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Air Quality Based on the Spatial-Temporal Variations of Particulate Matter (PM2.5 and PM10) Concentrations Using R

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Abstract

Air pollution is an escalating health problem in Iraq, particularly since dry and semi-dry conditions often exacerbate the loads of airborne dust and particles. We assess the impact of fine particulate matter PM2. with freely available Copernicus Atmosphere Monitoring Service (CAMS) products from the European Centre for Medium-Range Weather forecast (ECMWF) over Iraq. The analyses were performed on the year 2021, with a focus from January to March due to higher pollution levels within this period, it can be expected that particle concentrations are elevated. We also calculated the annual mean PM2. PM2. 5 and PM10 for 2021 are provided for a more global perspective with relevant international air-quality reference level. We used spatial methods in R to apply particulate matter fields to 20 of Iraq's major cities, which allowed us to map geographic inconsistencies and areas with chronically high pollution. Results show that regional contrasts are considered very strong: PM2. 5 and PH10 than cities situated north or southwest. The observed patterns are in line with the synergistic influences of weather variability, recurrent dust storms, and local emissions associated with oil industry activity and urban stressors. PM2. In the most polluted areas, it was trained to 2023 data. Large portion of fine particles as implied by 5 relative to PM10. In total, mean PM concentrations were above WHO guidelines for all the cities surveyed with high levels of exposure likely resulting in health consequences. These results support the case for air pollution control and place specific interventions in Iraq.

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1. Introduction

Industrialization and rapid urbanization have escalated urban air pollution worldwide [1]. Today, over 50% of the global population resides in urban areas, a figure expected to more than double by 2050. In Iraq, the urban population in 2021 was 30,960,655, comprising 71.12% of the total population of 43.53 million [2]. Currently, Iraq faces escalating environmental challenges, particularly worsening air pollution. This is attributed to the adverse impacts of three wars, population growth, climate change and inadequate land use planning [3]. Consequently, many people experience continuous exposure to harmful levels of pollution. According to the United Nations International Children's Emergency Fund (2023 [4], Iraq ranked as the world's second-worst country in terms of air quality out of 118 countries, and data reveal that the concentrations of several pollutants, such as PM2.5 and PM10, are substantially above the WHO air quality guidelines (AQG). The main air pollutant sources in Iraq contributing to cli-mate change are emissions from transportation, industry and electricity generation. Major sources of air pollution in Iraq also include oil related activities, especially in urban areas in the southern region of the country [5]. Recent studies also show that air pollution over Iraq exhibits significant spatial and temporal variability with elevated levels of NO_2 and aerosols detected in major cities [6]. The combined effects of air pollution adversely impact terrestrial and aquatic ecosystems, causing biodiversity loss and environmental degradation. Elevated particulate matter concentrations can also harm ecosystems, reduce visibility, and degrade soil and water quality, in addition to their well-documented impacts on human health [7]. Moreover, air pollution poses a major global health threat and is one of the major global risk factors responsible for premature deaths [8]. Globally, air pollution is considered the greatest environmental threat to public health, responsible for approximately 7 million premature deaths annually [8]. Exposure to extremely levels of fine particles is estimated to reduce life expectancy, primarily due to the increased risk of lung cancer and respiratory diseases, and other illnesses, as diabetes, also can cause mental health problems in children [9]. In Iraq, the estimated death rate attributed to ambient particulate matter in 2019 was 121.6 per 100,000 people [10]. One method to determine emissions involves using short-term emission measurements extrapolated over an extended period [11]. The present work goal is to study the spatial distribution and short term temporal variability of $PM_{2.5}$ and PM_{10} concentrations across Iraq using gridded atmospheric composition data. The analysis focuses on the first quarter of 2021 (January - March), a period often shaped by seasonal meteorological conditions that can elevate particulate matter levels. When the concentrations of the fine particulate matters are particularly higher due to reduced wind speed, atmospheric stability, and increased dust activity [12]. Additionally, we study the annual mean concentrations of PM2.5 and PM10 across Iraqi cities during 2021 compared to the resulting concentrations of WHO air quality guidelines.

2. Materials and Methods

2.1. Description of the study area

The present study was conducted in Iraq, located in the Middle East, southwest Asia (Figure 1). Based on the statistics published in the World Atlas 2021 [13], Iraq is divided into 18 governorates with a total population of 44,496,122. Almost 71% of Iraq's population resides in urban areas, and a considerable share of the inhabitants live in Baghdad. Iraq's total area is 435,052 km² and is comparatively low at an average elevation of 312 meters above sea level [14]. Iraq has a subtropical semi-arid climate, except for mountainous regions in the north and northeastern half with a Mediterranean climate. The land experiences cool winters and dry summers, with a variation between hot and extremely hot temperatures. The annual mean temperature in most parts of the country exceeds 25 °C; temperatures are low in the north and relatively high in the remaining regions, particularly in the south and central west, and the relative humidity varies from 18% to 59% [15].

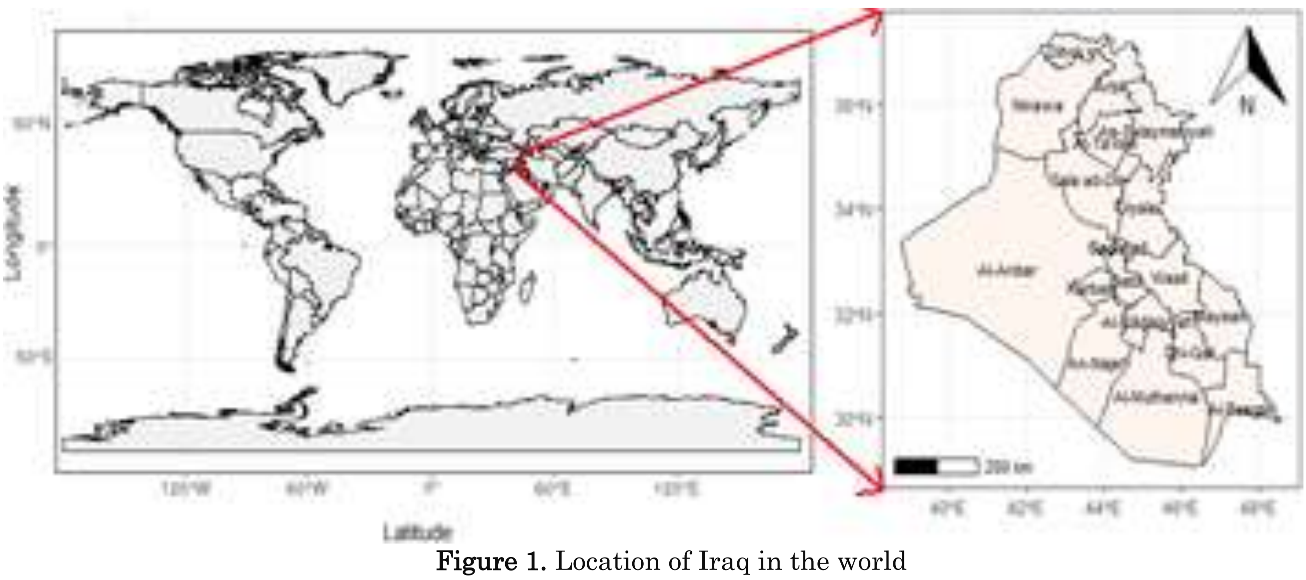


Figure 1. Location of Iraq in the world

2.2. Data Reduction

This study utilised $PM_{2.5}$ and PM_{10} data with respect to the open access climate variables from the Copernicus Atmosphere Monitoring Service (CAMS) Global Atmospheric Composition Forecast. It is important to note that the CAMS products used in this study are model based estimates of atmospheric composition rather than direct ground based measurements. This is especially useful for Iraq, where long term monitoring networks and dense station coverage are limited. By integrating satellite observations with atmospheric modelling, CAMS provides consistent, spatially continuous air quality fields that are well suited for regional scale assessment. The CAMS operational system is produced by the European Centre for Medium-Range Forecasting (ECMWF). It can continuously monitor the composition of Earth's atmosphere at global and regional scales [16]. The CAMS global near-real-time service offers daily analyses of atmospheric pollutants every six hours with a spatial resolution of 0.7×0.7^{o} from Earth's surface up to 5000 m [17]. Furthermore, the CAMS regional system provides hourly analyses and one four-day forecast every day of the main air quality species and analyses of the day before [18].

CAMS forecasts are available on the CAMS forecasting system at https://atmosphere.copernicus.eu/data, and the CAMS Global Near-Real Time can be downloaded freely from the CAMS Atmosphere Data Store, initialised daily from analyses at 00 UTC with data availability guaranteed by 08:00 UTC. Please refer to [19] for more details about the multi-model forecast system. To produce a global map of yearly average $PM_{2.5}$ and PM_{10} in 2021 and compare the data with those of Iraq, the study also used data from the WHO Archives on air pollution in 2021, which is available at the (https://www.who.int/data/gho/data/themes/theme-details/GHO/air-pollution), in addition to yearly average data in 2021 in IQAir's World Air Quality Reports: https://www.iqair.com/us/world-air-quality-report. To analyse, handle and visualise CAMS data, we implement R packages, functions and methods for handling geospatial analysis and mapping. The R system is a free software environment for statistical computing and graphics (https://www.r-project.org/:R). This system is also a powerful analytics engine for mapping and geographic analysis, and it offers many important packages for statistical modelling, air quality data analysis and visualisation using many libraries for numerical analysis, which can easily be linked or extended to code written in Fortran, S, C++, C or Java. This will be relevant to researchers and spatial data analysts who intend to use R to access and analyse spatial data in detail [20]. The first step to handling and displaying the CAMS data in the form of two-dimensional maps is to read and extract the downloaded zip file from the CAMS to classify how the spatial data are organised and stored in the zip file. For example, the range spanned by the spatial coordinates is the coordinate reference system (degrees longitude/latitude or the UTM zone), in addition to more details about air pollutants of a specific spatial class. To read and write the data via spatial statistics packages needs to a conversion of data between the 'sp classes' and the 'package's classes' in an interface package between R and the open-source GRASS GIS and the handling of spatial-temporal data in GIS file formats [21].

2.3. Data processing and analytical methodology

Daily, gridded $PM_{2.5}$ and PM_{10} concentration fields were retrieved from the Copernicus Atmosphere Monitoring Service (CAMS) and spatial handling and extraction were performed with geospatial packages in the R environment. For the short-term component, the daily grids were summarised into monthly mean concentration surfaces for January, February and March 2021 by averaging values within each grid cell across the days of each month. These monthly products were then used to explore both geographic contrast and month to month changes in particulate matter across Iraq. The CAMS raster dataset was imported and converted into appropriate spatial formats, after which Iraq's national boundary and city point locations were layered onto the concentration grids. This overlay enabled the extraction of $PM_{2.5}$ and PM_{10} values for major Iraqi cities. For each city, minimum, maximum, and mean concentrations were computed and used to generate the statistical summaries and visual outputs presented in section 3. To characterise longer term conditions, annual mean $PM_{2.5}$ and PM_{10} for 2021 were calculated from CAMS by averaging daily concentrations over the full year, providing a broader context, global annual $PM_{2.5}$ and PM_{10} distribution maps. These maps were used to contextualise Iraq relative to global patterns and to support comparisons with WHO guideline values.

3. Results and Discussion

3.1. Spatial variation of PM2.5 and PM10 concentrations

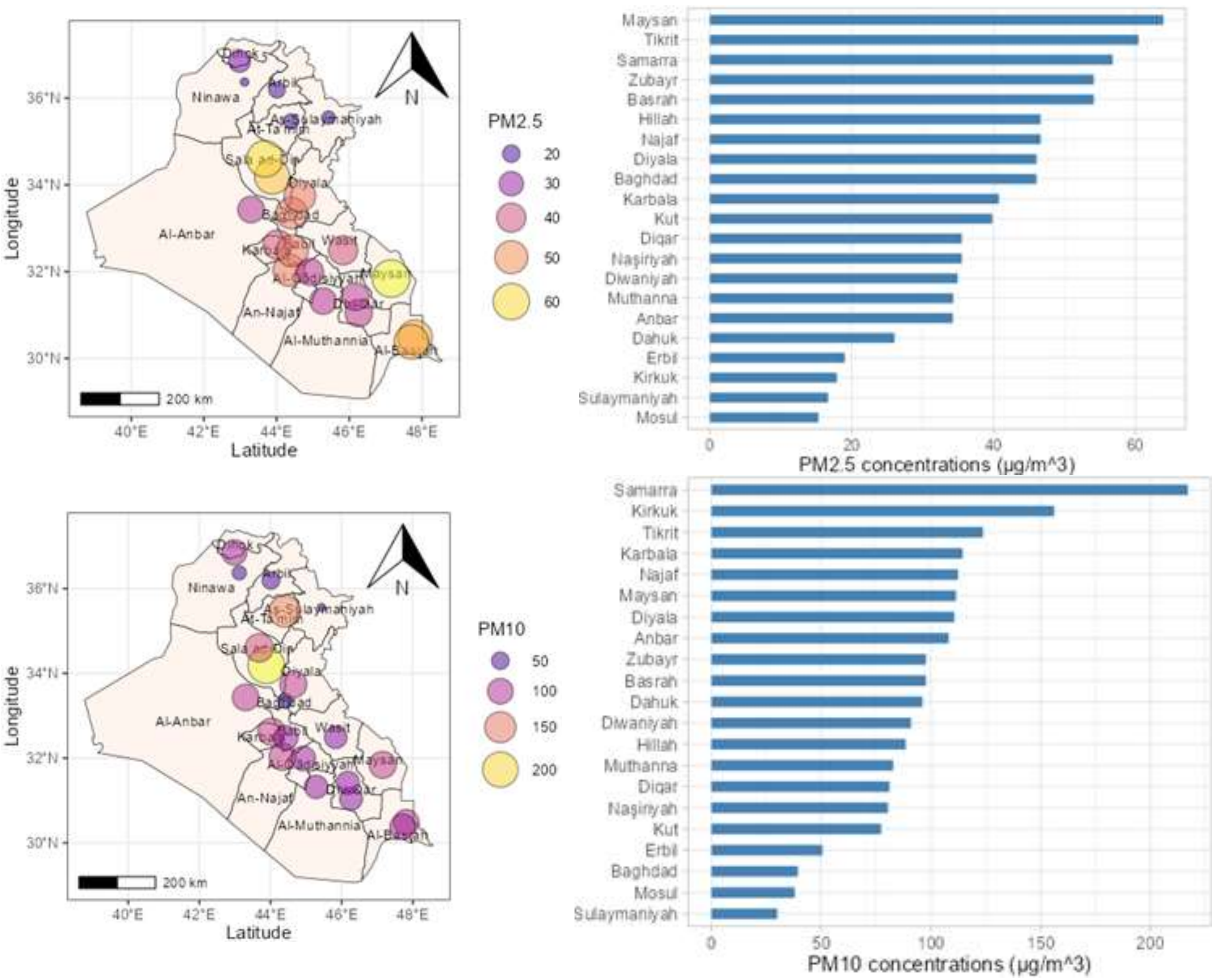
Fine $PM_{2.5}$, and PM_{10} particulate matter was monitored in 20 Iraqi cities. Figure 2 illustrates the monthly mean concentrations recorded during January, February, and March 2021 for each city. The spatial maps depict the distribution of ($PM_{2.5}$ and PM_{10}) concentrations of emission at a spatial resolution of 1 km², enabling comparison of regional and temporal variations. Based on the analysis of data collected during January, February, and March 2021, ($PM_{2.5}$ and PM_{10}) concentrations were higher in the central and southern regions of Iraq compared with other parts of the country. *In* contrast, the northern regions exhibited a substantial decrease in particulate matter concentrations during this period, with average levels approximately 72% lower than those recorded in the central and southern regions. Figure 2 presents the spatial distribution and monthly average concentrations of $PM_{2.5}$ and PM_{10} across Iraqi cities during the January–March 2021 study period. The analysis reveals distinct temporal and regional variations in particulate matter concentrations within these three months. During the study period, the higher PM_2. Higher concentrations of $_5$ were normally recorded in January and March, however, compared to February, the lowest level reached. Monthly average PM_2. Monthly modelled $_5$ concentrations from January through March, displayed larger values over many central and southern cities at >60 μg/m³ (e.g. Baghdad, Basra), with neighbouring areas showing less pronounced pollution increases (i.e. northern Iraq generally 300 μg/m³) during March, followed by January and February, whilst northern areas (NE-Iraq, NW-Iraq, Syria) maintained much lower PM_{10} levels with very low monthly mean concentrations (<50 μg/m³) found for almost every month in this area. In general, it can be observed that the values of particulate matter concentrations in central and southern regions of Iraq were significantly higher than those from northern regions during January–March 2021. Average PM_2. Calculated annual mean PM_5 concentrations (2012) in the large urban centers of the central and southern areas ranged from 30 to 60 μg/m³ relative to ~18 μg/m³ in northern Iraq. In the central and southern Iraq, PM_{10} concentrations ranged from 50 to350 μg/m³, while a factor 10 lower values were recorded in the northern direction.

The lower values of particulate matter concentration in February can be attributed to the seasonal meteorological conditions affecting during the winter months over Iraq, which are characterized by greater precipitation and lower levels of dust storms. Nevertheless, given that the present study did not quantitatively assess meteorological parameters, this interpretation must be made cautiously and merits further investigation.

3.2. Statistical analysis of $PM_{2.5}$ and PM_{10} concentrations

Tables 1 and 2 present the statistical characteristics of $PM_{2.5}$ and PM_{10} concentrations, respectively, calculated from values averaged over the three-month study period (January–March 2021) for each Iraqi city. These characteristics summarize the minimum, maximum, and mean concentrations derived from the combined three-month dataset, rather than individual monthly values. Figure 3 presents the monthly average concentration levels of $PM_{2.5}$ and PM_{10} during the study period. The period from January to March, 2021 was characterised by a clear difference in emission levels of fine particles with a diameter of 2.5 and 10 μm. The monthly averages of PM2.5 and PM10 concentrations measured in Iraq were 18.4–49.22 and 48.28–242.51 μg/m³, respectively. Results display that the lowest $PM_{2.5}$ concentration was observed in the range of 15.31–22.76 μg/m³ in Mosul in north Iraq, followed by Sulaymaniyah, Kirkuk, Erbil, Dahuk, Diqar, Muthanna, Kut, Anbar, Diwaniyah, Hillah, Karbala, Najaf, Diyala, Zubayr, Basrah, Baghdad, Tikrit and Samarra, and the highest PM2.5 concentration was of 38.74–63.95 μg/m³ in Maysan in southern Iraq. Moreover, minimum PM10 concentrations ranged from 30.03–66.54 μg/m³ in Sulaymaniyah, followed by Sulaymaniyah, Erbil, Mosul, Dahuk, Kut, Basrah, Diqar, Hillah, Muthanna, Maysan, Zubayr, Baghdad, Najaf, Kirkuk, Karbala, Diwaniyah, Diyala, Anbar and Samarra, while maximum PM10 concentrations (217.12–267.89 μg/m³) were observed in Tikrit city, 140 km northwest of Baghdad, the capital of Iraq. Overall, cities and provinces in the south and central regions have higher $PM_{2.5}$ and PM_{10} levels than those in the north. The PM2.5 and PM10 concentrations have considerably higher variations from January to March in the northern part of Iraq than those in the middle and south of Iraq (see Figure 4).

The monthly average $PM_{2.5}$ concentrations during the study period were 21.16 μg/m³ in the northern cities, 43.73 μg/m³ in the southern part, 40.082 μg/m³ in Baghdad and the neighbouring regions, 35.3875 μg/m³ in the south-east part and 32.03 μg/m³ in the west part of Iraq. Conversely, the monthly average PM_{10} concentrations in the different parts of Iraq were 60.46 μg/m³ in the north, 120.97 μg/m³ in the south, 155.79 μg/m³ in the middle part, 123.67 μg/m³ in the southwestern and 86.51 μg/m³ in the eastern region.



(a) (b)

Figure 2. Monthly average mass concentration of (a) $PM_{2.5}$ and (b) PM_{10} in Iraq in January – March, 2021.

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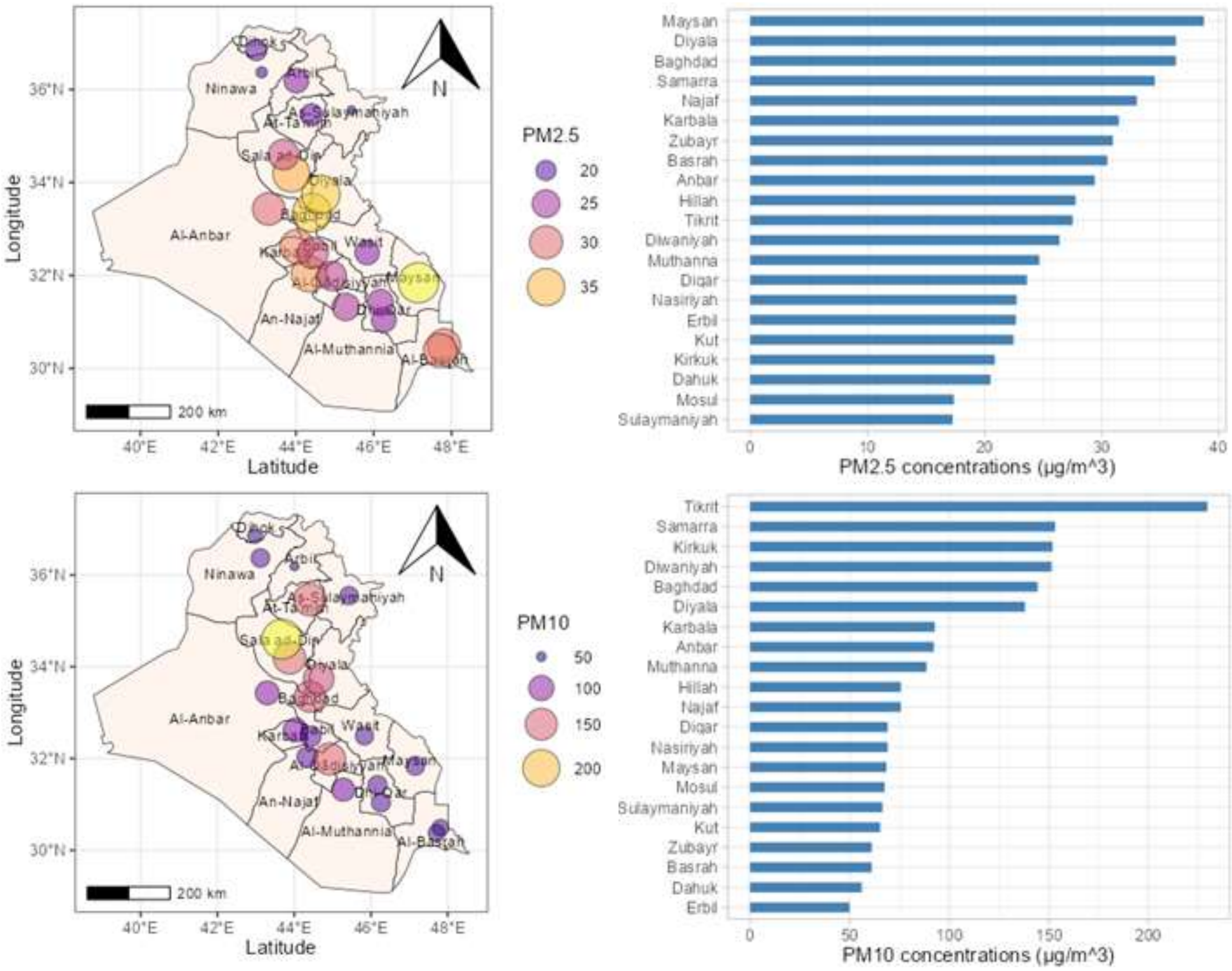

(a) (b)

Figure 2. Continued: February

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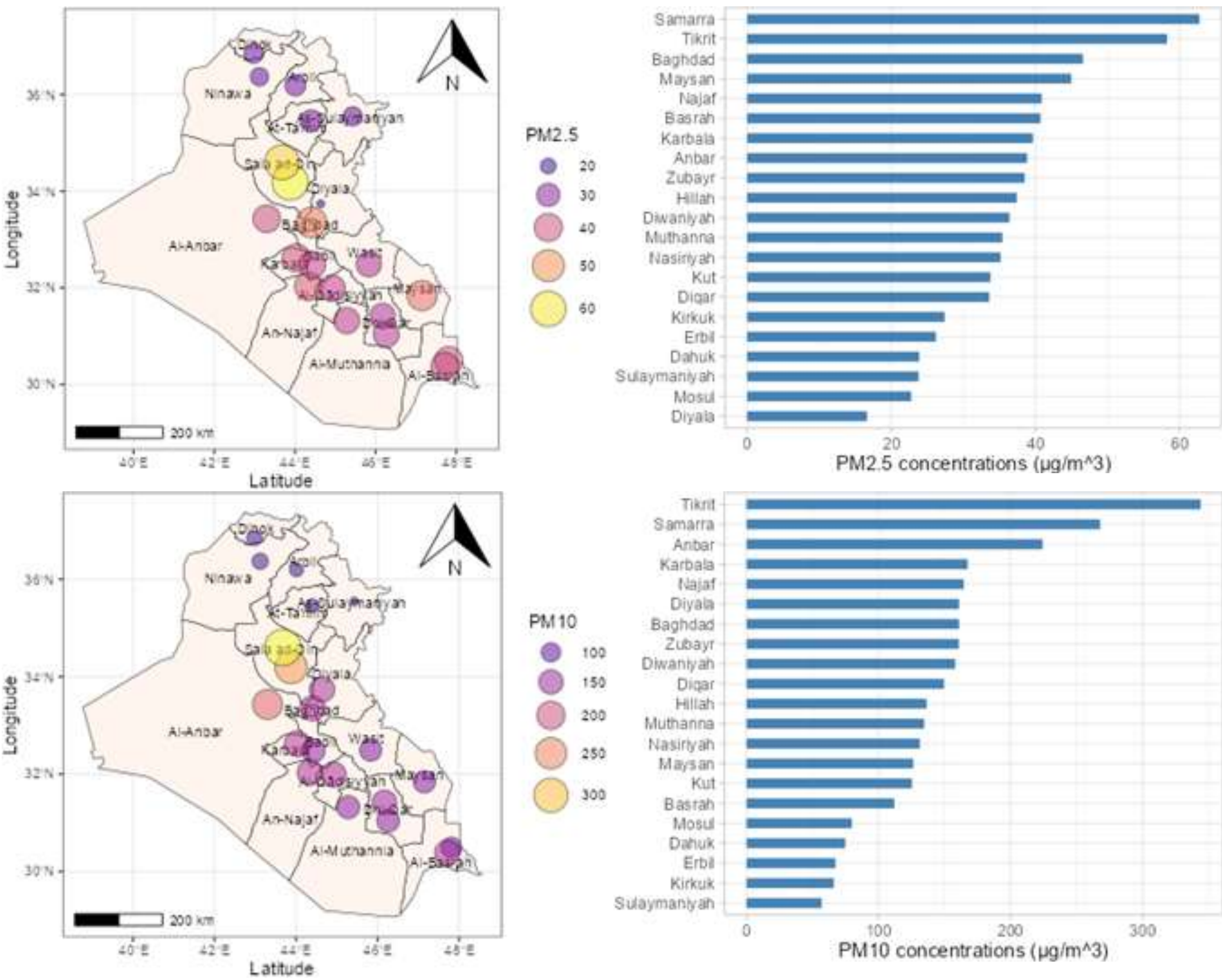


(a) (b)

Figure 2. Continued: March

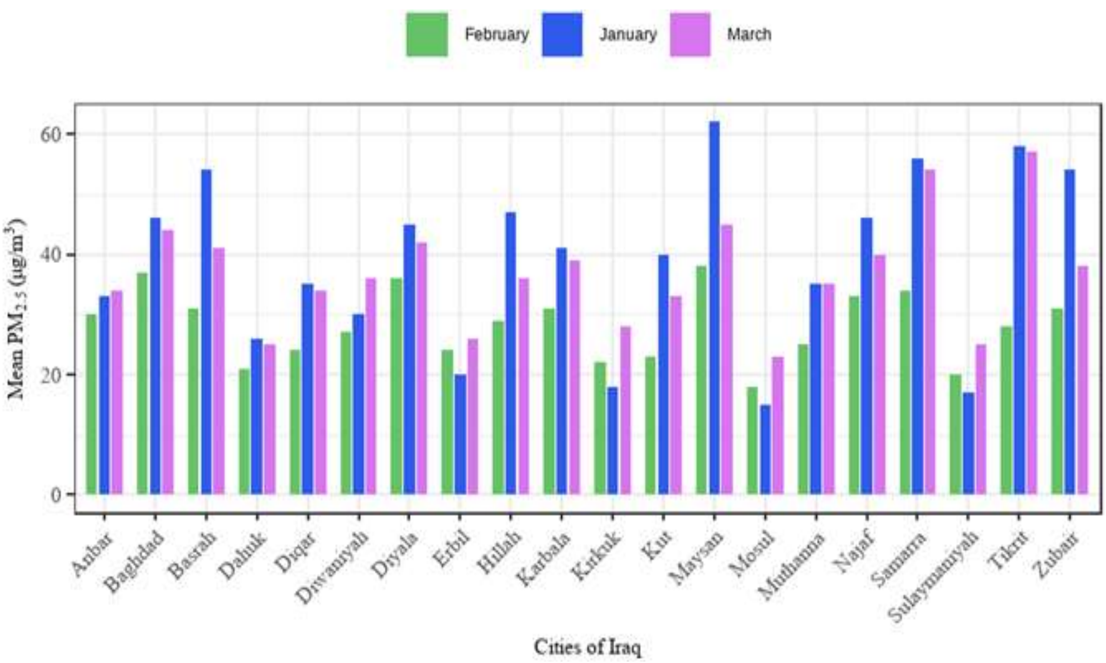
Table 1. Summary of the descriptive statistic $PM_{2.5}$ concentrations in Iraq.

City	Min. $PM_{2.5}$ (μg/m³)	Max. $PM_{2.5}$ (μg/m³)	Mean (μg/m³)
Mosul	15.31	22.76	18.4
Sulaymaniyah	16.69	23.76	19.25
Kirkuk	17.91	27.40	22.07
Erbil	19.04	26.18	22.63
Dahuk	20.53	26.05	23.48
Diqar	23.63	35.54	30.92
Muthanna	24.70	35.42	31.48
Kut	22.49	39.84	32.03
Anbar	29.43	34.27	32.52
Diwaniyah	26.41	36.41	32.59
Hillah	27.79	46.65	37.28
Karbala	31.49	40.77	37.31
Najaf	33.02	46.65	40.17
Diyala	36.36	46.07	40.18

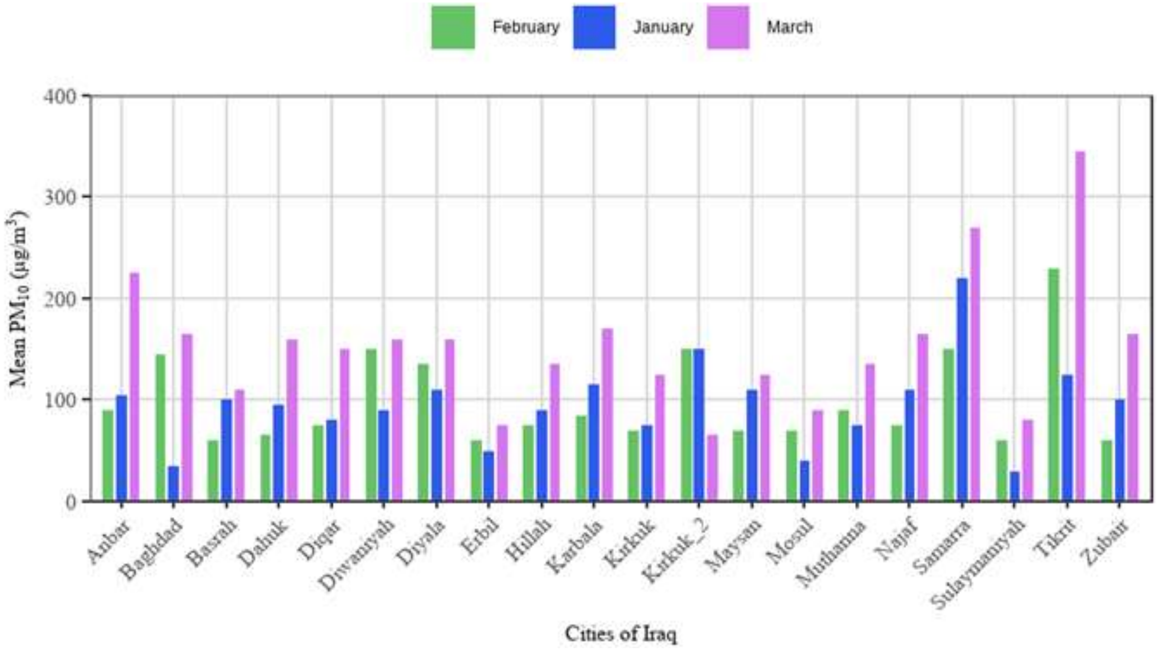
Zubayr	30.98	54.15	41.21
Basrah	30.50	54.15	41.78
Baghdad	36.36	46.07	42.01
Tikrit	27.55	60.44	48.42
Samarra	34.56	56.79	48.71
Maysan	38.74	63.95	49.22

Table 2. Summary of the descriptive statistic PM_{10} concentrations in Iraq.

City	Min. PM_{10} ($\mu g/m^3$)	Min. PM_{10} ($\mu g/m^3$)	Mean ($\mu g/m^3$)
Sulaymaniyah	30.03	66.54	48.28
Erbil	49.92	67.30	58.61
Mosul	37.97	79.68	58.83
Dahuk	56.08	96.13	76.11
Kut	61.13	111.89	86.51
Basrah	65.34	125.29	95.32
Diqar	68.48	126.20	97.34
Hillah	75.73	136.41	106.07
Muthanna	82.83	134.49	108.66
Maysan	69.11	149.49	109.30
Zubayr	61.13	160.79	110.96
Baghdad	66.05	156.18	111.11
Najaf	75.74	164.50	120.12
Kirkuk	90.97	158.01	124.49
Karbala	92.75	167.46	130.10
Diwaniyah	110.68	160.96	135.82
Diyala	92.40	224.30	158.30
Anbar	39.40	160.96	160.96
Samarra	123.75	344.10	233.93
Tikrit	217.12	267.89	242.51



(a)



(b)

Figure 3. Monthly variations of (a) mean $PM_{2.5}$ and (b) mean PM_{10} in Iraq from January to March, 2021.

3.3 $PM_{2.5}$/ PM_{10} Ratio Analysis

The $PM_{2.5}/PM_{10}$ ratio was also examined to gauge the relative contribution of fine versus particulate matter in Iraq cities. The values shown in Table 3 range from 0.18 to 0.45, indicating clear spatial differences influenced by human activities, natural dust processes, and oil production processes.

Table 3. PM2.5/PM10 ratio Iraqi cities för the period January- March, 2021.

City	$PM_{2.5}$/ PM_{10}
Kirkuk	0.18
Tikrit	0.19
Anbar	0.20
Samarra	0.20
Diwaniyah	0.23
Diyala	0.25
Karbala	0.28
Muthanna	0.29
Dahuk	0.30
Mosul	0.31
Diqar	0.32
Najaf	0.33
Hillah	0.35
Kut	0.37
Zubayr	0.37
Baghdad	0.38
Erbil	0.38
Erbil	0.38
Sulaymaniyah	0.39
Basrah	0.43
Maysan	0.45

As shown in Figures 4, the $PM_{2.5}/PM_{10}$ ratio estimates from the sampled Iraqi cities show clear geographic differences. The largest values were recorded in Maysan 0.45 and Basrah (0.43), with relatively high ratios also seen in Sulaymaniyah (0.39), Baghdad (0.38), Erbil (0.38) and Kut (0.37). These elevated ratios are consistent with settings where combustion related and other human driven emissions, such as traffic, industrial activity,and oil sector operations, contribute more to the particulate mix. In contrast, the lowest ratios occurred in Kirkuk (0.18), Tikrit (0.19), Samarra (0.20), Anbar (0.20), and Diyala (0.25), pointing to a larger coarse particle component is typically associated with windblown dust and other natural sources. The mapped distribution of the $PM_{2.5}/PM_{10}$ ratio (Figure 4) therefore supports the earlier concentration results, showing that particulate pollution in Iraq reflects a combination of anthropogenic emissions and dust related processes, with their relative influence varying from different regions.

3.3. Three-month average Concentrations of $PM_{2.5}$ and PM_{10} Compared to the WHO Guidelines

This section presents a regional analysis of $PM_{2.5}$ and PM_{10} concentrations in Iraq and compares the observed values with the World Health Organization (WHO) air quality guideline limits for annual mean concentrations. Figures 5 and 6 illustrate the variations in mean particulate matter concentrations across Iraqi cities based on data monitored during (1 January to 31 March 2021). Although the WHO guideline values are defined as annual averages, they are used here as reference benchmarks to contextualize the magnitude of particulate matter levels observed during the monitoring period, rather than to imply direct annual compliance. The results revealed that all cities in Iraq exceed the WHO guideline and are far higher than the AQG in 2021 (Figure 5(a)). Figure 5(a) shows that emissions of PM2.5 were considerably increased in Mosul, Sulaymaniyah, Kirkuk, Erbil, Dahuk, Diqar, Muthanna, Kut, Anbar, Diwaniyah, Hillah, Karbala, Najaf, Diyala, Zubayr, Basrah, Baghdad, Tikrit, Samarra and Maysan. The lowest and highest $PM_{2.5}$ average concentrations recorded in Iraq during January–March was 27.17 µg/m³ and 41.16 µg/m³, respectively. Compared to the WHO guidelines, the minimum $PM_{2.5}$ concentration exceeded the permitted limit by 5.4 times, while the maximum $PM_{2.5}$ concentration surpassed the limit by 8 times. The percentage of average $PM_{2.5}$ concentrations in the study sites during the study period is summarised and shown in Figure5 (b). The $PM_{2.5}$ percentage in Maysan, Tikrit, and Samarra demonstrates increasing trends, in contrast to other cities where variations are relatively lower. Conversely, provinces in northern Iraq, like Mosul and Sulaymaniyah, exhibit the opposite trend. Concentration of the $PM_{2.5}$ has been calculated in five main parts in Iraq: the northern, southern, southwest, southeast and central regions. These regions encompass 20 cities and are home to nearly 43.5 million people based on the World Bank's Open Data (The World Bank, 2022). Overall, the percentage of the average $PM_{2.5}$ concentrations was in the following order: 24% in the southern, 23% in the central, 22% in the southeast, 18% in the southwest and 13% in the northern regions of Iraq. The cities and provinces in the south, central and southeast have higher percentage levels than those in the north and southwest. The local distribution of average PM_{10} concentrations shows similar trends as $PM_{2.5}$, and the observed values indicate that PM_{10} concentrations were also very high in the study sites. In Figure 6(a), we display areas in ascending order according to the average PM_{10} concentrations across the study period. PM10 concentrations increased significantly across all Iraq regions, with sporadic areas near Baghdad recording extremely high concentrations exceeding 200 µg/m³. This surpasses the recommended annual mean PM_{10} limits by 172%. Additionally, other regions exhibited high concentrations exceeding 50 µg/m³, approximately 107% higher than the recommended limits. In Baghdad and surrounding areas, these concentrations accounted for 29% of the total average PM_{10} levels during the study period. Conversely, northern Iraq experienced a notable decrease in PM10 concentrations, constituting only 13% of the total average levels. In general, PM_{10} concentrations tended to increase in cities in the central areas and decrease in the northern regions (Figure 6(b)).

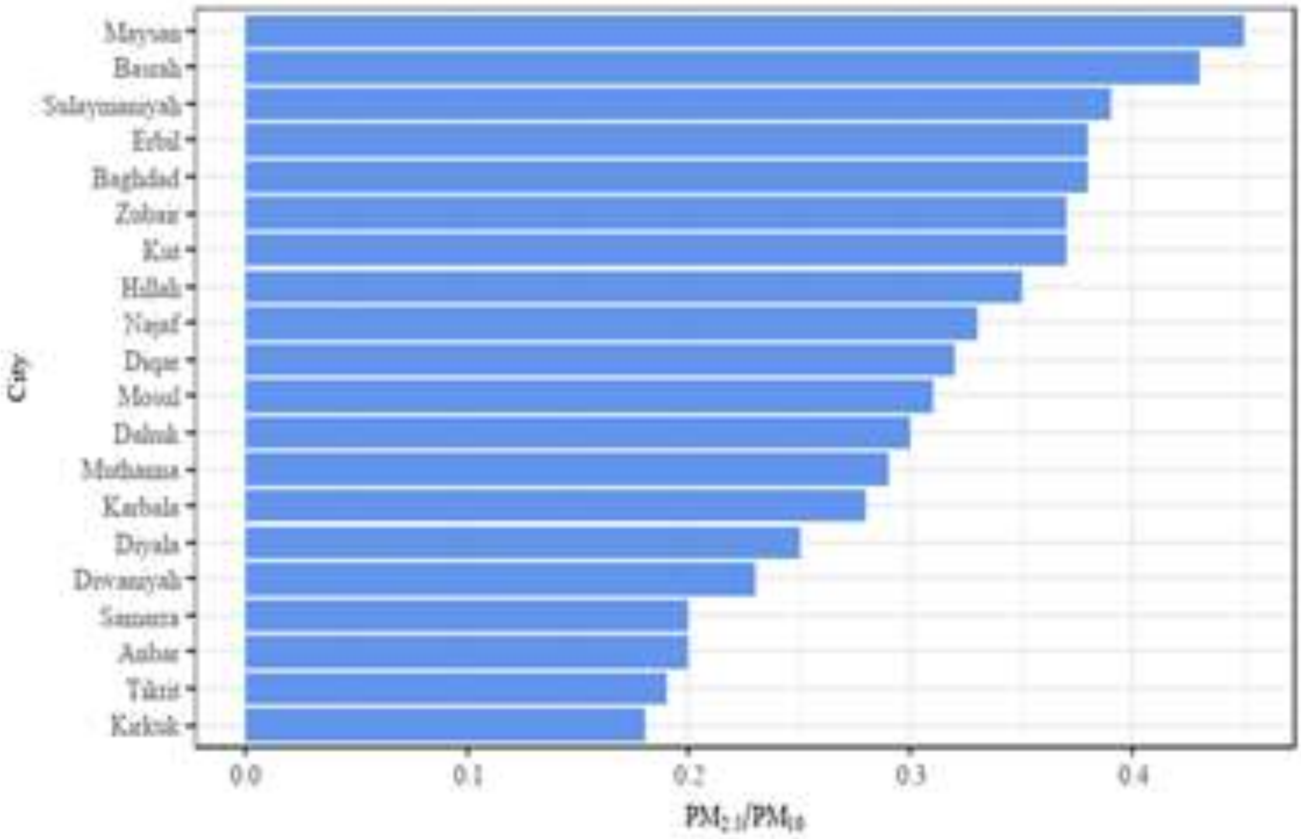


Figure 4. $PM_{2.5}$/ PM_{10} ratio by city

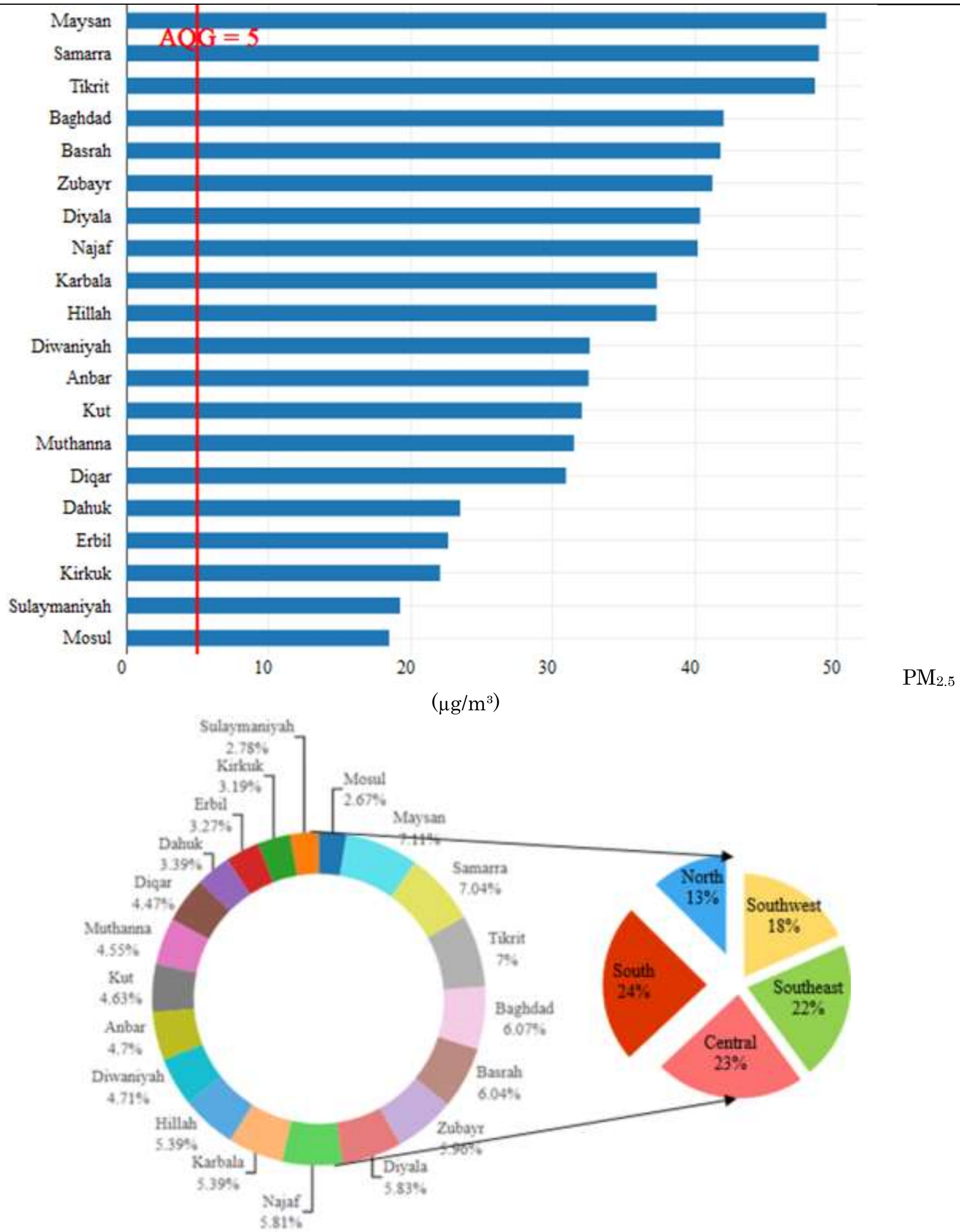


Figure 5. Average concentration levels of PM $_{2.5}$ in Iraq over three months compared to the WHO air quality guideline (Upper panel), and average percentage distribution of $PM_{2.5}$ concentration levels during the same period (Lower panel).

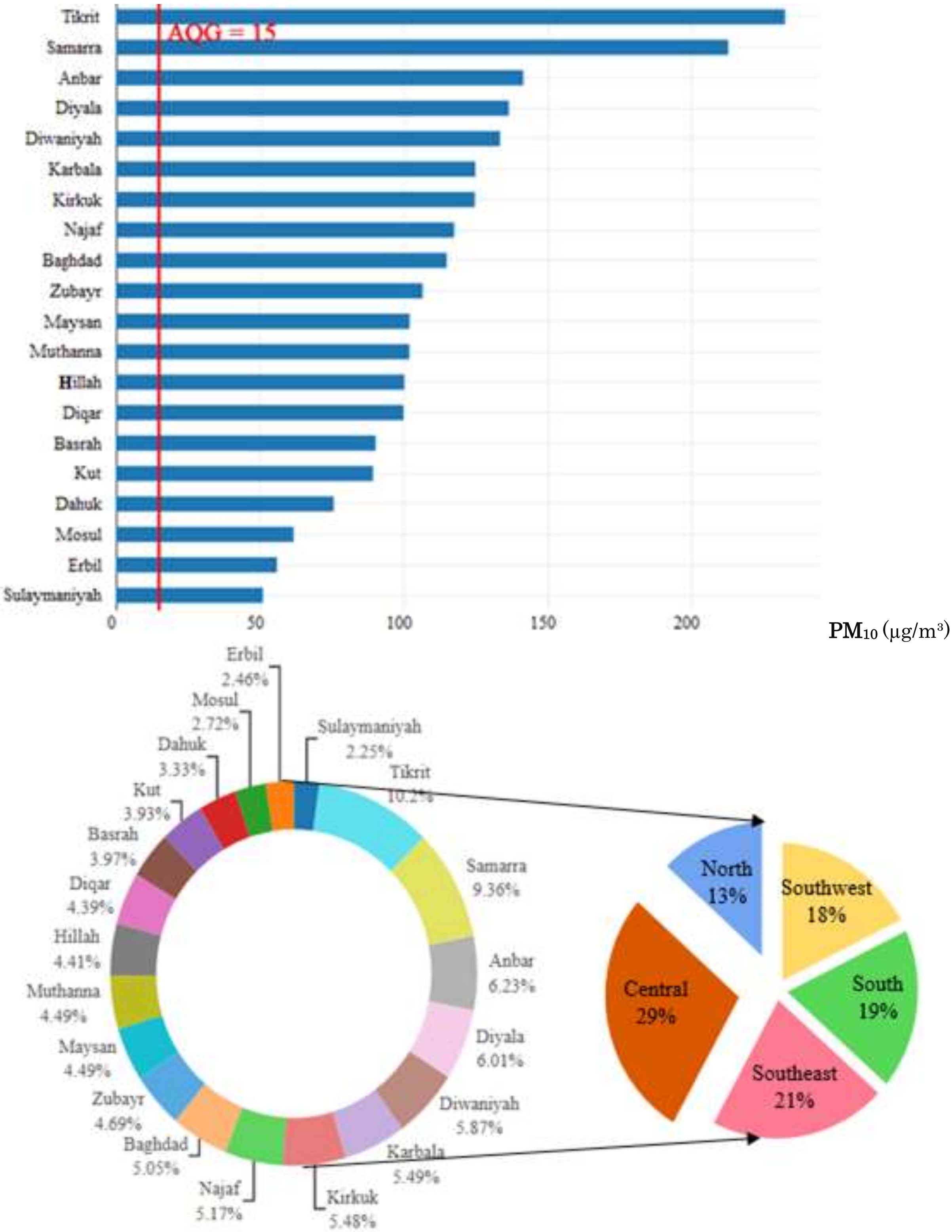


Figure 6. Average concentration levels of PM_{10} in Iraq over three months compared to the WHO air quality guideline (Upper panel), and average percentage distribution of PM_{10} concentration levels during the same period (Lower panel).

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3.4. Annual mean concentrations of PM$_{2.5}$ and PM$_{10}$ compared to the WHO guidelines

In this section we will display the annual mean PM2.5 and PM10 concentrations in Iraq in 2021. The annual mean values were measured using CAMS products by finding the monthly average values over the entire year. We have then compared the resulting mean values with Air Quality Guidelines (AQGs) from 2021 provided by the World Health Organization (WHO) to place the results in a broader international context. WHO guidelines establish recommended levels for long-term exposure to PM2.5 and PM10, indicating that exceeding these levels can pose risks to public health [23]. Figure 7 and Figure 8 provide an overview of annual mean concentrations of PM$_{2.5}$ and PM$_{10}$ worldwide, including specific data for Iraq. Based on the global maps shown in Figure 7 and Figure 8, the mean annual concentrations of PM$_{2.5}$ and PM$_{10}$ experienced a global increase in 2021. In particular, the annual average PM$_{2.5}$ concentrations increased from 5 μg/m^3 to more than 50 μg/m^3, and the annual average PM$_{10}$ increased from 20 μg/m^3 to above 150 μg/m^3. In terms of the annual mean PM$_{2.5}$ concentration, Iraq ranked as the second most polluted country worldwide, with PM$_{2.5}$ levels of 35–50 μg/m^3. Based on the annual World Air Quality, this range exceeded WHO guidelines by over 7 times in 2021. The areas with high PM$_{2.5}$ concentrations were predominantly distributed in Baghdad and some neighbouring cities in the northern and southern parts of Iraq as well as south and southwestern Iraq, while sporadic areas with high values were found in other parts of Iraq (Figure 7). Conversely, an analysis of PM$_{10}$ data reveals that Iraq ranks among the most-polluted countries globally, with many areas exceeding 150 μg/m^3, which is over 7 times higher than the WHO guidelines (Figure 8). The northeastern region had the highest PM$_{10}$ concentrations. In addition, other high concentrations were distributed in other sporadic areas of Iraq. By comparing the observed PM$_{2.5}$ and PM$_{10}$ values with the WHO guideline levels, it is clear that the air quality in Iraq is categorised as unhealthy to very unhealthy, and Iraq is ranked as the 2nd polluted country in the world, indicating potential health risks and the need for further health impact studies. However, quantitative estimates of health impacts (e. g., mortality or disease burden) were beyond the scope of this work. The guideline values presented in Table 4 were used as a benchmark to assess the severity of particulate matter pollution observed in Iraqi cities in 2021. Comparison with these thresholds indicates that the measured PM2.5 and PM10 concentrations in several central and southern regions substantially exceeded both the AQG levels and interim targets, highlighting a significant public health concern [23].

Table 4. Summary of the recommended air quality guidelines long term (AQG) levels and interim targets in 2021 [23].

Averaging time		Pollutant		Exceedances of WHO target	Category
Annual		PM$_{2.5}$	PM$_{10}$		
Interim target	1	35	70	5-7	Unhealthy
	2	25	50	3-5	Unhealthy for sensitive people
	3	15	30	2-3	Moderate
	4	10	20	1-2	Good
AQG Level		5	15		

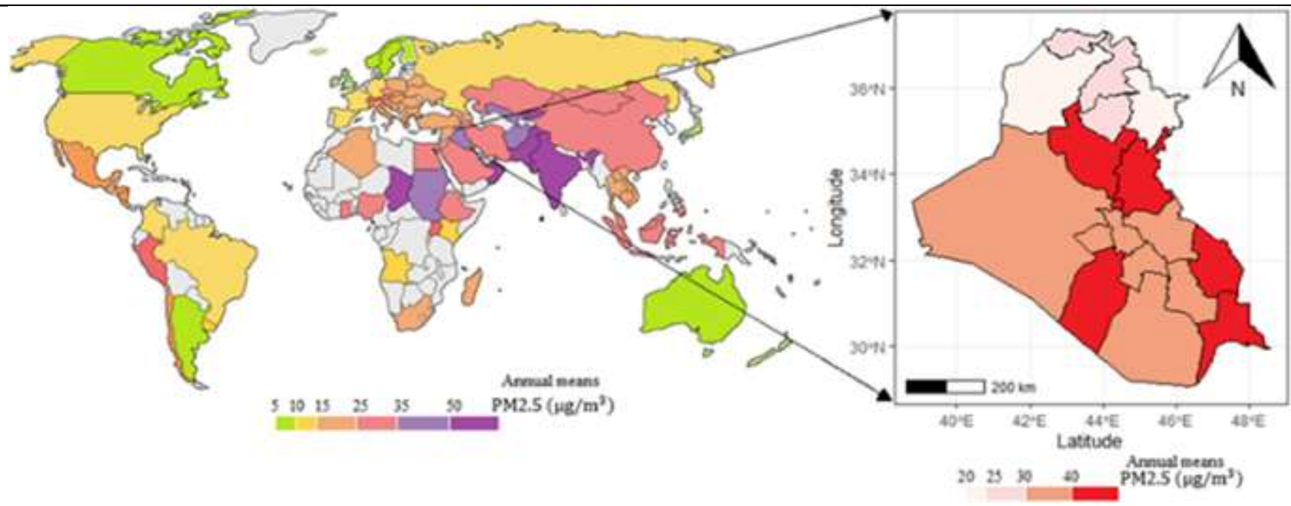

Figure 7. Global map shows annual average PM2.5 in 2021.

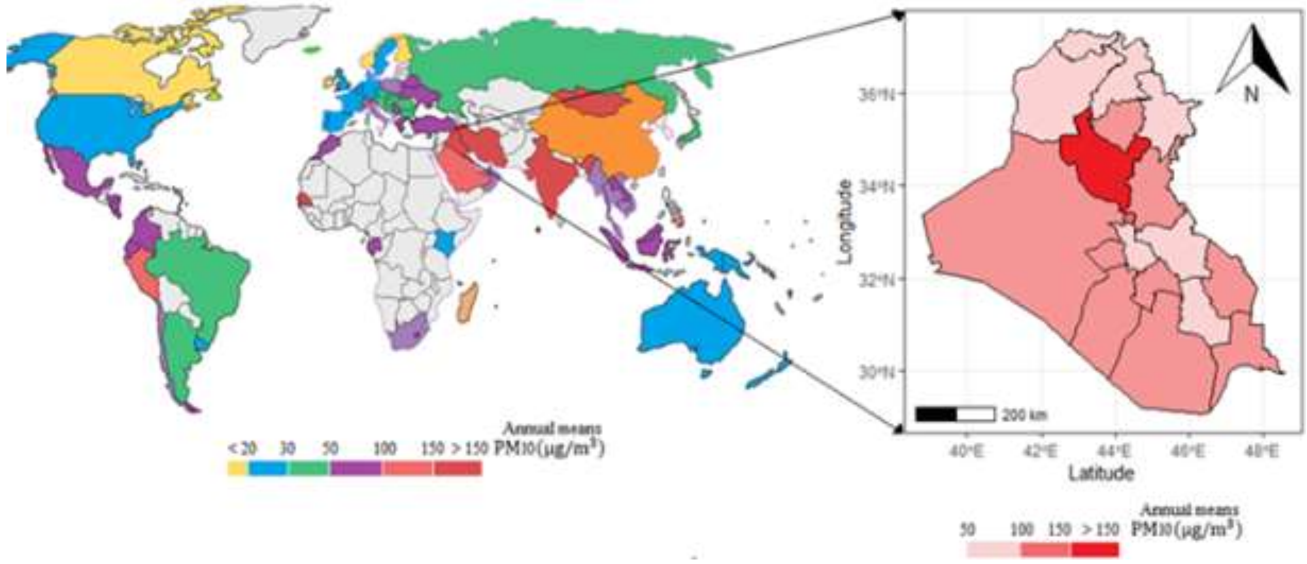

Figure 8. Global map shows annual average PM10 in 2021.

4. Conclusions

This study characterises the spatial and short-term temporal variation of PM2. An examination of the spatiotemporal characteristics of PM2. These results indicate considerable regional variation in ambient particulate matter levels indicating that higher concentrations of PM4were consistently seen throughout the three years of study period, particularly for the central, southern and southeastern regions of Iraq compared to all other regions found near northern Iraq. These results may be due to spatial heterogeneity in ambient air pollution rather than a temporal change or correlation with specific AQR actions. The observed variability in PM_2. The variations of $PM_{2.5}$ and PM_{10} concentrations could be partially explained by the prevailing meteorological conditions during the study period. The potential transference of pollutants through the surface air layer is influenced by principles of atmospheric science and WHO assessment work on air quality- it is known that winter atmospheric stability, especially temperature inversion events will inhibit vertical mixing of the air column, trapping pollutants in elevated concentration levels close to the earth's surface. Moreover, reduced wind speeds in this season limit horizontal dispersion so that PM remains over affected surface areas. Higher PM concentrations are further aggravated in central and southern Iraq with episodic dust storm activity. Taking into account the meteorological context rather than a direct extension of area and dust emission results, it may actually explain the observed higher concentrations in January and March when compared to those during February, due to action of both atmospheric stability and wind conditions. From a public health perspective, the PM concentrations in several Iraqi provinces were higher than WHO Air Quality Guidelines (AQG). This may be justified by health risk assessment indicators. Many provinces were evidenced to have critically high Hazard Quotient (HQ > 1) (an indicator of health hazards found in non-carcinogenic health effects assessment endorsed by WHO and international risk assessment frameworks). Furthermore, the annual mean PM2. The significantly higher %ELCR for PM2.5 and PM10 in 2021 as compared to the WHO guidelines indicates that three regions have Excess Lifetime Cancer Risk values well above severely high limits, making these potential risks unacceptably high under WHO-aligned health risk criteria Therefore, further studies are needed to estimate the mortality or disease burden. The spatial distributions of ELCR were highlighted with large inter-regional differences. Lower ELCR levels were generally detected in Northern provinces, while some considerably higher values were determined in the central and southern regions. The high ranges of ELCR signify the health risk of cancer with chronic exposure to $PM_{2.\ 4}$) and particulate matter (PM_2. This kind of spatial variability indicates that health risks from air pollution are not uniformly distributed across Iraq, and is consistent with WHO reports showing that greater long-term exposure to particulate matter is associated with higher levels of health impacts. By comparison to air quality assessments reported by the WHO for 2021, Iraq is part of a group of countries with very high annual mean PM2. 5 and PM10 concentrations worldwide. While this study has a reduced monitoring period and does not conduct an annual trend analysis, concentrations observed during the months of interest could pose health risks to sensitive population groups at the national or subnational level over the years. In summary, these results underscore the necessity of province-specific air pollution control policies. The prioritization of intervention measures such as stricter emission controls, effective dust storm management and better urban and regional air quality planning is needed in provinces with the highest concentrations of particulate matter and health risks. Long-term monitoring, reinforced by WHO recommendations and climate data analysis is necessary to minimize population exposure and reduce the health burden associated with PM pollution from all sources in Iraq

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