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Research Paper

Effects of meteorological factors on greenhouse gas emissions at traffic intersections in Baghdad: a seasonal analysis

ZAINAB N. ABDULATEEF [1*], ADEL H. TALIB[1] and MAITHAM A. SULTAN[2]

[1]Department of Biology, College of Science for Women, University of Baghdad, Baghdad, Iraq
[2]Scientific Research Commission, Research and Technology of Environment, Water and Renewable Energy Centre, Baghdad, Iraq
** Corresponding author E-mail: zainab.abd2102p@csw.uobaghdad.edu.iq*

ABSTRACT

Baghdad has experienced notable changes in its climate over recent decades. This study aims to evaluate the impact of meteorological factors, such as temperature, humidity, and wind speed, on greenhouse gas emissions at traffic intersections in Baghdad city. The study focuses, in particular, on comparing greenhouse gas concentrations during summer (June and July 2023) and winter (January 2024), highlighting how climatic conditions affect the accumulation and spread of these emissions. The results indicated that the greenhouse gas concentrations were much higher during summer than in winter because of high temperatures and strong winds contributing to the accumulation of gases in crowded areas. In contrast, high humidity and weak winds in winter contributed to the accumulation of gases differently. The analysis implies that low humidity during summer months because of heat and drought worsens greenhouse gas emissions, while small thermal changes affect the level of emissions from vehicle fuel. It explicitly shows the pivotal relationship that exists between climate conditions and emissions within a city, further pinpointing the human contribution— especially from traffic—to climate change, therefore meriting attention within urban planning in climate policies regarding emissions.

Keywords: Greenhouse gases, Climate change, Meteorological factors, Vehicle exhaust, Traffic pollutants, Atmospheric pollution.

Climate change is one of the world's most significant challenges, driving extreme weather events and warming temperatures due to emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Human activities mainly produce these emissions, including burning fossil fuels, transportation, agriculture, and industry. Recent reports indicate an 80% chance that annual global temperatures will temporarily rise by 1.5°C above pre-industrial levels over the next five years (WMO, 2024). Global studies indicate that the transportation sector is one of the most significant contributors to greenhouse gas emissions. In the United States, transportation accounts for about 28% of total greenhouse gas emissions, according to the U.S. Environmental Protection Agency (EPA, 2022). Road transportation accounts for 73% of greenhouse gas emissions in Europe's transportation sector, with passenger cars and light-duty trucks being the main contributors (Kazancoglu *et al.,* 2021). In India, a recent study confirms that vehicle emissions account for about 14% of the country's total emissions, further exacerbating urban pollution (Gupta and Jose, 2024). In Iraq, despite limited data on transport sector emissions, reports show a significant increase in GHG emissions, with total emissions in 1997 being about 83.1% CO_2, 9.2% CH_4, and 7.7% N_2O, with substantial contributions from the energy and transport sectors (IINC, 2016). Climate change and urban expansion in Baghdad increased temperatures and decreased rainfall, directly affecting air quality and local ecosystems (Dhamin *et al.,* 2023; Al-Ramahi *et al.,* 2022; Mohammed Ali and Al-Ramahi, 2020; Ali *et al.,* 2024; Nasser *et al.*, 2024; Ghanim *et al.,* 2024).

Increased greenhouse gas emissions exacerbate extreme heat and reduce extreme cold, with precise spatial effects (Yang *et al.,* 2021). Higher temperatures increase the efficiency of heat engines but lead to higher emissions due to fuel evaporation and reduced engine efficiency at higher temperatures (Raza *et al.,* 2022). High humidity negatively impacts fuel combustion efficiency, increasing fuel consumption by up to 40% due to air conditioning at

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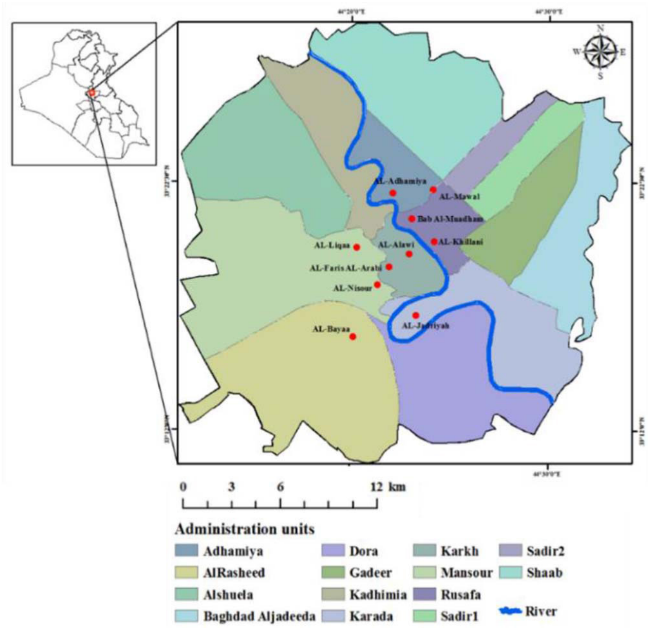

Fig. 1: Map of Baghdad showing study sites

80% relative humidity, which increases greenhouse gas emissions. Low wind speeds also contribute to the concentration of pollutants in urban areas, especially at traffic intersections, where stagnant air conditions exacerbate traffic-related pollutant levels (Xiong *et al.,* 2023; Pospisil and Jicha, 2019). Ali *et al.,* (2024) examined the relationships between meteorological factors and air pollutants in Karbala, Iraq, their principal component analysis (PCA) revealed that photochemical smog (45-46%), particulate matter (20-22%), and meteorological effects on particulates (14-16%) are the main factors influencing air pollution. This study aims to evaluate the effect of climate factors such as temperature, relative humidity, and wind speed on GHG emissions from vehicle exhausts at crowded traffic intersections in Baghdad.

MATERIALS AND METHODS

Study area

Baghdad, the capital of Iraq, is located in central Iraq along the Tigris River, which divides the city into two sections: the eastern section, known as Rusafa, and the western section, referred to as Karkh (Fig. 1). The geographic coordinates of Baghdad are approximately 33.452°-184°N and longitude 44.189°-576°E; it covers an area of roughly 4,555 km^2, which is 1% of the country's total land and is composed of 37 administrative units divided into 15 districts. As of 2022, the estimated population of the Baghdad Governorate was 9,006,001 people (ASGIS, 2023); this makes it the most densely populated governorate in Iraq and the area with the most vehicles per unit area.

Data sources

Meteorological data, including temperature, humidity, and rainfall, were obtained from the Iraqi Meteorological Organization and Seismology (IMOAS) provided the monthly average meteorological data from 1991 to 2023 (https://meteoseism.gov.iq). Measure the change or variation in the recorded values over time to indicate the increase between two periods (past and present).

Sample collection

Baghdad city, the capital, is known for its heavy traffic. Traffic intersections crowded with vehicles and close to state institutions were chosen away from industrial sites to measure the concentrations of greenhouse gases emitted from vehicle exhaust. Ten sites were selected in central Baghdad, five on the Rusafa side and five on the Al-Karkh side, as shown in (Fig. 1). Ten samples of GHGs, including CO_2, CH_4, and N_2O, were collected using a Gasmet FTIR gas analyzer (model DX4000) Gasmet Technologies Oy, supplied by Nederman Company. Measurements were conducted on the street at a one-meter height beside the road. Five replicates of GHGs were collected at each location during June and July 2023 and in January 2024 to depict the winter season. Meteorological factors, temperature, humidity, and wind speed were collected along with gas measurements from the Iraqi Meteorological Organization and Seismology (IMOAS) (https://meteoseism.gov.iq) at the study sites. The samples were gathered between 9:30 AM and 12:00 PM.

Statistical analysis

The ArcMap desktop 10.8 system was used to draw study locations. The Mann-Whitney test was used to analyze the data, as it does not follow a normal distribution. This analysis compared the levels of greenhouse gases during two different seasons: summer and winter. Spearman's correlation coefficient was calculated to examine the nonlinear relationships between greenhouse gases and atmospheric factors. This coefficient describes the strength and direction of the relationship between two continuous variables, enhancing our understanding of their interconnections. The values range from -1 (indicating a strong negative correlation) to 1 (indicating a strong positive correlation). Principal Component Analysis (PCA) was used to reduce the dimensionality of data related to greenhouse gases while preserving as much variance as possible. This analysis helped identify the most influential variables in the dataset, making it easier to understand the relationships between different gases and environmental conditions. All statistical analyses were performed using OriginPro 2024b.

RESULTS AND DISCUSSION

Meteorological variables

Fig. 2 shows Baghdad's analyzed monthly mean temperature, humidity, and rainfall data from 1991 to 2023. The study focused on seasonal changes (summer and winter) and the general change in the annual average. The study showed that the average summer temperature increased by 4.80%. This percentage reflects the moderate impact of global warming on summer temperatures. The average winter temperature increased more, by about 22.44%. This result shows that global warming significantly impacts reducing the intensity of winter cold. From 1991 to 2023, the annual average temperature increased by about 7.20%, reflecting the overall warming trend of the local climate, consistent with the global trend associated with increased GHG concentrations.

The average relative humidity in the summer (Fig. 2b) decreased by 16.4%, reflecting the impact of rising temperatures

Table 1: Mann-Whitney U test for winter and summer during the study period

Parameter	N	Winter season				Summer season				U-statistic	*p*-value
		Min	Max	Mean	SD	Min	Max	Mean	SD		
CO_2 (ppm)	20	416.20	572.4	476.25	51.20	527.29	589.71	557.99	26.47	15	0.009^{**}
CH_4 (ppm)	20	1.54	1.91	1.70	0.12	2.00	2.14	2.06	0.06	2.5	0.000^{***}
N_2O (ppm)	20	0.27	0.37	0.32	0.03	0.32	0.35	0.33	0.01	22	0.036^{*}
Temp. (°C)	20	10.79	12.03	11.41	0.65	31.95	35.81	33.98	1.52	0	0.000^{***}
RH (%)	20	66.25	71.89	69.07	2.97	22.02	31	25.29	2.64	100	0.000^{***}
WS ($m.s^{-1}$)	20	1.17	2.55	1.86	0.73	2.02	2.99	2.41	0.43	35	0.264^{NS}

*: $(0.01 \leq p < 0.05)$, **: $(0.001 \leq p < 0.01)$, ***: $(p < 0.001)$, NS: $(p > 0.05)$

Table 2: Correlation table of GHG and meteorological factors

Parameters	CO_2	CH_4	N_2O	Temp	RH	WS
Winter season						
CO_2	1					
CH_4	0.81	1				
N_2O	-0.64	-0.46	1			
Temp.	-0.47	-0.04	0.37	1		
RH	0.88	0.64	-0.46	-0.59	1	
WS	0.53	0.27	-0.34	-0.89	0.62	1
Summer season						
CO_2	1					
CH_4	0.81	1				
N_2O	0.78	0.77	1			
Temp.	0.21	0.46	0.63	1		
RH	0.72	0.77	0.49	0.04	1	
WS	0.44	0.65	0.56	0.81	0.42	1

and increased dryness at this time of year. The relative humidity in the winter was also reduced by 7.7%, a smaller decrease than in summer, but it still indicates the impact of climate change at this time of year. The annual average relative humidity decreased by 11.4%, reflecting the general trend of reducing humidity due to global warming and climate change. These results are consistent with the findings of Moussa and Alwehab (2023), who noted similar influences of meteorological factors on climate change. The rainfall data analysis (Fig. 2c) results show significant changes in annual and seasonal patterns. The average annual precipitation increased by 21.5%, reflecting an overall increase in annual rainfall. However, a sharp decrease of 100% in the summer indicated an arid season that could harm agriculture and water activities. In contrast, there was a 40.1% increase in precipitation in the winter months, suggesting the effects of climate change in increasing precipitation in this season. These results reflect the precise impact of climate change on precipitation dynamics in the region, consistent with what Moussa and Alwehab (2022) found, which showed fluctuation in the precipitation rates of Baghdad between (1981 and 2021).

Seasonal variations in the concentration of GHG and meteorological factors

Iraq's climate shows extreme seasonal variation, with summer and winter showing the most marked change, thus offering better insight into environmental and atmospheric variation. The measured rates of GHGs (CO_2, CH_4, and N_2O) in the selected traffic intersections, as shown in (Table 1), illustrated that in winter, their concentrations are 476.25 ppm, 1.70 ppm, and 0.32 ppm, respectively, while in summer, they increase to 557.99 ppm, 2.06 ppm, and 0.33 ppm. This data indicates that greenhouse gas concentrations are higher in summer than winter. The statistical analysis revealed U = 15 with a p-value of 0.009, indicating a highly significant difference in CO_2 levels between the two seasons. For CH_4 gas, the U-value was 2.5 with a p-value of 0.000, indicating a very strong significant difference. In the case of N_2O gas, the U-value is 22 with a p-value of 0.036, signifying a slightly significant difference between the two seasons. The meteorological factors recorded during winter were a temperature of 11.41°C, humidity of 69.07%, and wind speed of 1.86 $m.s^{-1}$.

In contrast, summer showed higher values, with a temperature of 33.98°C, humidity of 25.29%, and wind speed of 2.41 m/sec. This data indicates that humidity levels decreased while temperatures and wind speeds increased in the summer. The statistical analysis for temperature shows U = 0 with a p-value= 0.000, indicating a highly significant difference between the two seasons. For humidity, the values are U = 100 and p = 0.000, which also reflect a significant difference. In contrast, the WS analysis showed U = 35 and p = 0.264, suggesting no significant difference between the seasons. Most elements exhibit significant differences between summer and winter, such as CO_2, CH_4, N_2O, temperature, and RH. However, the WS does not significantly differ between the two seasons. It is worth noting that GHG are usually measured during normal times, so their concentrations can vary during traffic

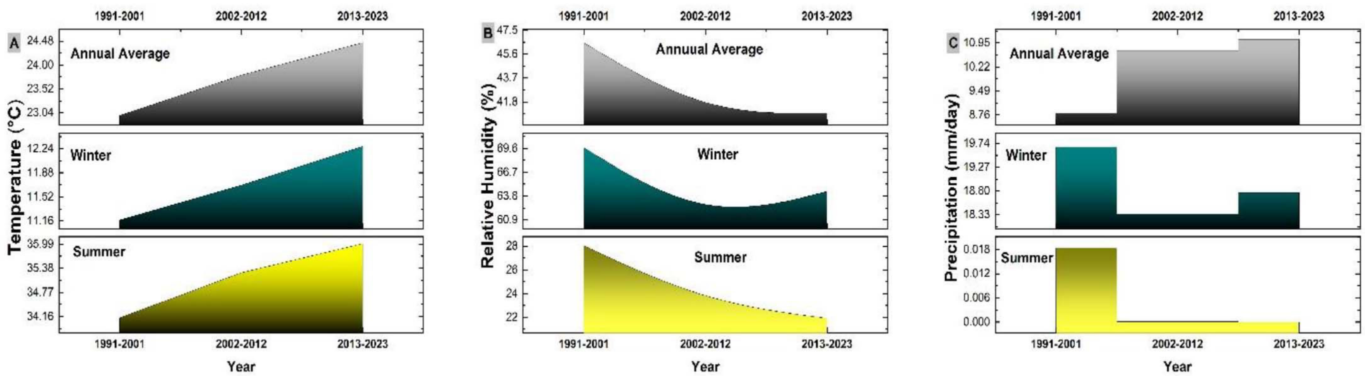

Fig. 2: Monthly changes in (A) temperature, (B) humidity, and (C) rainfall in Baghdad during (1991-2023)

congestion.

Effects of meteorological factors on GHGs

In winter, CO_2 strongly positively correlates with CH_4 at 0.81, indicating that similar sources, such as traffic and fuel combustion, are responsible for the emission of these two gases (Table 2). For CO_2, it has a strong positive correlation with RH, at 0.88, indicating that increased humidity contributes to its stability in the atmosphere. CO_2 also shows a moderate positive correlation with WS, at 0.53, reflecting wind's limited role in gas distribution. In contrast, CO_2 shows a moderate negative correlation with temperature, at -0.47, reflecting the effect of winter cold in increasing its accumulation due to lack of dispersal. In turn, CH_4 shows a strong positive relationship with RH, at 0.64, as high humidity contributes to the stability of CH_4 near the earth's surface, perhaps due to less dispersion. However, the correlation of CH_4 with WS is weak at 0.27, meaning that wind movement has a limited effect on the distribution of this gas. CH_4 also shows a weak negative correlation with temperature, at -0.042, reflecting the impact of winter cold on its concentration is insignificant.

On the other hand, N_2O exhibits a moderate negative correlation of 0.46- with RH, implying that humidity helps reduce N_2O concentration through wet deposition processes or chemical reactions in the atmosphere. N_2O is also weakly negatively correlated with WS at -0.34, reflecting the role of wind in reducing its concentrations through dispersion. In contrast, N_2O shows a weak positive correlation with temperature, at 0.37, indicating that a slight increase in temperature in winter enhances the production or reaction of N_2O. As for temperature, it shows strong negative correlations with RH at -0.59 and WS at -0.89, reflecting that winter cold increases near-surface gas stability and reduces the influence of wind movement. Meanwhile, RH shows a moderate positive correlation with WS at 0.62, suggesting that high humidity may be associated with slight air movement, thus facilitating the distribution of moisture. These results demonstrate high RH, weak winds, and winter cold affect the dynamics of GHGs from vehicle fuels. Humidity contributes to the stability of CO_2 and CH_4 while reducing the concentration of N_2O due to precipitation and chemical reaction processes. These results confirm the crucial role of winter climatic factors in controlling the distribution of GHGs.

In summer, CO_2 showed a strong positive correlation of 0.78 and 0.81 with N_2O and CH_4, respectively, highlighting the close relationship between vehicle gas emissions (Table 2). It suggests that factors present during the dry season contribute to increased concentrations of GHGs. Moderate positive correlations of 0.72 were observed between CO_2 and RH, while CO_2 has a weak positive correlation of 0.44 and 0.21 with WS and temperature, respectively. These results indicate that humidity plays a significant role in retaining CO_2, whereas wind contributes to its partial dispersal, and temperature has a lesser effect on CO_2 levels during summer than winter. CH_4 exhibits a strong positive correlation of 0.77 with N_2O, implying that the same factors influencing CH_4 emissions are likely to affect N_2O emissions.

Similarly, CH_4 shows a strong positive correlation of 0.77 with RH, while WS has a moderate positive correlation of 0.65. Humidity contributes to the rise in CH_4 concentrations, whereas wind helps modify its levels. The correlation between CH_4 and temperature is weak at 0.46; although heat can increase CH_4 emissions, it is not the most significant factor. N_2O shows a moderate positive correlation with temperature at 0.63, indicating that higher temperatures during the dry season contribute to increased concentrations of N_2O, likely due to various chemical reactions or environmental processes. RH and WS show weak to moderate positive correlations with N_2O, with coefficients of 0.49 and 0.56, respectively, implying that RH and WS may influence the distribution of N_2O. Still, their effects are less significant than temperature and other gases. During summer, a positive correlation appears between gas concentrations and climatic factors, such as temperature and humidity, implying that climatic conditions contribute to increased emissions, particularly of N_2O. Results demonstrate that climatic factors influence all gases differently according to the season, illustrating the diverse mechanisms of emission and dispersion under wet and dry conditions.

Principal component analysis (PCA)

The statistical analysis of the provided data uses principal components analysis (PCA) to examine the variation in the data across summer and winter. During winter, (Fig. 3a) shows that The strong positive relationship between RH and CO_2 suggests that increased humidity stabilizes CO_2 in the near-surface layers due to its reduced dispersion, especially under cold winter conditions. In contrast, the negative relationship between temperature and

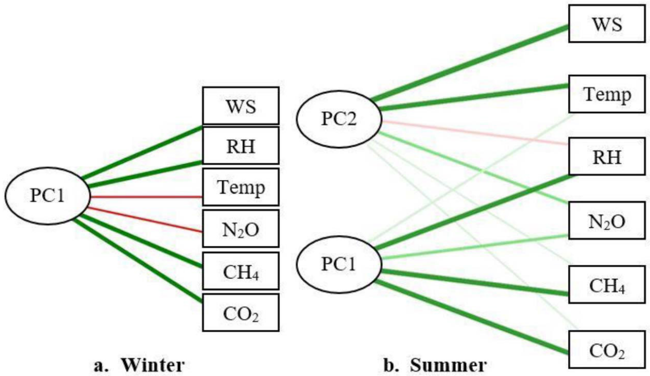

Fig. 3: Principal component analysis of GHG and Meteorological factors

CO_2 suggests that cold promotes the accumulation of this gas, as air movement becomes restricted, preventing its dispersion away from emission sources. N_2O shows a moderate negative relationship with humidity, reflecting the role of wet deposition in reducing its concentration, while WS is also negatively correlated with it, suggesting that wind plays a limited role in the distribution of this gas in winter. CH_4 shows a limited effect compared to the other gases, as it is positively correlated with humidity but shows less sensitivity to wind and temperature. Ultimately, these results highlight how high humidity and cold winters contribute to the stabilization of CO_2 and CH_4, while factors such as deposition and wind reduce the concentration of N_2O.

As shown in (Fig. 3b), CO_2, RH, and CH_4 relationships with the first principal component (PC1) are very strong in summer. It reflects a common impact of vehicle emissions on these gases; RH positively correlates with CO_2 and CH_4. Temperature and WS significantly contribute to the second principal component (PC2), reflecting how atmospheric conditions influence the distribution of gases. High temperatures increase chemical activity in the atmosphere, contributing to the accumulation of ground-level pollutants. Strong winds reduce the concentration of gases in a specific area but may transport them to other places, leading to a widespread environmental impact. Higher temperatures enhance water evaporation, which may reduce RH but increase the concentration of greenhouse gases such as CO_2 and CH_4 due to vehicle-related emissions. The emissions from vehicle fuel combustion increase as the summer temperature increases and the vertical movement of air decreases due to the effects of wind and humidity. CH_4 and CO_2 show a positive correlation with RH, reflecting the dependence of their accumulation on local conditions such as humidity. N_2O overlaps between both components, highlighting its complex and diverse impact, which may be associated with vehicle emissions and varying weather conditions.

CONCLUSION

The study confirms that climate factors such as temperature, humidity, and wind speed influence GHG emissions from vehicle exhaust at crowded traffic intersections in Baghdad. The results show that GHG concentrations increase significantly, especially in summer, due to high temperatures and low relative humidity, leading to increased thermal activity and fuel combustion emissions. In contrast, winter climate conditions help stabilize near-surface gases due to winter cold and weak wind movement.

The research is based on limited temporal and spatial measurements, and incorporating field data during peak traffic hours is expected to reveal even higher emissions. While the methodology relies on statistical analysis to explore the relationships between variables, it does not include predictive modelling. Future studies should expand to industrial areas to provide a comprehensive overview of emissions sources and analyse more extended periods to identify trends and align them with regional climate models. The study highlights the importance of considering seasonal and climate impacts when formulating environmental policies and calls for effective measures to reduce greenhouse gas emissions, especially in densely populated urban areas. These results will help support Iraq's efforts to fulfil its commitments under the Paris Climate Agreement, improve sustainable development strategies, and enhance air quality.

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