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Seasonal Variations of Gaseous Air Pollutants (SO_4 and Black Carbon) and Particulates ($PM_{2.5}$, PM_{10}) in the Tamale Metropolis of the Northern Region, Ghana

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Abstract

Urban air quality is deteriorating due to elevated pollutant levels resulting from human activities and shifting weather patterns. This study utilized hourly long-term datasets spanning 23 years. Air quality and meteorological data were obtained from the NASA GES DISC platform, which focused on air pollutant parameters such as sulphate (SO_4) (ppb), black carbon (ppb), $PM_{2.5}$ and PM_{10} (μg/m^3). The study investigated the seasonal variability of PM_{10}, $PM_{2.5}$, sulphate (SO_4), and black carbon (BC) concentrations in a tropical environment. PM_{10} levels peaked in July during the rainy season, while $PM_{2.5}$ concentrations decreased during the rainy season and increased during the dry season, peaking in February. SO_4 concentrations deviated from expected patterns, with a minimum in May and elevated levels in October and January, suggesting a complex interplay of factors. BC concentrations exhibited a distinct seasonal pattern, with a minimum in May, a plateau until October, and a peak in December followed by a decline in April. These findings highlight significant seasonal variability in air pollutant concentrations, emphasizing the need for nuanced air quality management strategies.

Keywords

Pollutants, Gaseous, Particulate, Seasonal Variability

1. Introduction

Air pollution is a major environmental and public health concern in urban areas, particularly in developing countries [1] [2]. The Tamale metropolis is located in the northern region of Ghana and experiences rapid urbanization and industrialization, leading to increased emissions of air pollutants [3]. Particulate matter (PM) with aerodynamic diameters ≤2.5 μm ($PM_{2.5}$) and ≤10 μm (PM_{10}), sulfate (SO_4), and black carbon (BC) are key air pollutants of concern due to their adverse health effects [4] [5].

Seasonal variability in air pollutant concentrations is influenced by factors such as meteorological conditions, emission sources, and atmospheric processes [6] [7]. In tropical regions, seasonal patterns are often driven by precipitation and temperature fluctuations [8]. Understanding the seasonal variability of $PM_{2.5}$, PM_{10}, SO_4, and BC is crucial for developing effective air quality management strategies and mitigating health impacts.

Air pollution levels are alarmingly high in urban environments [9], with substantial regional variations [10] [11]. Over 80% of urban residents monitored for air quality exceed WHO standards. Air pollution poses significant risks to public health, ecosystems, and economies [12]-[14], accounting for around 6.7% of global mortality from respiratory and cardiovascular diseases [15]. In Africa, Ghana was ranked as the sixth most polluted country on the continent, and in the city rankings, Accra, Ghana's capital city, is among the top ten most polluted cities on the African continent, with only 3.8% of African cities meeting the WHO annual $PM_{2.5}$ guideline in 2023 [16]. Rapid urbanization and industrialization are primary factors contributing to increasing air pollution in developing countries [10] [17] [18]. Identifying pollution sources and implementing effective long-term emission control measures are crucial. Understanding air pollutant origins, seasonal variations, and characteristics at a regional level is essential [19].

Previous studies indicate that regional variations in air pollutant concentrations depend on emissions, meteorology [18] [20], physicochemical transformations, urbanization, and policies [12]. Meteorological factors significantly contribute to variations in air pollutant concentrations, with wind speed and direction being critical factors.

However, research on the relationships between meteorological factors and air pollutants is inadequate. Investigating these relationships and seasonal variations is vital for developing effective air pollution control strategies.

Some studies have investigated air pollution in Ghana, particularly in the northern region (Amegah & Agyei-Mensah, 2017; Owusu et al., 2019). This study aims to extend the problem to include seasonal variability of $PM_{2.5}$, PM_{10}, SO_4, and BC concentrations in the Tamale metropolis. The aim is to investigate the seasonal patterns of $PM_{2.5}$, PM_{10}, SO_4, and BC concentrations, and also to identify factors influencing seasonal variability, and to inform air quality management strategies and policy decisions.

2. Methods

Study area

The Northern region comprises 16 districts, with Tamale as its capital city (See

Figure 1). Due to its proximity to the Sahel and Sahara, the region experiences a dry climate compared to its southern counterpart. It is characterized by grasslands, savanna, and drought-resistant trees like baobabs, neem, and acacias. The region has a distinct dry season from January to March and a rainy season from July to October, with annual rainfall ranging from 750 to 1050 mm. Temperature fluctuations are significant, with daytime highs reaching 40˚C and nighttime lows dropping to 14˚C. The region's air quality is a concern, particularly due to cooking and biomass burning activities. Despite its vast land area, the Northern region has a relatively small population of 2,310,934 individuals, comprising 1,167,495 females and 1,143,439 males (HPS, 2021).

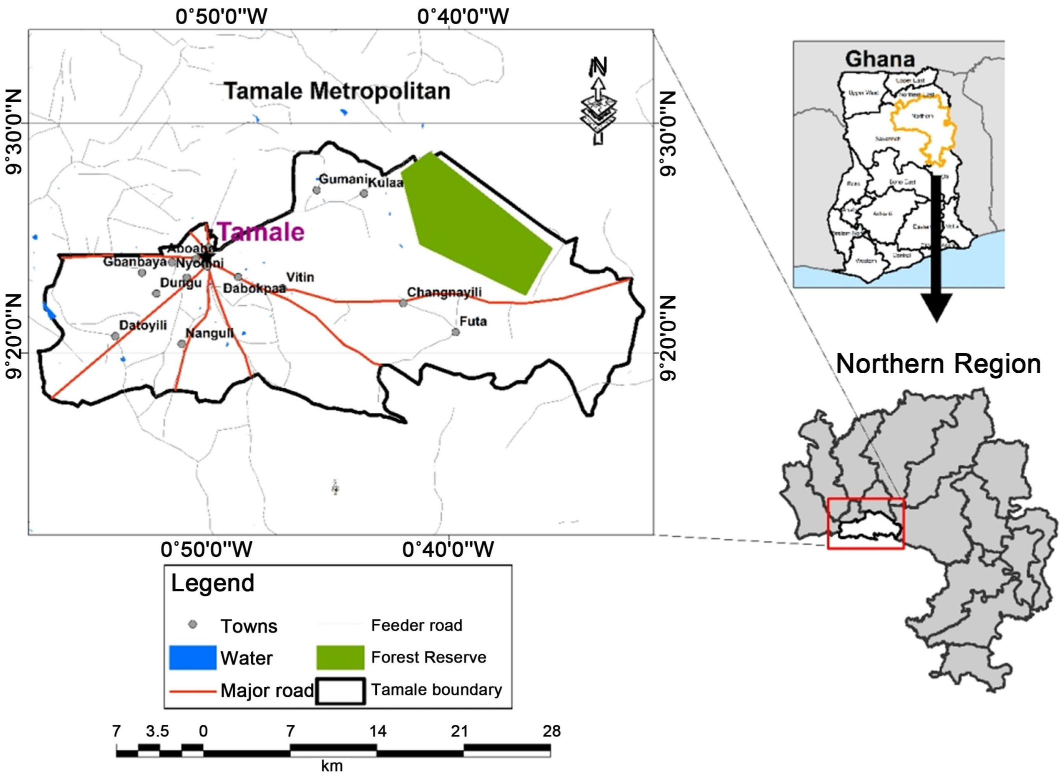

Figure 1. Map of Tamale Metropolitan.

3. Data Collection

This study utilized hourly long-term datasets spanning from January 1, 2000, to December 31, 2023, from the study area. The air-quality and meteorological data were obtained from the NASA GES DISC platform [21], and were continuously monitored and calibrated. The study focused on the following air pollutant parameters: SO_4 (ppb), black carbon (ppb), $PM_{2.5}$ and PM_{10} (μg/m^3).

4. Data Analysis

To investigate the spatial and temporal patterns of air pollutants in the area, time series data were analyzed. Monthly mean concentrations were calculated by averaging hourly measurements to examine trends over the study period. The data were then smoothed using Locally Weighted Scatterplot Smoothing (LOESS) to visually identify non-linear trends [22]. The data were compiled and organized into an Excel spreadsheet for efficient management. Following data entry, frequency analysis was conducted to identify and address outliers, ensuring data accuracy and reliability. The data underwent rigorous cleaning and validation processes to enhance its integrity. Soil sample analysis was facilitated by a scientific calculator, and all local units were standardized for consistency. Subsequent statistical analyses were performed using SPSS software (Version 20.0) to extract meaningful insights from the data.

5. Results and Discussion

5.1. Seasonal Variation of $PM_{2.5}$

Figure 2 presents the rainy (May to October) and dry (October to April) seasonal variations of $PM_{2.5}$ concentration over the Tamale metropolis. $PM_{2.5}$ levels exhibited a declining trend from May to August (the lowest attained was 17.3 μg/m^3), coinciding with the onset of the rainy season, which lasts from May to September. Conversely, a rising trend was observed from August to February, culminating in a peak concentration of 257 μg/m^3. This increase occurred during the dry season, which spans from October to April. Following the peak, $PM_{2.5}$ levels decreased from February to April.

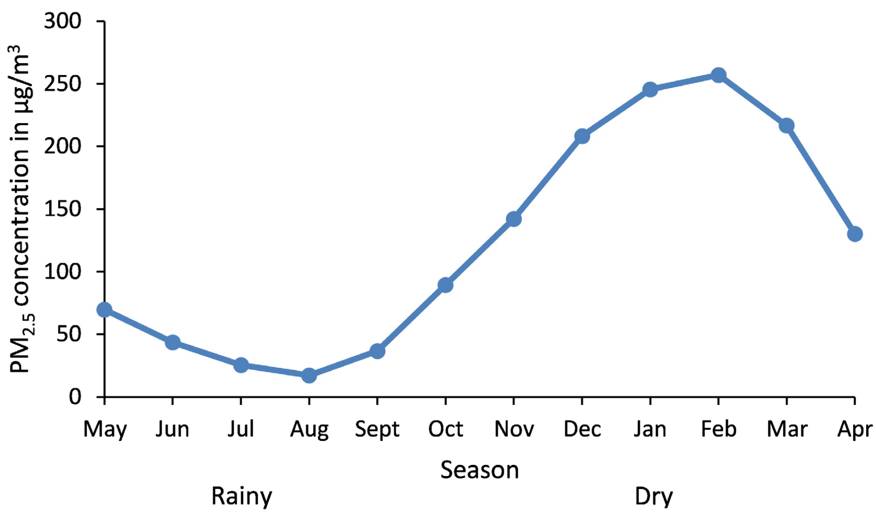

Figure 2. Seasonal variation of $PM_{2.5}$ concentration in Tamale.

The mean annual concentration of $PM_{2.5}$ is highest in February in Tamale, due to the Harmattan season, which typically occurs from December to February. This observation may be attributed to any or all of the following: 1) Dry and dusty conditions: The Harmattan season brings dry and dusty air from the Sahara Desert, leading to increased particulate matter (PM) concentrations [23] [24]; 2) Low humidity: The low humidity during Harmattan allows PM to remain suspended in the air for longer periods, contributing to higher concentrations [25]; 3) Wind-blown dust: Strong winds during Harmattan pick up dust and sand from the dry landscape, increasing PM levels [26]; 4) Biomass burning: In the Harmattan season, farmers often burn crop residues, leading to additional PM emissions [27]; 5) Temperature inversion: Cold air from the Harmattan can lead to temperature inversions, trapping PM close to the ground and increasing concentrations [28]. These factors combined create a perfect storm that elevates $PM_{2.5}$ concentrations in February, making it the highest during the year in Tamale.

5.2. Seasonal Variation of PM_{10}

The PM_{10} concentrations exhibited significant variability throughout the year, with a notable increase from 172.89 to 457.87 μg/m^3, followed by a sharp decline to 84.5 μg/m^3 in August (**Figure 3**). A further decrease to 34.00 μg/m^3 in September was observed, before rising to 190.9 μg/m^3 in October. Subsequent fluctuations included a decrease to 78.10 μg/m^3 in November, an increase in December, and a decrease in January, reaching a peak of 190.19 μg/m^3 in February. A decline in March and an increase in April were also observed. Notably, the highest PM_{10} concentration occurred in July (457.87 μg/m^3) during the rainy season, while the lowest concentrations were Recorded in January (34.00 μg/m^3) during the dry season and September (34.00 μg/m^3) during the rainy season.

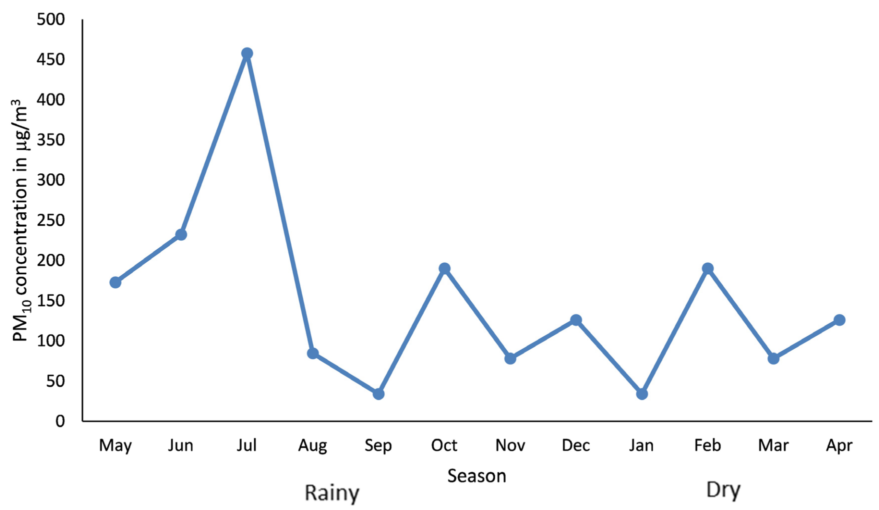

Figure 3. Seasonal variation of PM_{10} concentration in Tamale.

The highest PM_{10} concentration in July (rainy season) could be attributed to: 1) Rain-induced resuspension: Heavy rainfall can resuspend particulate matter from the ground, leading to increased PM_{10} concentrations [29]; 2) Increased vegetation burning: In some regions, July might coincide with agricultural burning or wildfires, contributing to higher PM_{10} levels [30]; 3) Humidity and atmospheric conditions: High humidity during the rainy season can lead to increased particle growth and retention in the atmosphere, resulting in higher PM_{10} concentrations

[31].

On the other hand, the lowest PM_{10} concentrations are in:

1) September (rainy season): could be due to: washing effect: continuous rainfall might "wash out" particulate matter from the atmosphere, leading to lower concentrations [32]; reduced human activities: lower human activities during the rainy season might result in decreased emissions [33];

2) January (dry season): could be attributed to: low dust emissions: reduced soil moisture during the dry season might lead to lower dust emissions [34]; atmospheric dispersion: dry season conditions might facilitate better atmospheric dispersion, reducing PM_{10} concentrations [35].

5.3. Seasonal Variation of SO_4

Figure 4 presents the seasonal variation of sulphate (SO_4) concentrations. The temporal distribution of SO_4 concentrations revealed a notable deviation from expected patterns, with a minimum concentration observed in May (0.22 mg/m^3) during the rainy season. Conversely, elevated concentrations were recorded in October (0.61 mg/m^3) and January (0.66 mg/m^3), respectively, with the latter occurring during the dry season. This discrepancy suggests a complex interplay of factors influencing SO_4 levels, warranting further investigation.

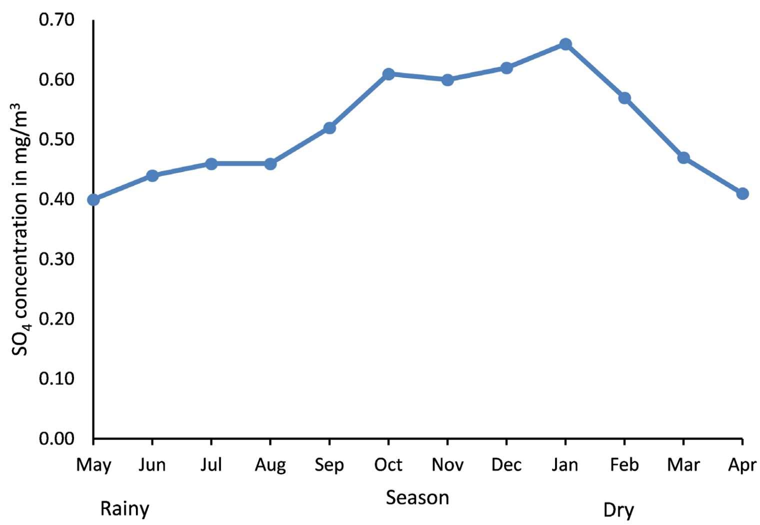

Figure 4. Seasonal variation of SO_4 concentration in Tamale.

The observed pattern could be attributed to the following:

a) Minimum SO_4 concentration in May (rainy season):

1) Washing effect: high rainfall in May might have "washed out" sulphate particles from the atmosphere, leading to lower concentrations [36].

2) Reduced human activities: lower industrial and vehicular activities during the rainy season could result in decreased SO_4 emissions [37].

3) Increased wet deposition: sulphate particles might have been removed from the atmosphere through increased wet deposition during the rainy season [38].

b) Maximum SO_4 concentration in January (dry season):

1) Dry conditions: low humidity and reduced precipitation in January might have led to increased sulfate particle retention in the atmosphere [39];

2) Increased human activities: higher industrial and vehicular activities during the dry season could result in increased SO_4 emissions [40].

3) Biomass burning: January might coincide with agricultural burning or other biomass burning activities, contributing to increased SO_4 levels [41].

4) Atmospheric stagnation: dry season conditions might lead to atmospheric stagnation, trapping sulfate particles and increasing concentrations [42]. These are potential explanations and might not be specific to the northern region or context. Local factors such as pollution sources, climate, and weather patterns can influence sulfate concentrations.

5.4. Seasonal Variation of Black Carbon

The temporal distribution of black carbon (BC) concentrations revealed notable seasonality, characterized by a minimum value in May (0.29 μg/m^3) and a maximum in December (2.29 μg/m^3) (**Figure 5**). An intervening period of relative stability was followed by a marked increase, suggesting a shift in dominant emission sources or atmospheric processes. The subsequent decline in April (0.34 μg/m^3) implies a return to reduced emission levels and/or enhanced atmospheric dispersion. Further investigation is warranted to elucidate the underlying factors driving this seasonal pattern.

This seasonal variability suggests a complex interplay of factors influencing BC levels, including:

1) Reduced biomass burning and anthropogenic activities during the rainy season (May) [10]; 2) Increased atmospheric stability and reduced ventilation during the dry season (October-December) [25]; Enhanced emissions from biomass burning and fossil fuel combustion during the winter months (December) [24]; Improved atmospheric dispersion and reduced emissions during the spring transition (April) [19].

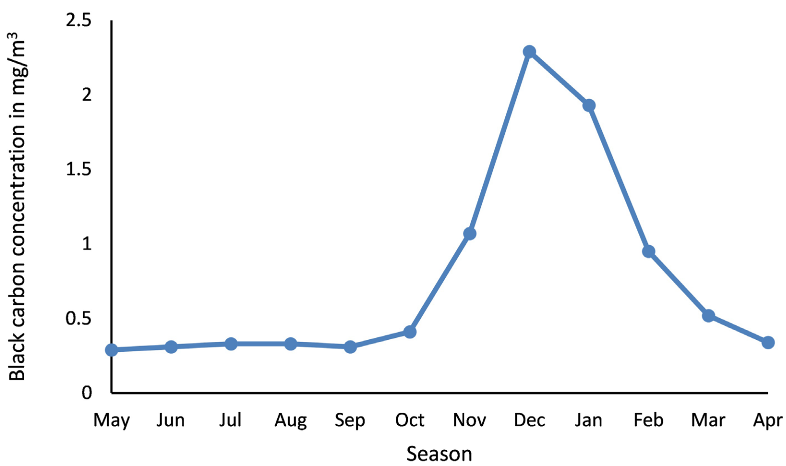

Figure 5. Seasonal variation of black carbon concentration in Tamale.

6. Policy Implication

The Ghana government, policymakers, and other stakeholders should implement season-specific emission control measures, focusing on reducing $PM_{2.5}$, PM_{10}, SO_4, and BC emissions during peak periods (dry season for $PM_{2.5}$ and BC, rainy season for PM_{10}). In addition, precipitation-induced air quality improvement during rainy seasons through optimized urban planning and infrastructure development should be enhanced. Also, cleaner energy sources, especially during dry seasons, to mitigate increased emissions must be promoted. Furthermore, targeted public health interventions focusing on vulnerable populations during peak pollution periods should be sustained. Finally, a comprehensive monitoring network to understand complex air pollution dynamics and inform policy decisions should be established.

7. Recommendations

It is recommended that further research on factors influencing SO_4 levels should be conducted. Additionally, authorities should investigate local emission sources and develop emission inventories, collaborate with regional authorities to address transboundary air pollution, and educate the public about air quality issues, health impacts, and individual actions to reduce emissions.

8. Conclusion

This study reveals distinct seasonal patterns in $PM_{2.5}$, PM_{10}, SO_4, and BC concentrations, with varying peaks and troughs across rainy and dry seasons. The findings suggest a complex interplay of factors influencing air pollution levels, including precipitation, emissions, and atmospheric processes. Notably, SO_4 concentrations deviated from expected patterns, warranting further investigation. The results have significant implications for air quality management, highlighting the need for season-specific emission control measures, optimized urban planning, and targeted public health interventions. Further research is necessary to elucidate the underlying factors driving these seasonal patterns and to develop effective strategies for mitigating air pollution impacts.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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