Research article

Longitudinal analysis of annual $PM_{2.5}$ concentration variations in Blantyre City, Malawi

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Abstract

This study presents current levels of fine particulate matter, with aerodynamic diameter of less than 2.5 micrometre ($PM_{2.5}$) in the city of Blantyre, Malawi measured between June 2021 to May 2022. $PM_{2.5}$ measurements were done in 18 different locations (spanning greater than 2 km apart) using Dylos DC1100 PRO Laser Particle Counter (2018 model). The sampling points were; 3 school campuses, 3 hospitals, 3 industrial areas, 3 open markets, 3 residential areas, and 3 commercial/ business centres (CBC) of Blantyre. $PM_{2.5}$ monitoring was conducted between 10:00-12:00 hours and 15:00-17:00 hours local time. The results showed that the hourly mean $PM_{2.5}$ concentrations (µg/m^3) for the 10:00-12:00 time period were; 43 ± 23 µg/m^3 for school campuses, 35 ± 16 µg/m^3 for hospitals, 62 ± 38 µg/m^3 for industrial areas, 44 ± 26 µg/m^3 for markets, 40 ± 21 µg/m^3 for residential areas and 35 ± 16 µg/m^3 for CBC. The results showed that the hourly mean $PM_{2.5}$ concentrations (µg/m^3) for the 15:00-17:00 time period were; 38 ± 22 µg/m^3 for school campuses, 34 ± 18 µg/m^3 for hospitals, 57 ± 37 µg/m^3 for industrial areas, 42 ± 25 µg/m^3 for markets, 36 ± 23 µg/m^3 for residential areas and 34 ± 18 µg/m^3 for CBC. Significant increases of $PM_{2.5}$ levels were observed in school campuses, residential areas and CBC during the months of June-October, which are windy and drier. On the other hand, lowest concentration of $PM_{2.5}$ was observed during the warm season (November-March) across the sampling locations over Blantyre. Based on these findings, this study recommends further investigation of long-term concentration of $PM_{2.5}$ in Blantyre city because it is hazardous and likely to cause health implications to the local population. Furthermore, interventions should be sought to reduce $PM_{2.5}$ concentration in the city.

Keywords

Air Quality, Air Pollution, Concentration, Particulate Matter, Environment

Introduction

Continuous air quality monitoring and evaluation are critical for protecting public health and the environment, enforcing regulations, and making informed policy decisions. Industrialisation and technological growth are expected to continue in Africa; as such, it is also expected that air pollution will continue to rise (Fisher et al., 2021). Exposure to air pollution causes harm and discomfort to humans or other living organisms. It damages the natural environment and the atmosphere (Okello et al., 2023). Particulate matter (PM) consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air (Leon et al., 2019). Particulate matter ($PM_{2.5}$) are particles with sizes less than or equal to 2.5 micrometers. Concentration changes of $PM_{2.5}$ are originated from both natural and anthropogenic sources (Cachon et al., 2023). Some of the natural sources include; volcanic emissions, forest fires, pollen scattering and sand storms (Xu et al., 2020).

Anthropogenic sources generally emit much higher levels of $PM_{2.5}$ than natural sources (Jahandari, 2020). Anthropogenic activities have resulted into many sources of $PM_{2.5}$ on the Earth (Triki and Said, 2021). Some of the $PM_{2.5}$ sources are; factories, burning of fossil fuels in engines like those of automobiles, and chemical substances created in the process of waste disposal (Osipov et al., 2022). Generally, $PM_{2.5}$ of anthropogenic origin significantly exceeds the natural background. Most of these anthropogenic sources of $PM_{2.5}$ are present in Blantyre city (Kaonga et al., 2021).

Finer particles like $PM_{2.5}$, can settle in the bronchi and lungs (Ahmed et al., 2022). $PM_{2.5}$ can cause health problems and contribute to the risk of development of respiratory and cardiovascular disease, including lung cancer. $PM_{2.5}$ are small enough to enter deep into the lungs and can cause respiratory and cardiovascular problems, including asthma, bronchitis, and even heart attacks (Pai et al., 2022). Long-term exposure to high levels of $PM_{2.5}$ can increase the risk of premature death (Nilsa, 2007; Toro-Heredia, Jirau-Colón and Jiménez-Vélez, 2021). High levels of $PM_{2.5}$ can also harm the environment, including reducing visibility, damaging crops and forests, and contributing to climate change (Sturm, 2020).

Many countries have regulations in place to limit the amount of $PM_{2.5}$ in the air to protect public health and the environment. From Malawi Standard on Industrial Emissions (MS 737:2011), the limit values for $PM_{2.5}$ concentration in ambient air are 25 µg/m³ and 8 µg/m³ for 24 hour and annual average concentrations, respectively. The focus on population–oriented monitors stems from health information that forms the basis for the annual $PM_{2.5}$ standard. This information relates from area-wide health statistics to area-wide air quality (MBS, 2017). The current WHO guidelines state that annual average concentrations of $PM_{2.5}$ should not exceed 5 µg/m³, while 24-hour average exposure should not exceed 15 µg/m³ (World Health Organization, 2021).

There has been no scientific study of $PM_{2.5}$ using monitors that capture data in real time in Blantyre. Spatial and temporal variation of $PM_{2.5}$ concentrations in Blantyre city or evaluation of the effectiveness of air quality policies has never been reported (Nyasulu et al, 2023). Blantyre city has high vehicle and motorcycle traffic in its main roads, many manufacturing industries and a lot of construction activities (National Statistical Office, 2019).

Monitoring of $PM_{2.5}$ levels in Blantyre city could also be beneficial in several ways. Citizens can benefit from $PM_{2.5}$ monitoring by being aware of the air quality in their community, which can help them take measures to protect their health. For example, people with respiratory conditions can take steps to avoid outdoor activity during periods of high $PM_{2.5}$ levels. Also, $PM_{2.5}$ monitoring can provide researchers with valuable data for studying the effects of air pollution on human health and the environment. By analysing the data, researchers can identify trends and patterns in $PM_{2.5}$ levels and their impact on various populations. Furthermore, $PM_{2.5}$ monitoring might be crucial for the government to develop and implement effective policies and regulations for air quality management. The data collected can help the government and regulatory bodies evaluate the effectiveness of existing policies and make informed decisions about future policies to protect public health and the environment. The data collected for $PM_{2.5}$ monitoring can be used by businesses to make informed decisions about their operations. For example, companies in Blantyre could use the data to determine the best location for a new factory or to develop strategies to reduce their impact on air quality. This necessitated this study which determined $PM_{2.5}$ pollution at 18 different locations with varying background activities in Blantyre city, Malawi.

Materials and methods

Study area

Malawi is a landlocked country located in South-Eastern Africa with a dense population. It is bordered by Tanzania to the North, Zambia to the North-West with Mozambique joining it on the east, south and west. The country has a tropical climate consisting of a dry season lasting from May to October and a wet (rainy) season extending from November to April.

Blantyre city is the urban centre of Blantyre District in Malawi, which is found in the southern region of this nation at −15°29′59.99″S, 35°00′0.00″E and has an area of 240 km². With a population of about 1 million with a growth rate of 3.5%, Blantyre is a commercial and industrial city located in the southern region of Malawi (National Statistical Office, 2019). It has an estimated elevation of 1039 meters above sea level which is significant in moderating the climate which is tropical. In terms of the climate, like most of the districts in Malawi, Blantyre has two dominant seasons during the year namely the dry and wet seasons. The wet season spans from November to May and the rest of the year is dry, with temperatures rising until the next rains arrival. 20.7°C is the average temperature in Blantyre, and approximately 1086 millimeters of rain is received each year, a typical characteristic of Malawian weather as shown Figure 1 (Zandbergen, 2022).

This study aimed at measuring the concentration changes of $PM_{2.5}$ in school campuses (SCH), hospitals (HSP), industrial areas (IND), markets (MKT), residential areas (RES) and commercial and business centre (CBC) of Blantyre City, in Malawi. A total of 18 locations with varying pollution sources, such as dusty roads, industrial emissions, and residential combustions, were selected for $PM_{2.5}$ monitoring. The chosen locations were at a distance of not less than 2 km from each other so as to give an overview of the entire city. The map showing $PM_{2.5}$ measurement locations selected in Blantyre city has been presented in Figure 2 below. These sites have higher number of people present during daytime in Blantyre.

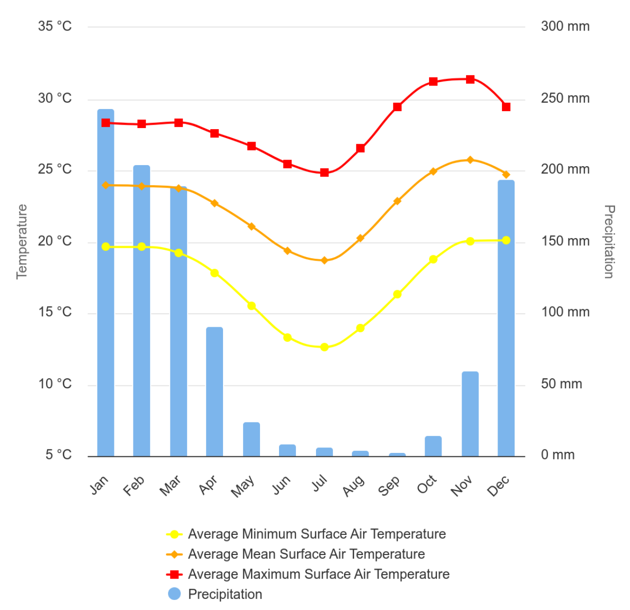

Figure 1: *Monthly climatology of average minimum surface air temperature, average mean surface temperature, average maximum air temperature and precipitation 1991-2020 (Data source: Malawi Department of Climate Change and Meteorological Services, 2024)*

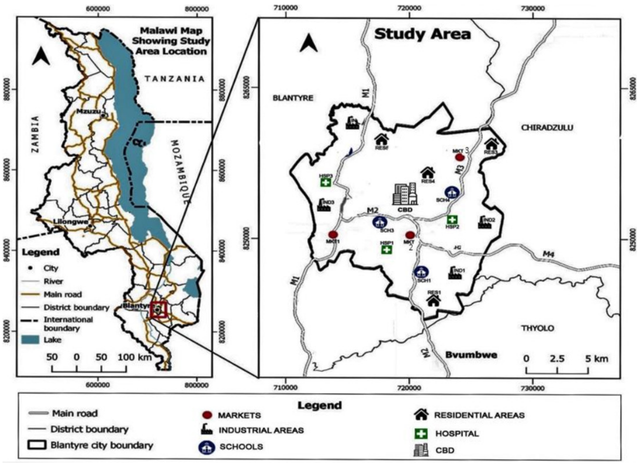

Figure 2: *Map of measurement locations of $PM_{2.5}$ in Blantyre city, Malawi.*

Instrumentation

In all the 18 monitoring locations, active mobile PM monitors (Dylos DC1100 PRO Laser Particle Counters of 2018 model, manufactured by Dylos Corporation, USA) were used to measure the concentration of $PM_{2.5}$. The particulate monitoring equipment were placed at 1.5 m above ground level. The position of the Dylos instruments at a sampling height of 1.5 m, was a representation of a typical breathing level, to simulate human exposure to $PM_{2.5}$ as shown in Figure 3. An hourly average value was recorded. The measurements were made twice on the same day; one in the morning (10:00-12:00 hours) and another in the afternoon (15:00-17:00 hours). There is a lot of human mobility and industrial activities happening during 10:00-12:00 and 15:00-17:00 time intervals in Blantyre city, which could lead to emission of air pollutants including $PM_{2.5}$ (Thulu, 2023). This $PM_{2.5}$ measurement exercise took place from 1 June 2021 up to 31 May 2022 on a daily basis.

Figure 3: *Monitoring setup at one of the schools (Credit: Kingsly Kabango).*

Airborne PM at can be measured quickly and precisely using laser particle counters. The Dylos DC1100 PRO PC Interface option allows one to download the air quality data to a PC for graphing and analysis. Vyas et al, (2016) and Dlyos Corporation (2016), comprehensively explain the details and a description of the Dylos DC1100's specifications and site theory of use. The Dylos DC1100 PRO Laser Particle Counter operates based on the principle of light scattering. The device emits a laser beam into the air sample. As the laser beam travels through the air, it interacts with particles present in the sample. When a particle passes through the laser beam, some of the light is scattered in various directions. The intensity and pattern of the scattered light depend on the size and characteristics of the particle. The Dylos DC1100 PRO has a light detector that captures the scattered light. Then, the device processes the data received from the light detector to determine the number and size distribution of particles in the air. The device categorizes particles based on their size, and for $PM_{2.5}$ measurements, it specifically focuses on particles with a diameter of 2.5 micrometers or smaller. Thereafter, the processed information is then displayed on the device's screen or output to a connected system, providing real-time data on particle concentrations, including $PM_{2.5}$ levels.

The monitors were calibrated for accuracy and reliability. Calibration was deemed crucial to ensure accurate measurements with the Dylos instruments used in this study. The manufacturer's guidelines for calibration, which involves comparing the instrument's readings to a reference monitor were done at Malawi Bureau of Standards (MBS) at the commencement of the study. The Dylos DC1100 PRO Laser Particle Counters were calibrated with reference monitor GRIMM reference instrument. High reproducibility level with R^2 value between 0.99 and 1 were attained between the 1-hour PM concentrations generated by all Dylos DC1100 PRO Laser Particle Counter sensors used during 2-day calibration exercise at Malawi Bureau of Standards. The R^2 value of concentration achieved are acceptable by Malawi Bureau of Standards, such that the Dylos DC1100 PRO Laser Particle Counter could indicate consistence and similarity in the readings. The WHO guidelines on air quality standards and guidelines on $PM_{2.5}$ monitoring were used. The guidelines provide recommendations on monitoring equipment, sampling strategies, and data analysis methods (WHO, 2021).

Data analysis

Completeness, and consistency of the monitored $PM_{2.5}$ values was done at the end of every month using R-Instat Version 0.7.9.42. This ensured that there are no gaps or missing data in the monitored records. $PM_{2.5}$ concentration values were then analysed using appropriate statistical methods. This involved calculating the monthly average concentration from daily averages of $PM_{2.5}$ over a monitored period and identifying trends over time. Mann Kendall test for trend was carried out in R programming language and environment to determine trends of average $PM_{2.5}$ concentration levels at all the study sites. This helped to statistically check the significant trends in changes for $PM_{2.5}$ concentration levels in school campuses, hospitals, residential areas, CBC and markets. The $PM_{2.5}$ concentration levels were subjected to a trend statistical analysis from June to September, September to December, and December to May. Analysis of $PM_{2.5}$ during these periods in Malawi is crucial due to the country's distinct seasonal climate patterns. These periods coincide with significant weather transitions, including the windy/gusty, dry and wet seasons in Malawi. Therefore, doing $PM_{2.5}$ statistical trend analysis during these periods provides valuable insights into how seasonal variations impact air quality in Blantyre.

Results and discussion

Supplementary Table S1 and Table S2 highlight the monthly captured data for all the monitoring sites. Figures 4 and 5 show an overview of the mean comparison of $PM_{2.5}$ concentrations per category of sites for the 12 months (1 year). High values of $PM_{2.5}$ concentrations were observed in industrial sites (62 ± 38 µg/m³) followed by market areas (44 ± 26 µg/m³) for the 10:00-12:00 time period. Gas emissions and land construction activities in these sites could be attributed to high values of $PM_{2.5}$ concentrations. There was a lot of dust in the markets during drier months. Also, open fire cooking using firewood was observed in the market area. This could also lead to high $PM_{2.5}$ concentrations. From Table S3 and Table S4, it can be seen that during August, many of the sites had higher $PM_{2.5}$ concentrations during 10:00-12:00 and 15:00-17:00. It was also observed that $PM_{2.5}$ concentrations were much lower between 15:00-17:00 for January and February in all sites. It was also observed that there were site specific sources and activities that contributed to particulate loadings in industries and hospitals (open fire cooking areas). At all sites, it was observed that the $PM_{2.5}$ peak gradually increased, and then decreased for days with low prevailing winds for the morning monitored hours. This was somewhat different during 15:00-17:00, mostly for wet months for hospitals, schools and residential areas. This agrees with the fact that meteorological factors such as wind affect $PM_{2.5}$ concentrations e (Hou, 2023; Pardo 2023).

In a city like Blantyre, industries and open markets might have had higher levels of $PM_{2.5}$ compared to schools and hospitals due to the concentration of activities that produce particulate matter. Industries typically emit pollutants from manufacturing processes, machinery, and combustion of fuels, while open markets may generate dust from vehicular traffic, food preparation, and waste disposal. These activities release pollutants directly into the surroundings, which could also have contributed to higher levels of $PM_{2.5}$. In contrast, schools and hospitals registered lower $PM_{2.5}$ concentrations. This could be due to measures put in place to restrict outdoor activities, resulting in lower $PM_{2.5}$ concentrations within their premises.

Residential areas and Blantyre CBC experienced moderate levels of $PM_{2.5}$. This might be due to a combination of factors. In residential areas, sources of particulate matter include vehicular emissions from nearby roads, household combustion activities such as cooking and heating, as well as dust from construction

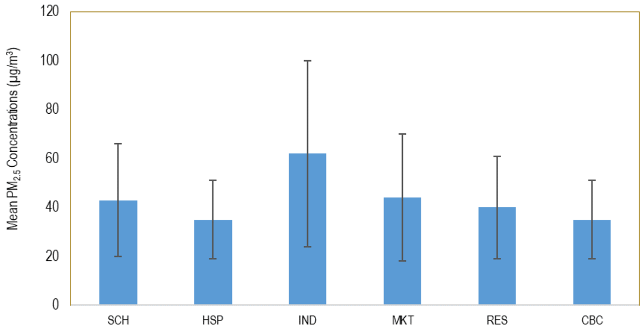

Figure 4: *10:00-12:00 hours mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

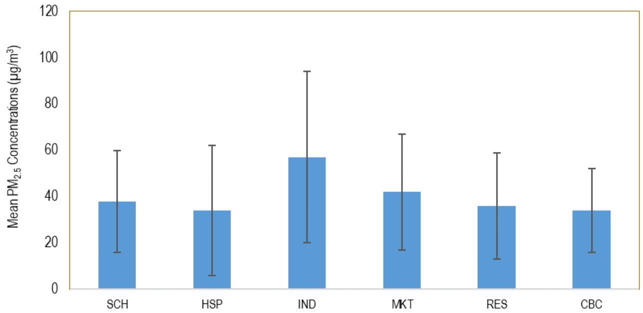

Figure 5: *15:00-17:00 hours mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

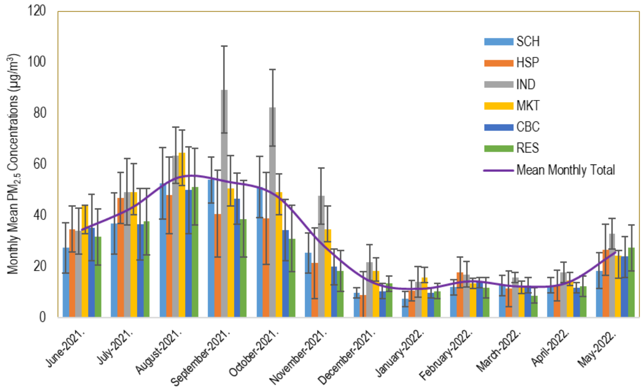

Figure 6: *10:00-12:00 hours monthly mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

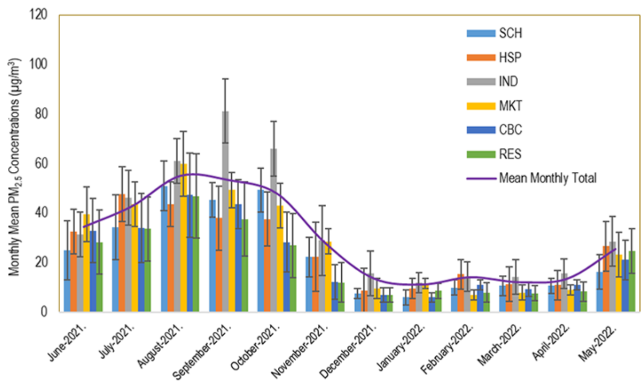

Figure 7: *15:00-17:00 hours monthly mean $PM_{2.5}$ concentration across the sites (bars indicate standard deviations).*

and landscaping. Similarly, CBC often have high traffic volumes and commercial activities which contribute to $PM_{2.5}$ emissions. While these areas may have some regulations in place to mitigate pollution, the low density of human activities might also have contributed to low $PM_{2.5}$ concentrations. Additionally, tall buildings in CBC may trap pollutants, leading to moderate $PM_{2.5}$ concentrations.

Figure 6 and 7 show the comparison of $PM_{2.5}$ concentrations across each group per month. The results showed that the monthly mean $PM_{2.5}$ concentrations (µg/m³) were higher between the months of July to October with the highest observed in the month of September during for the 10:00-12:00 time period and 15:00-17:00 time period. Similarly, the results showed that the monthly means of $PM_{2.5}$ concentration (µg/m³) was lower in the months from December to April. This can also be seen in Supplementary Table S2.

The monthly mean ambient concentrations of $PM_{2.5}$ levels across the 18 monitored sections of Blantyre city are shown in Figures 8 to 19. These give a detailed understanding of how $PM_{2.5}$ concentration varied among the sampling sites for the twelve months of the monitoring period.

In schools, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of September. The $PM_{2.5}$ values were almost constant between the months of November and May, with a start of an increment in June (Figure 8). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of October. A sharp decrease was observed in November, then the $PM_{2.5}$ were constant from December to May (Figure 9). A sharp rise in $PM_{2.5}$ was observed in the month of June.

In hospital sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of July to October, with the highest values in June. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of an increment in May (Figure 10). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of June as well. A sharp decrease of $PM_{2.5}$ was observed in November, and then the $PM_{2.5}$ values were constant from December to April (Figure 11). A sharp rise in $PM_{2.5}$ was in the month of May. During February 2022, there was a road rehabilitation near HSP 3. This could be the reason in rising $PM_{2.5}$ for this site during this month.

For industrial sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the months of September to October. There was a big drop of $PM_{2.5}$ in November. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of an increase in May (Figure 12). Site 3 of industrial area had the highest particulate loadings (97 µg/m³) starting at 10:00 as compared to the remaining site 1 and site 2. This indicates that there might be a specified or defined source contributing to increased concentration at this site. During 15:00-17:00 hours,

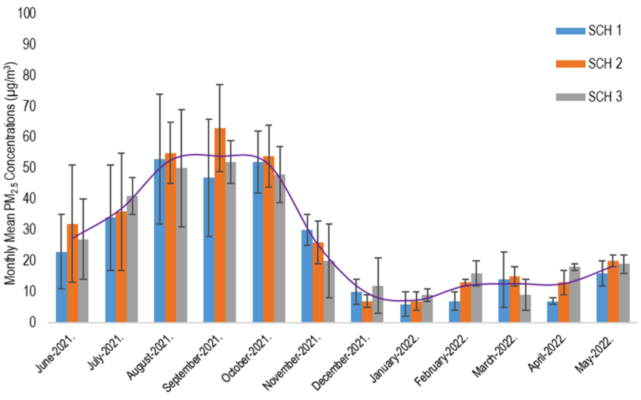

Figure 8: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for schools (bars indicate standard deviations).*

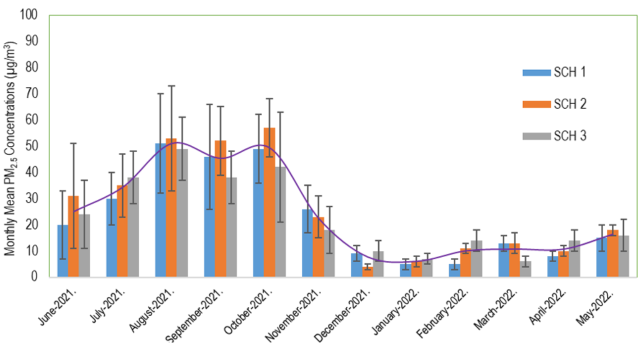

Figure 9: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for schools (bars indicate standard deviations).*

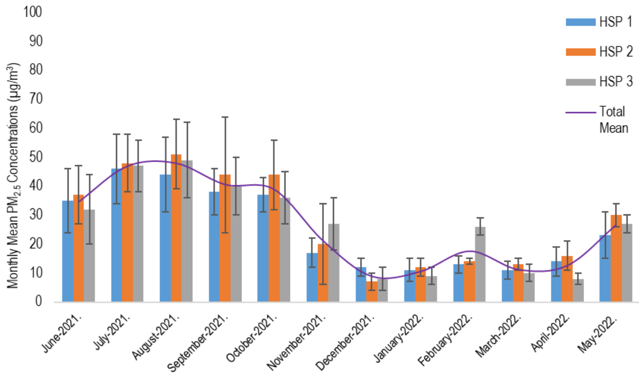

Figure 10: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for hospitals (bars indicate standard deviations).*

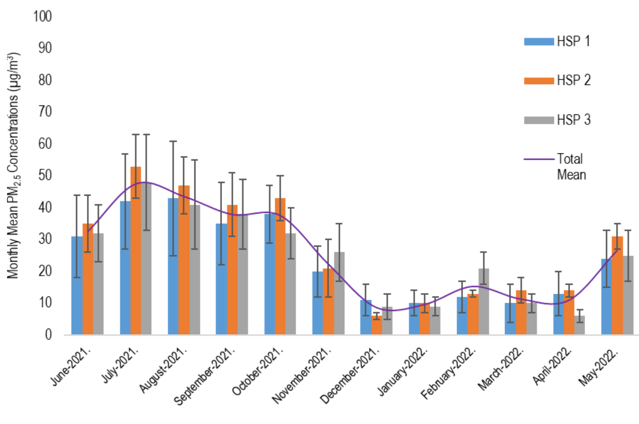

Figure 11: *15:00-17:00 hours mean monthly ambient $PM_{2.5}$ concentration for hospitals (bars indicate standard deviations).*

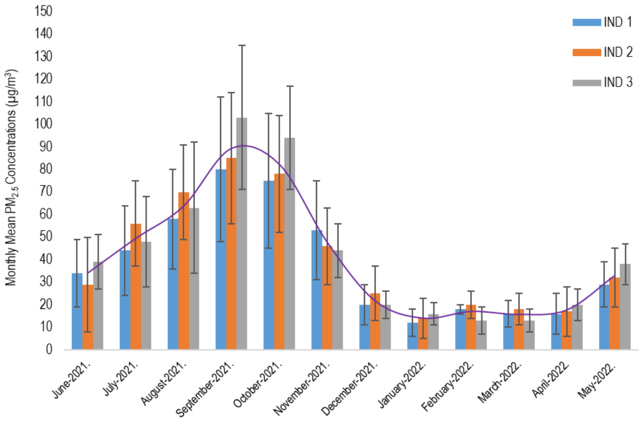

Figure 12: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for industrial areas (bars indicate standard deviations).*

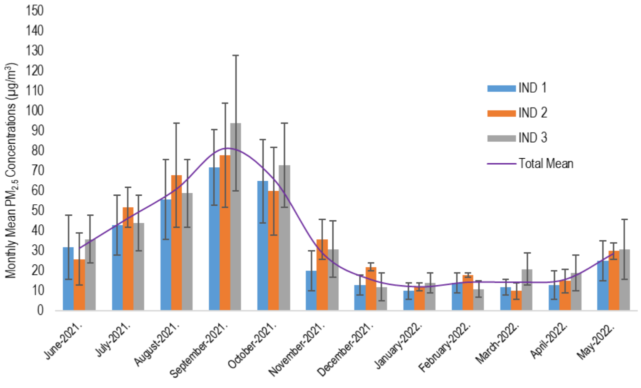

Figure 13: *15:00-17:00 hour monthly mean ambient $PM_{2.5}$ concentration for industrial areas (bars indicate standard deviations).*

high $PM_{2.5}$ values were recorded in the month of September. A sharp decrease of $PM_{2.5}$ was observed in November, then the $PM_{2.5}$ values did not fluctuate much from December to April (Figure 13). A rise in $PM_{2.5}$ was observed in June 2021. Between the month of August and September there was a lot of heavy vehicles moving in and out of cement factory at IND 1. This could be the reason in rising $PM_{2.5}$ for this site during these months. Thereafter, another route was opened out of the factory, which could have reduced the $PM_{2.5}$ at the monitoring point.

For market sites, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. Low levels of $PM_{2.5}$ were observed in November and then, there was a rise of $PM_{2.5}$ in June. The $PM_{2.5}$ values were almost constant between the months of December and April (Figure 14). During 15:00-17:00 hours, high PM values were recorded in the month of August. $PM_{2.5}$ values decreased in November while it remained constant from December to April (Figure 15). A rise in $PM_{2.5}$ was observed in the month of July. During the month of September of 2021, it rained for 3 days, which might be the reason in the decrease of $PM_{2.5}$ at MKT 1 during this month. Also, during January of 2022, there was a dry spell for most of the days in Blantyre, which could be the cause of a build-up in $PM_{2.5}$ as observed at MKT 1 and MKT 3. The drier the soils, the higher the chances of dust emissions (Erdenebayar, 2016).

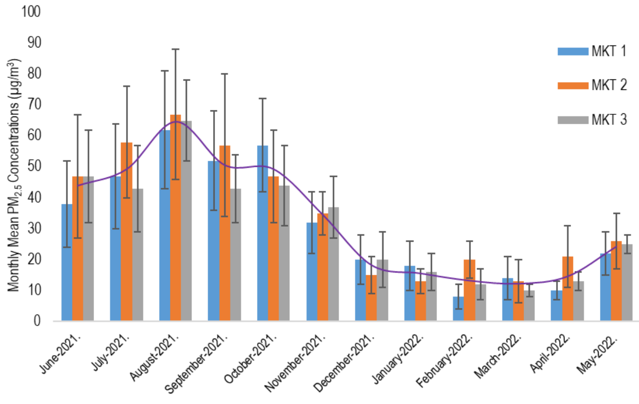

Figure 14: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for markets (bars indicate standard deviations).*

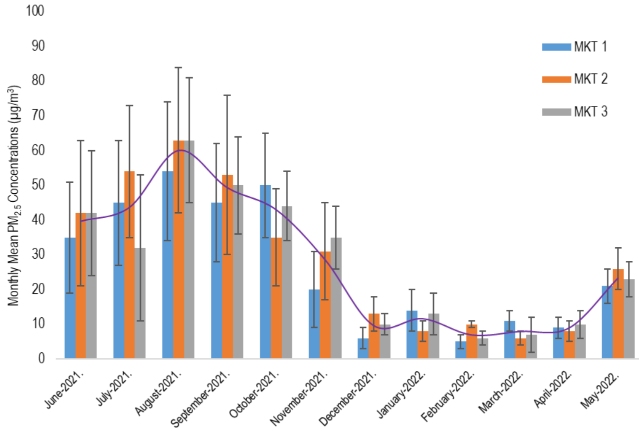

Figure 15: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for markets (bars indicate standard deviations).*

In residential areas, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. A drop of $PM_{2.5}$ was observed in October. The $PM_{2.5}$ values were almost constant between the months of December and April, with a start of increment in May (Figure 16). During 15:00-17:00, high $PM_{2.5}$ values were recorded in the month of August. A sharp decrease was observed in October, then the $PM_{2.5}$ remained constant from December to April (Figure 17). A rise in $PM_{2.5}$ was seen in the month of June. Vegetative cover was poor around RES 3, and it is densely populated as compared to RES 1 and RES 2. This could be a possible reason why RES 3 had higher $PM_{2.5}$ as compared to RES 1 and RES 2.

Lastly, at the sites of Blantyre CBC, high $PM_{2.5}$ values between 10:00-12:00 were observed in the month of August. The PM values were almost constant between the months of November and April, with a start of an increase in May 2022 (Figure 18). During 15:00-17:00 hours, high $PM_{2.5}$ values were recorded in the month of August to September. There was a $PM_{2.5}$ decrease in October, then it remained unchanged from December to April (Figure 19). There was a rise in $PM_{2.5}$ in the last days of the month of May 2022. In July 2021, $PM_{2.5}$ decreased at CBC 3. The road passing through the sampling point was closed, due to building rehabilitation which was happening ahead of the sampling point. This reduction in mobility of people and vehicles could be the cause in a decrease in $PM_{2.5}$ at this site.

The results indicate that $PM_{2.5}$ concentrations can be grouped into two periods based on seasons, namely, November-April and May-October. The $PM_{2.5}$ concentrations were lower during the period November-April. This can be attributed to the fact that these are wet months as shown in Figure 1. Generally, there was more vegetative cover within the city during these months due to rains (Mawenda, 2020). Rains and vegetation are known to filter particulate matter from the atmosphere (Przybysz, 2019). In Blantyre, the dry season ranges from July to October and it tends to be windier than the wet months. This leads to more dust storms within the city. This could be a contributor to the high $PM_{2.5}$ values observed during these months. Mapoma et al. (2014) also reported that there are a lot of human activities during this period such as; roads and buildings construction, waste disposal, burning of crop residues and industrial emissions which are known to release large amounts of PM in the air in Blantyre.

The highest $PM_{2.5}$ concentration was recorded at industries and markets as shown in Supplementary Table S3. For example, for industry and markets, the highest $PM_{2.5}$ concentration values observed in August were 138 µg/m³ and 135 µg/m³, respectively. The observed exceedances at these sites may be attributable to the direct exposure to emissions from fuel combustion and dusty storms (Kaonga et al., 2021). Low levels of $PM_{2.5}$ in schools and hospitals were likely due to less emissions from domestic fuel combustion and good vegetative cover, among others. It should be noted that the monitors were placed outdoors. At these sites, it was observed that fuel combustions happened outdoors as well, such as women (guardians) cooking using firewood outside the hospital premises. From this study, it was clear that there are still significant higher concentrations of $PM_{2.5}$ over the industrial areas, markets and residential areas within Blantyre.

The Mann-Kendall test revealed that significant trends were observed for $PM_{2.5}$ levels at school campuses, industries, residential areas, and CBC while markets and hospitals did not show any significant trend (Table 1). Mann Kendall's Tau varies between -1 and +1. It is negative when the trend decreases and positive when the trend increases. The Mann- Kendall test evaluates whether a series of random observations is consistent with presence of a trend. The null hypothesis is that the data do not exhibit a trend and the alternative hypothesis says the data exhibit a trend (Kulkarni, 1995).

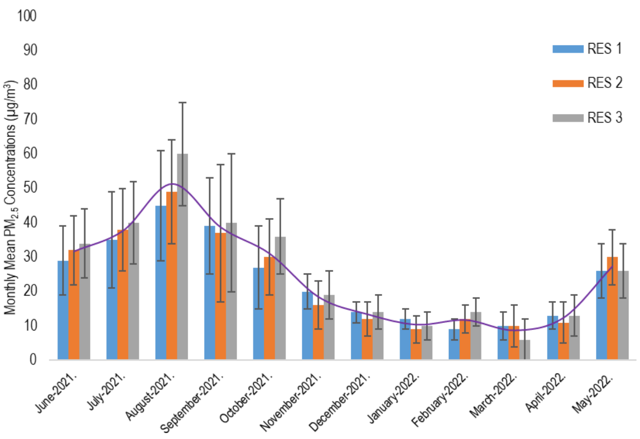

Figure 16: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for residential areas (bars indicate standard deviations).*

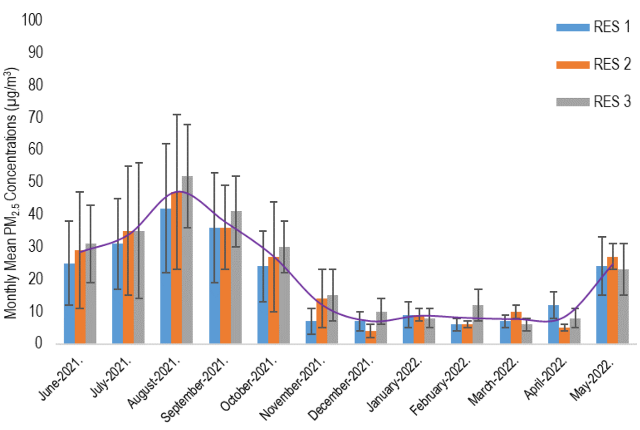

Figure 17: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for residential areas (bars indicate standard deviations).*

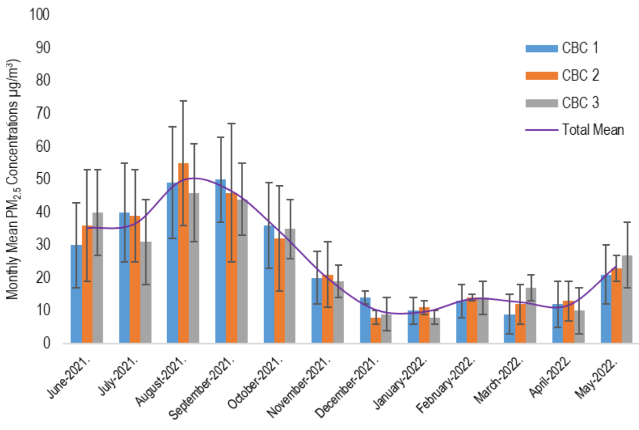

Figure 18: *10:00-12:00 hours monthly mean ambient $PM_{2.5}$ concentration for CBC (bars indicate standard deviations).*

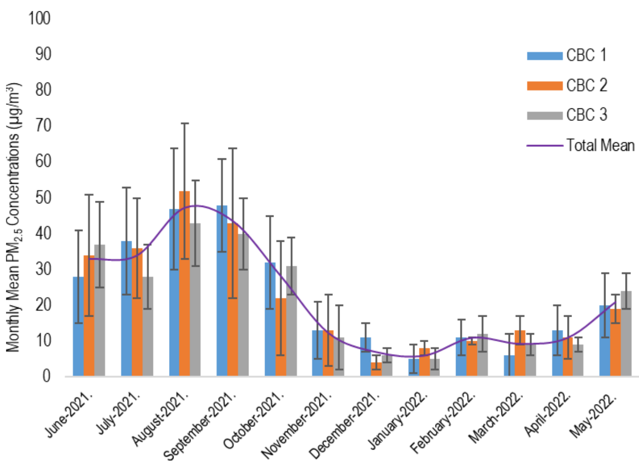

Figure 19: *15:00-17:00 hours monthly mean ambient $PM_{2.5}$ concentration for commercial and CBC (bars indicate standard deviations).*

Table 1: *Mann Kendall Trend test for June 2021 to September 2021, September 2021 to December 2021, and December 2021 to May 2022 in all the locations.*

		10:00-12:00		15:00-17:00	
Site	**Period**	**tau**	***p*-value**	**tau**	***p*-value**
School	June 2021-September 2021	1.000	0.089	0.667	0.308
	September 2021-December 2021	-1.000	0.027*	-0.800	0.086
	December 2021-May 2022	0.950	0.043*	0.949	0.043*
Hospital	June 2021-September 2021	0.330	0.734	<0.001	0.999
	September 2021-December 2021	0.800	0.086	-0.738	0.129
	December 2021-May 2022	0.527	0.312	0.527	0.312
Industry	June 2021-September 2021	1.000	0.089	1.000	0.089
	September 2021-December 2021	-1.000	0.027*	-1.000	0.027*
	December 2021-May 2022	0.800	0.086	0.949	0.043*
Market	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-1.000	0.027	-0.800	0.086
	December 2021-May 2022	0.200	0.807	<0.001	0.999
Residential	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-1.000	0.027*	-0.800	0.086
	December 2021-May 2022	0.527	0.312	0.120	0.999
CBC	June 2021-September 2021	0.667	0.308	0.667	0.308
	September 2021-December 2021	-0.949	0.043*	-1.000	0.027*
	December 2021-May 2022	0.400	0.462	0.738	0.129

*the *p*-value is less than 0.05 implying a significant trend in $PM_{2.5}$

In school campuses the $PM_{2.5}$ levels had a significant decreasing trend from September 2021 to December 2021 based on the measurements taken between 10:00 to 12:00 (tau = -1, *p*-value = 0.027, Table 1) and a no significant trend for the $PM_{2.5}$ levels obtained between 15:00 to 17:00 (tau = -1, *p*-value = 0.027, Table 1). However, the $PM_{2.5}$ levels were increasing significantly from December 2021 to May 2022 for both morning and evening measurements (Table 1). The $PM_{2.5}$ levels had a significant decreasing trend from September 2021 to December 2022 for both scheduled times for measurements (tau = -1, *p*-value = 0.027) while an increasing trend was observed between 15:00 to 17:00 during the same period (tau = 0.8, *p*-value = 0.043, Table 1).

In residential areas, the trend of $PM_{2.5}$ decreased significantly between September and December 2021 (tau = -1, *p*-value = 0.027, Table 1) whereas trends for June to September 2021 and December to May 2021 were not significant (*p*-value >0.05, Table 1). For CBC the trend of $PM_{2.5}$ levels were significantly decreasing between September and December 2021 (tau = 0.949, *p*-value = 0.027, Table 1) whereas no significant trend was observed from June to September 2021 and December to May 2022.

Conclusion

This study aimed at assessing the concentration changes of $PM_{2.5}$ in 18 sites at school campuses, hospitals, industrial areas, markets, residential areas and Blantyre CBC across Blantyre City, between 10:00-12:00 and 15:00-17:00. Climatology, vegetation, topography, domestic combustion of solid fuel and land clearing events across Blantyre may be associated with significant effects on ambient $PM_{2.5}$ concentrations. The yearly mean showed that high values of $PM_{2.5}$ concentrations was observed in industrial sites (62 ± 38 µg/m^3) followed by Market areas (44 ± 26 µg/m^3) for the 10:00-12:00 time period. The results showed a monthly diurnal variability, suggesting that rainfall season has a significant effect on $PM_{2.5}$ concentrations across Blantyre. Higher $PM_{2.5}$ concentrations were observed between the months of May and October, which are drier and windy months in Blantyre. Significant trends were observed for $PM_{2.5}$ levels in school campuses, industries, residential areas, and CBC while markets and hospitals did not show any significant trend. Since the $PM_{2.5}$ concentrations are high in Blantyre, it is important that people minimise the duration of stay in highly polluted areas and wearing of personal protective equipment like masks should be encouraged as well. Also, the local assembly should put in place measurers to improve air quality within the city. Although $PM_{2.5}$ concentration levels were lower between December and April, it is important to note that this was a characteristic of one year. Therefore, it is proposed that a long-term monitoring of $PM_{2.5}$ levels be done in Blantyre. A study of $PM_{2.5}$ concentrations source apportionment should also be done.

Conflict of interest

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

Data availability

The monitoring data used in this study are available upon request. Interested researchers can contact the corresponding author to obtain access to these data.

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Supplementary material

Supplementary material can be accessed at https://cleanairjournal.org.za/article/view/15662