropolis, which included the metropolitan region, while rural areas had the least pollution (Figure 3). CO is a colorless and odorless pollutant typically discharged from the incomplete combustion of fuel (Barbulescu and Barbes, 2017). The escalation in the level of CO in the atmosphere is predominantly caused by high traffic congestion, industrial activities, cooking, and waste incineration (Ernyasih *et al*., 2023; Mouronte-López and Subirán, 2023). Observing the LGA that makes up Benin City, the concentration of CO in 2019 was mostly distributed within Oredo, Egor, and Ikpoba okha compared to 2020, 2021, and 2022, which had CO concentration spread across the all four LGA. In general, the mean annual concentration of CO in 2019 changed significantly in 2020, but the years 2020, 2021, and 2022 did not change significantly, even if changes were observed in each month of the various years. 2020 was the COVID-19 pandemic (Behera *et al*., 2022) where strict movement regulations were implemented. However, the results of this study revealed that the year 2020 recorded the highest mean annual concentration throughout the study period. This could be due to the ineffective implementation of the COVID – 19 movement guidelines such as traffic reduction and company closures during the pandemic in 2020. In connection with this, almost every household in Benin City has a generator and constantly utilizes fuel or diesel on a daily basis (Clement and Dickson, 2011).

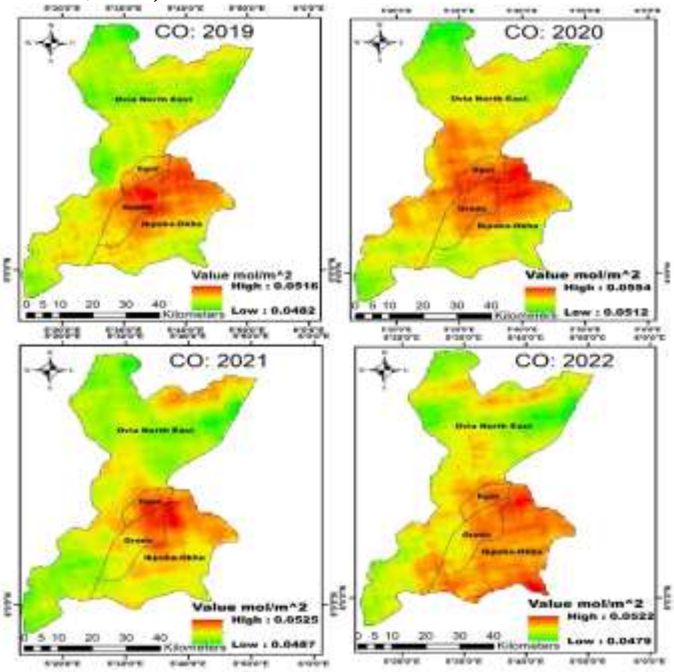

Fig. 3. Spatial mapping of CO in 2019, 2020, 2021, and 2022
Source: Researcher Field Work, 2023

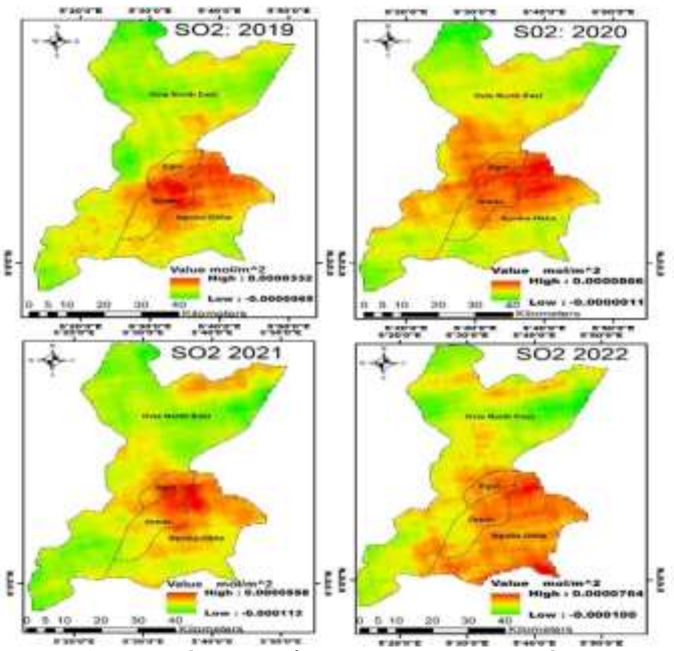

Fig. 4. Spatial mapping of SO_2 in 2019, 2020, 2021, and 2022
Source: Researcher Field Work, 2023

Spatial trend of SO_2 in 2019, 2020, 2021, and 2022: In Figure 4, 2019 recorded a maximum and minimum annual concentration of 0.0000332 and -0.0000965 mol/m^2 respectively. The highest annual concentration was recorded in 2020 (0.0000866 mol/m^2), while the maximum and minimum concentration values increased from 0.0000558 and -0.000112 mol/m^2 in 2021 to 0.0000764 and -0.000100 mol/m^2 in 2022. The results also revealed that the year 2020 had the highest SO_2 concentration throughout the study period which further confirms that despite the lockdown due to COVID-19, there was a drastic increase in the emission of fossil fuels because of high transportation activities in the LGA. The spatial map data derived from 2020, as shown in Fig 4, shows that the emission rate was greater in both Ovia North-East and Egor Local Government Areas than in the other local government areas. Multiple origins contribute to the discharge of SO_2 into the environment. For instance, the incineration of coal for the purpose of electricity production and industrial procedures represents a pivotal source of SO_2 emissions (Henneman *et al.*, 2023). The combustion of biomass, such as forests or agricultural remnants, can also contribute to the release of SO_2 (Gani *et al.*, 2023). Vehicles, specifically those that utilize diesel fuel, discharges SO_2 as a byproduct. Furthermore, the incineration of solid waste containing SO_2 materials can liberate SO_2 (Dawood, 2023). Lastly, the residential heating that involves the usage of solid fuels like wood or coal can contribute to the emission of SO_2 in rural regions (Mawusi *et al.*, 2023). The rise in SO_2 emissions in Ovia North-East might be attributed to increased anthropogenic activities such as domestic and industrial processes that utilize fossil fuels.

The rate of SO_2 emission in Ikpoba Okha Local Government also experienced a drastic increase in 2022, as shown in the spatial map. Ikpoba Okha is Edo State's second-biggest local government by population, with around 371,106 inhabitants residing in both urban and rural regions (Soluap, 2023).

This might be the cause of the emission increase experienced.

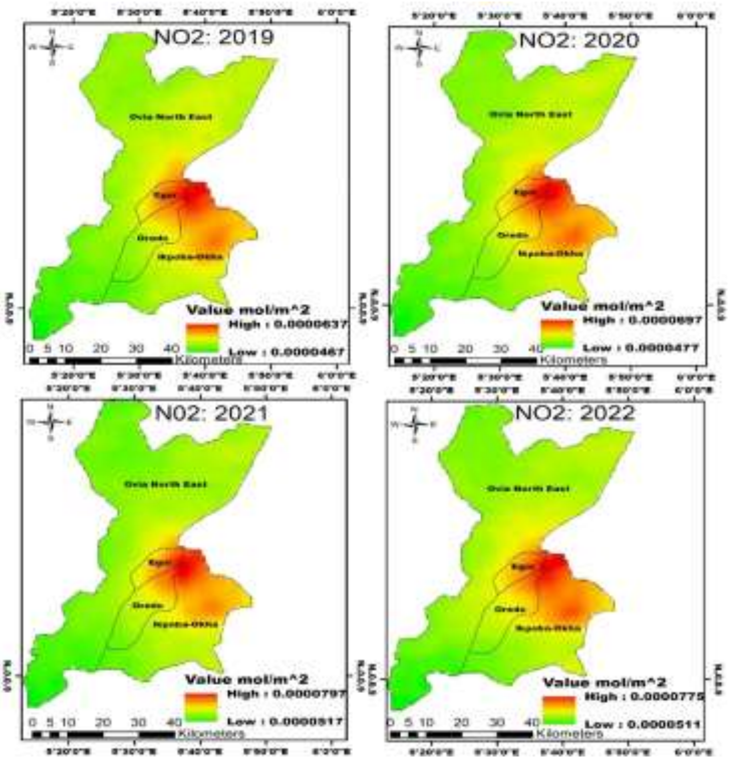

Fig. 5. Spatial mapping of NO_2 in 2019, 2020, 2021, and 2022
Source: Researcher Field Work, 2023

Spatial trend of NO_2 in 2019, 2020, 2021, and 2022: Figure 5 depicts that 2019 had a maximum and minimum annual concentration of 0.0000637 and 0.0000467 mol/m^2 respectively, while 2020 had as its maximum and minimum annual concentration value as 0.0000676 and 0.0000477 mol/m^2 respectively. The highest annual concentration of NO_2 was recorded in 2021 as 0.0000797 mol/m^2. The year 2022 recorded 0.0000775 and 0.0000511 mol/m^2 as its maximum and minimum annual concentration values. The chief origin of NO_2 in the air emanates from the combustion of fossil fuels (Shi *et al*., 2014). The concentrations of NO_2 in the four regions in Benin City were mostly present in the northeastern part of the city across the study periods. The trend of NO_2 concentration in Benin City in 2019, 2020, 2021, and 2022 changed considerably. However, after 2020, NO_2 concentration significantly increased in 2021 and 2022. This could be attributed to the fact that local business began to function which in turn increased vehicular activities in Benin City metropolis after the COVID-19 lockdown, which accelerated the concentration of NO_2. In summary, the study reveals that there was a significant difference ($p< 0.01$) in the concentration of CO between the years 2019 and 2020. It also showed that there was a significant difference ($p < 0.05$) in NO_2 concentration between the year 2019 and 2020. However there was no significant difference in the value of SO_2 between 2019 and 2020. Furthermore, while NO_2 concentration had high significant difference ($p < 0.01$) between 2020 and 2021, CO and SO_2 concentrations showed that there was no statistically significant difference ($p > 0.05$) between 2020 and 2021. Finally, the research revealed that the concentration of CO, SO_2 and NO_2 had no significant difference between the year 2021 and 2022.

Conclusions: Benin City is among the cities where air pollution necessitates scientific monitoring. Hence, this study presents a comprehensive monitoring and mapping assessment of the atmospheric concentrations of CO, SO_2, and NO_2 from 2019 - 2022 in Benin City, Southern Nigeria. The study finds that the COVID-19 lockdown protocol was loosely implemented in Benin City as results from this study did not effectively correlate with that of other studies. The study however contributes to monitoring programs that track environmental changes in CO, SO_2, and NO_2, providing an evidence-based foundation for decision-making among policymakers.

Acknowledgement: We wish to acknowledge the contribution of Adaigwe Adiel Igweze for proofreading the manuscript.

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