Spatio–temporal trends of air quality, Kampala City, Uganda, 2020–2022

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Abstract

Fine particulate matter ($PM_{2.5}$) is among the health damaging air pollutants that pose health risks to humans, with levels >15 μg/m^3 being associated with adverse health effects. $PM_{2.5}$ has been recommended as the best measure of air quality. Cities are more prone to poor air quality compared to non–urban areas. We assessed the spatio–temporal trends in air quality in Kampala City during January 2020–June 2022. We abstracted $PM_{2.5}$ concentrations generated by twenty–four Clarity© Node Solar–Powered monitors from January 1, 2020, to June 30, 2022, from the Clarity© dashboard. We computed 24–hour average $PM_{2.5}$ concentrations at city and division levels by combining data from all monitors. Average $PM_{2.5}$ concentrations per hour were compared by the hour of the day. We generated choropleth maps and line graphs to show trends in 24–hour average $PM_{2.5}$ concentrations in Kampala City over the study period. The seasonal Mann–Kendall statistical test was applied to assess the significance of observed trends based on Kendall's tau correlation coefficient (r) and p–values. Overall, the 24–hour average $PM_{2.5}$ concentration from January 1, 2020, to June 30, 2022, was 59 μg/m^3

(range: 18–182 μg/m^3). $PM_{2.5}$ concentrations exceeded 15 μg/m^3 in all city divisions: Kawempe (63 μg/m^3), Central (61 μg/m^3), Rubaga (60 μg/m^3), Nakawa (55 μg/m^3) and Makindye (53 μg/m^3). A statistically significant decline in PM2.5 occurred throughout the assessment period from January 2020 to June 2022 ($r = -0.27$, $p < 0.001$). $PM_{2.5}$ increased from April to June each year [2020 (55 μg/m^3, r=0.56, p=0.006), 2021 (45 μg/m^3, r=0.26, p=0.030), and 2022 (37 μg/m^3, r=0.37, p=0.030)] and declined from July to September in 2021 (57 μg/m^3, r=–0.43, p=0.008) and January to March in 2022 (60 μg/m^3, r=–0.41, p=0.011). $PM_{2.5}$ concentration peaked from 10am–midday (74–73 μg/m^3) and 8pm–9pm (73–77 μg/m^3). $PM_{2.5}$ concentrations exceeded targeted safe levels on all days in Kampala City during 2020–2022. In 2022, Kampala Capital City Authority developed the Kampala City Clean Air Action Plan with interventions to be undertaken by multiple partners aimed at improving air quality, including further monitoring.

Keywords: Particulate Matter, Fine Particulate Matter ($PM_{2.5}$), Air Pollutants, Cities, Uganda

Background

Air pollution, the contamination of air with substances that are harmful to human health, is one of the outstanding health concerns today [1]. It is a silent killer, accounting for an estimated 6.7 million premature death annually worldwide [2, 3]. Air pollution is associated with ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease, pneumonia, type 2 diabetes, and neonatal disorders, as well as infant mortality, low birthweight, pre–term delivery, mental health conditions, and neurological impairment [4]. Sources of air pollution include domestic solid biomass energy use, exhaust and non–exhaust emissions from vehicles, industrial emissions, and burning of solid waste [5].

Particulate Matter (PM), one of the major health–damaging air pollutants as classified by the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA), is formed in the atmosphere as a result of chemical reactions between different pollutants, and contains tiny liquid or solid droplets that can be inhaled dependent on their size and cause serious health effects [6]. Fine particulate matter ($PM_{2.5}$) poses adverse risks to humans due to its small size and diameter, which easily permit penetration into the lower respiratory tract [7]. Long term exposure to unsafe levels of $PM_{2.5}$ increases the risk of excess mortality from aggravated asthma, chronic obstructive pulmonary disease, lung cancer, stroke, diabetes mellitus, and incidence of maternal and fetal complications, among others [8]. According to the Global Burden of Disease Report, $PM_{2.5}$ caused 6.4 million premature deaths in 2019 [3, 4]. Globally, air pollution due to $PM_{2.5}$ is increasing; the population–weighted mean $PM_{2.5}$ increased by 0.04 ± 0.02 micrograms per cubic meter per year worldwide from 1998–2018 [9]. Remarkably, seasonal variations and meteorological conditions may either decrease or increase $PM_{2.5}$ concentration levels [10–13].

According to the 2021 WHO Air Quality Guidelines, the 24–hour average targeted safe level of $PM_{2.5}$ is less than or equal to 15 $\mu g/m^3$, and the annual targeted safe level is less than or equal to 5 $\mu g/m^3$. Kampala City has been ranked as one of the cities with the highest levels of $PM_{2.5}$ globally, exceeding WHO recommended air quality $PM_{2.5}$ levels by 5 to 7 times as of 2021 [14]. However, there is limited data on the spatial and temporal distribution of $PM_{2.5}$ across Kampala City. Understanding the spatial and temporal distributions of $PM_{2.5}$ concentrations is critical to act as a foundation for Kampala Capital City Authority and other government agencies to implement strategic, evidence–based decisions to improve air quality in the city. We assessed the spatio–temporal trends of $PM_{2.5}$ in Kampala City from January 2020 to June 2022.

Methods

Study setting

This assessment was conducted in Kampala, the capital city of Uganda. It is divided into 5 administrative divisions: Central, Kawempe, Makindye, Rubaga, and Nakawa. The city has a surface area of 189 km^2, including 176 km^2 of land and 13 km^2 of water [15]. The 2023 population was estimated at 1.76 million; however, the city has a dynamic and transient day population estimated at 5 million people [16]. Kampala Capital City Authority (KCCA) has been mandated to govern and administer Kampala Capital City on behalf of the Central Government of Uganda.

Study design, data source, study variables, and data abstraction

In December 2019, KCCA installed twenty–four Clarity© Node Solar–Powered monitors for outdoor air quality monitoring in all five divisions of Kampala City (Figure 1). Clarity© Node Solar–Powered monitors were permanently set up at least 1.5 meters above ground level in secure areas away from obstruction or emission sources that could interfere with air quality measurements. Calibration of Clarity© Node Solar–Powered monitors was based on co–location data with the reference air quality monitoring station at the US Embassy in Kampala City. Clarity© Node Solar–Powered monitors use inbuilt cellular connectivity to transmit raw data for $PM_{2.5}$, PM_{10}, nitrogen dioxide (NO_2), temperature, and relative humidity. Calibrated data generated by these monitors are accessed in real–time on the Clarity© Dashboard. We conducted a secondary analysis of air quality surveillance data generated by Clarity© Node Solar–Powered monitors. We abstracted hourly $PM_{2.5}$ concentrations generated by calibrated Clarity© Node Solar–Powered monitors from the Clarity© Dashboard from January 2020–June 2022.

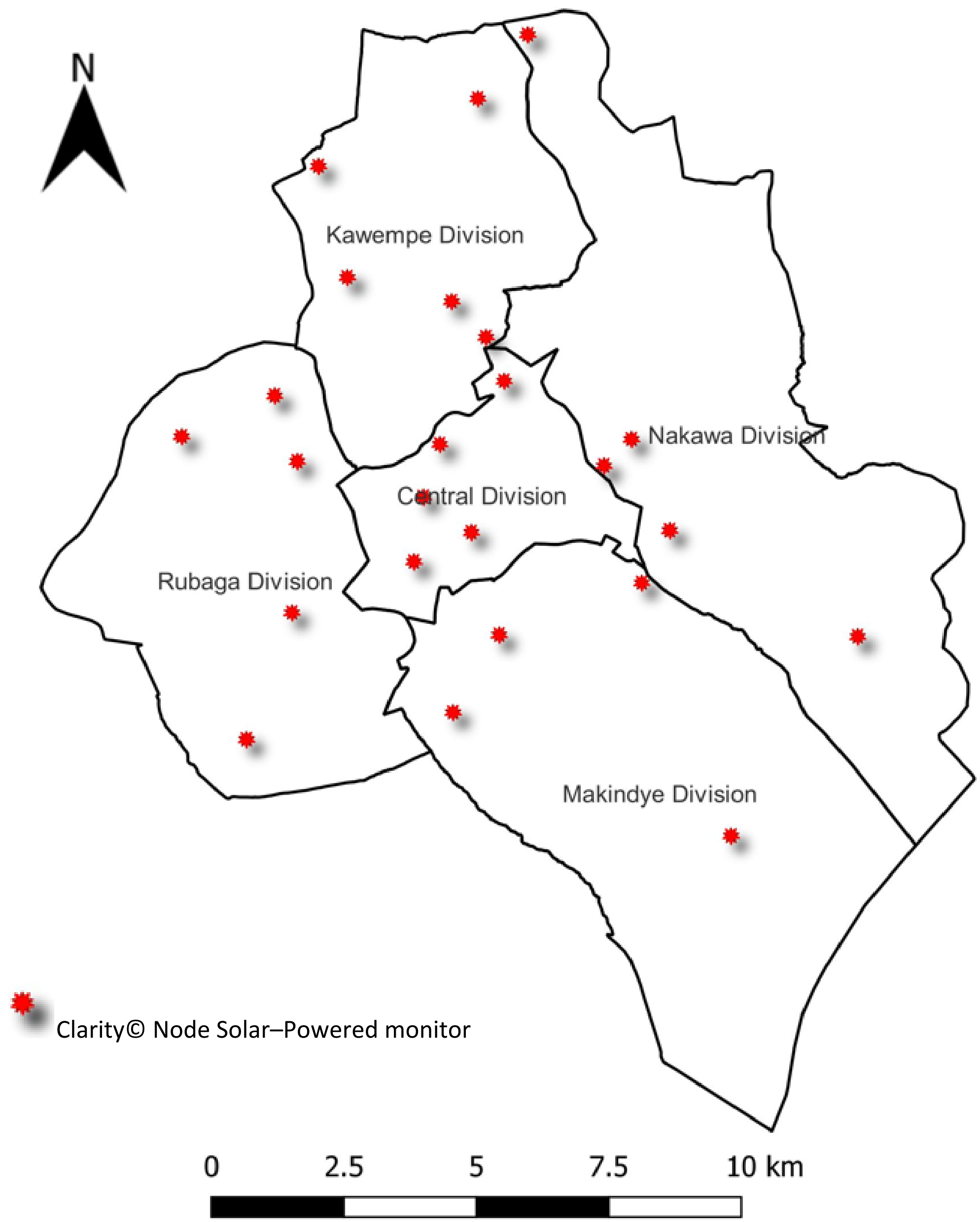


Figure 1: Location of Clarity© Node Solar–Powered monitors in Kampala City, Uganda

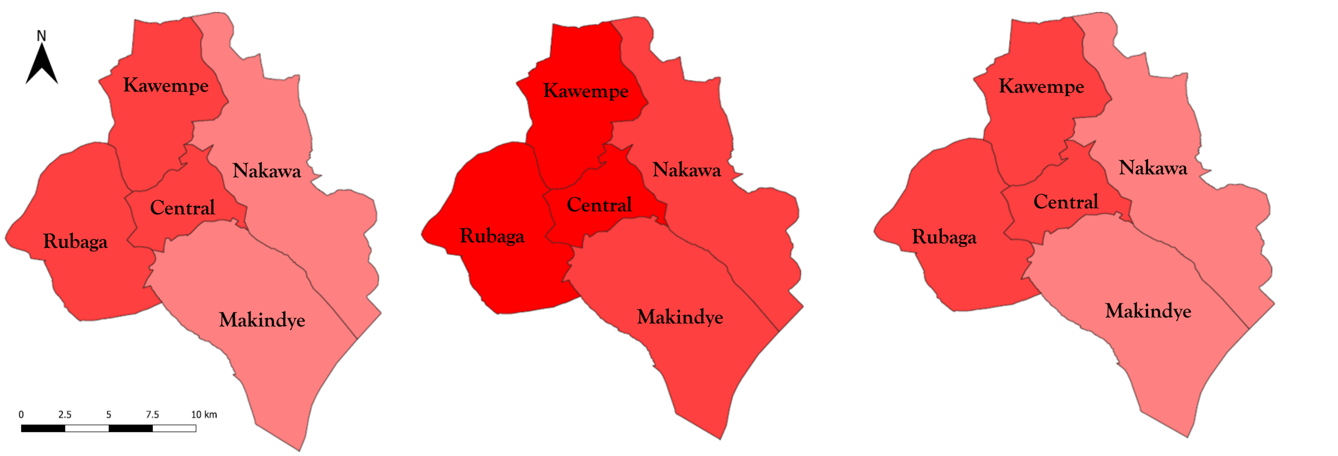
Data analysis

For spatial distribution, the 24–hour average $PM_{2.5}$ concentration from January 1, 2020, to June 30, 2022 was computed at the city and division levels. Choropleth maps were generated to show the distribution of 24–hour average $PM_{2.5}$ concentrations across the divisions of Kampala City stratified by biannual periods. We also used a line graph to show the trend of the 24–hour average $PM_{2.5}$ concentrations in Kampala City from January 1, 2020 to June 30, 2022. The seasonal Mann–Kendall statistical test was applied to assess the significance of the observed trends by quarterly periods based on Kendall's tau correlation coefficient (r) and p–values. We used a line graph to show the trend of the hourly average $PM_{2.5}$ concentrations by hour of the day (midnight–11pm), to understand the variations of air quality throughout the day.

Results

Spatial distribution of $PM_{2.5}$ in Kampala City, January, 2020–June, 2022

Overall, the 24–hour average $PM_{2.5}$ concentration was 59 µg/m^3 in Kampala City from January 2020 to June, 2022. There was a general decline in $PM_{2.5}$ across the 6–month periods during throughout the evaluation period. However, consistently higher $PM_{2.5}$ concentrations were observed in Kawempe and Central compared to other divisions (Figure 2).



January–June, 2020 **July–December, 2020** **January–June, 2021**

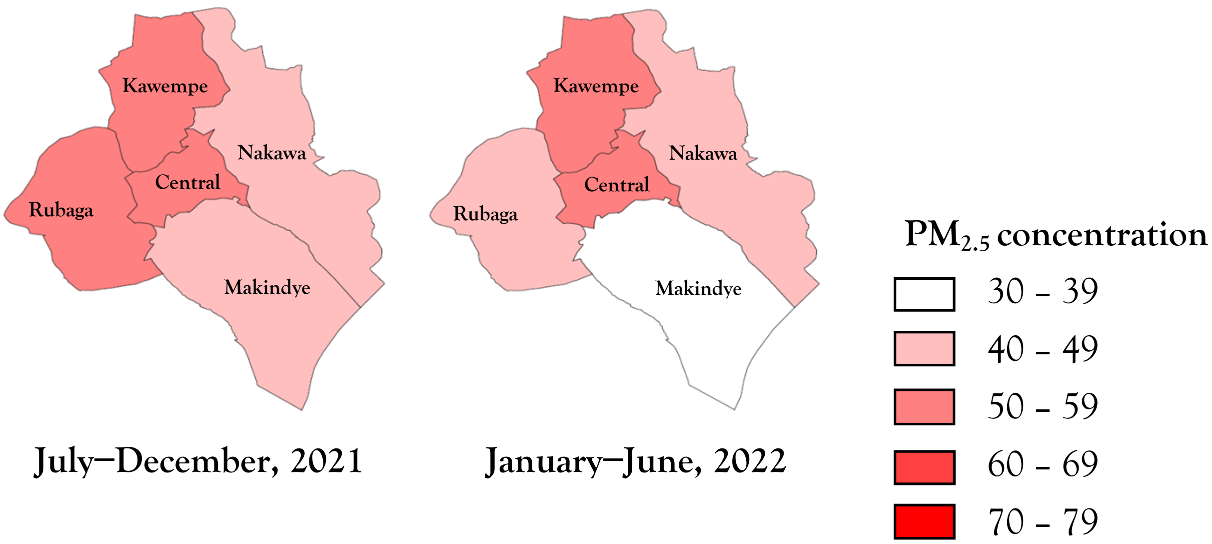


Figure 2: Spatial distribution of 24–hour average $PM_{2.5}$ concentration in Kampala City, January 2020–June 2022

Trends of $PM_{2.5}$ in Kampala City, January, 2020–June, 2022

There were daily cyclical variations of $PM_{2.5}$ concentration alternating between 18 μg/m^3 and 182 μg/m^3 (Figure 3). Based on the correlation coefficient and p–value ($r = -0.27$, $p<0.001$), there was a slight decrease in 24–hour average $PM_{2.5}$ concentration from January 2020–June 2022.

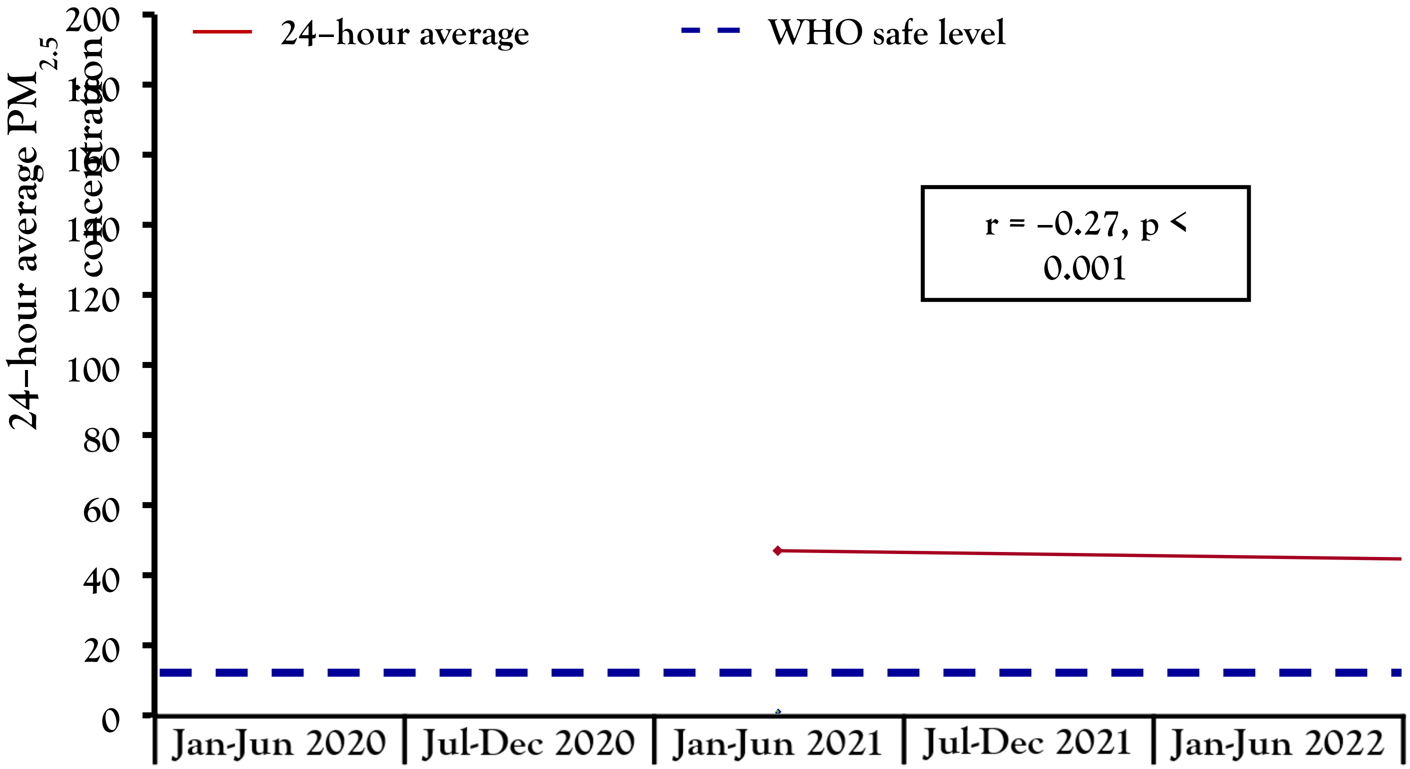


Figure 3: Trend of 24–hour average $PM_{2.5}$ in Kampala City, January 2020–June 2022

$PM_{2.5}$ increased during April–June throughout all evaluation years [2020 (55 μg/m^3, r=0.56, p=0.006), 2021 (45 μg/m^3, r=0.26, p=0.030), and 2022 (37 μg/m^3, r=0.37, p=0.030)], as well as during October–December, 2020 (68 μg/m^3, r=0.32, p=0.032) (Table 1). Significant decreasing trends were observed during July–September, 2021 (57 μg/m^3, r=–0.43, p=0.008) and January–March, 2022 (60 μg/m^3, r=–0.41, p=0.011).

Table 1: Trends of $PM_{2.5}$ concentrations in Kampala City, January 2020–June 2022

Quarterly periods	Average $PM_{2.5}$ concentration	$PM_{2.5}$ concentration range	Seasonal Mann–Kendall statistic (S')	Kendall's tau correlation coefficient	p–value
Jan – Mar 2020	65	32–119	–68	–0.27	0.051
Apr – Jun 2020	55	32–98	142	0.56	0.006
Jul – Sep 2020	76	49–182	–48	–0.19	0.054
Oct – Dec 2020	68	43–116	80	0.32	0.032
Jan – Mar 2021	74	44–152	–48	–0.19	0.138
Apr – Jun 2021	45	22–83	66	0.26	0.030
Jul – Sep 2021	57	25–85	–108	–0.43	0.008
Oct – Dec 2021	49	27–73	–2	–0.01	0.967
Jan – Mar 2022	60	24–141	–104	–0.41	0.011
Apr – Jun 2022	37	19–66	94	0.37	0.030

Variations of $PM_{2.5}$ concentrations by hour of the day, January 2020–June 2022

Two $PM_{2.5}$ concentration peaks were observed throughout the day (Figure 4). The first peak was observed between 10am and midday (74–73 µg/m^3), whereas the second peak was observed between 8pm and 9pm (73–77 µg/m^3). These represent time periods occurring shortly after the peak traffic hours in the city.

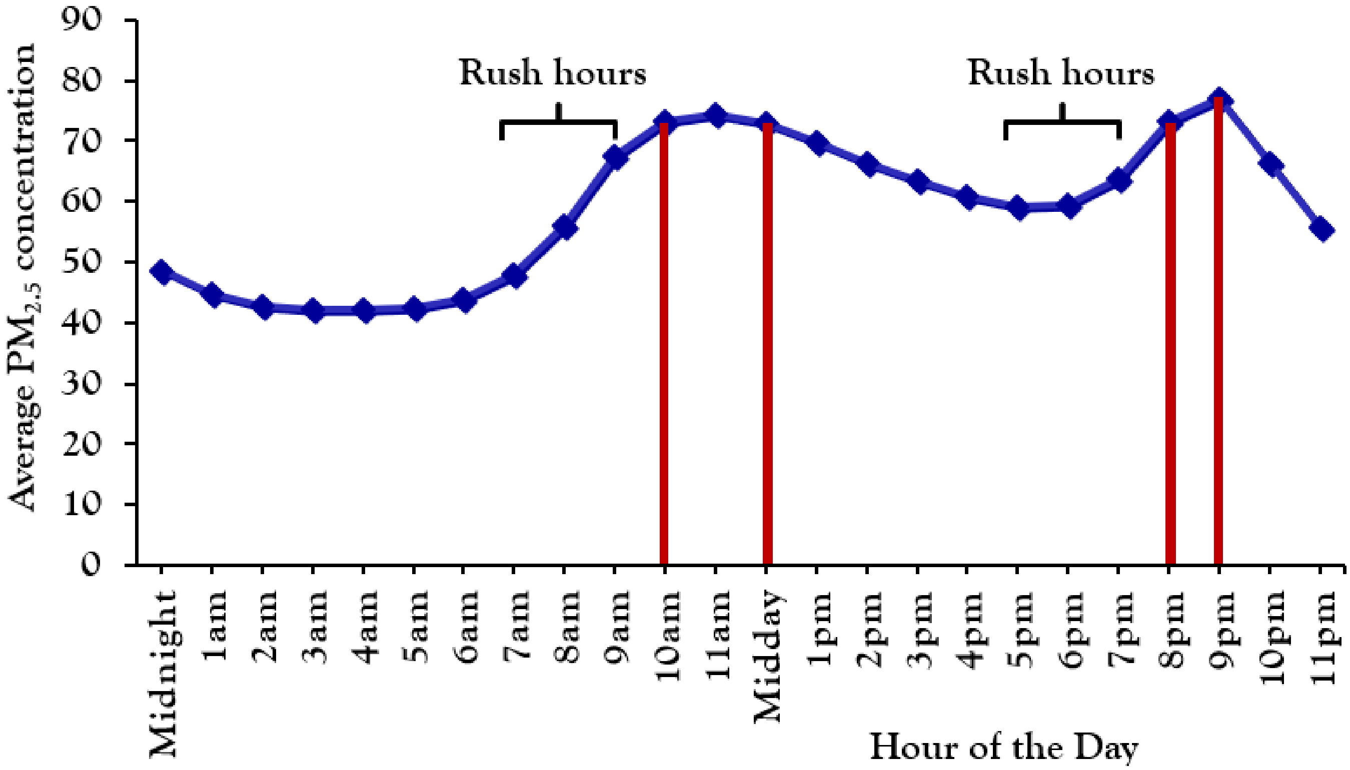


Figure 4: Average $PM_{2.5}$ concentrations by hour of the day, January 2020–June 2022

Discussion

The 24-hour average $PM_{2.5}$ concentration level in Kampala City exceeded the WHO targeted safe level at 15 µg/m^3 across all hours of the day during 2020–2022. There were two peak periods of $PM_{2.5}$ pollution each day. A general decreasing trend in the 24-hour average $PM_{2.5}$ concentration across the two years of the evaluation indicated a slight improvement in air quality in Kampala City.

Previous studies in Uganda have also indicated elevated $PM_{2.5}$ levels exceeding WHO-recommended maxima. A longitudinal study from December 2018—May 2019 across selected urban centers in Southern, Eastern, and Central Uganda showed that the 24-hourly average $PM_{2.5}$ varied between 34 and 107 µg/m^3 [17], and a pilot cross-sectional spatial assessment conducted in 2014 reported a 24-hourly average $PM_{2.5}$ concentration at 138.6 µg/m^3 in

Kampala City [18]. Ground assessments revealed that poorer air quality was observed in Kampala than in neighboring countries' capitals of Nairobi and Addis Ababa [19].

However, such high levels of pollution observed in capital cities appears to be the norm, rather than the exception. Estimates for 2019 suggested that only 0.18% of the global land area and 0.001% of the global population were exposed to $PM_{2.5}$ concentrations lower than the 2021 WHO safe level on a regular basis, with more than 70% of days in the remaining area and population having daily $PM_{2.5}$ concentrations higher than 15 $\mu g/m^3$ [20]. In Europe and the eastern United States, $PM_{2.5}$ concentrations decreased from 1998–2016 despite urban expansion and population growth, demonstrating the real potential to improve air quality in other areas, including developing sub–Saharan African cities [21]. However, achieving these results requires governments and city authorities to advocate for sustainable urbanization practices that take health and environmental protection into consideration [21]. Promotion of low–carbon utilization strategies such as using cleaner household energy alternatives, conducting regular vehicle maintenance, and proper household, commercial, and industrial solid waste management have been key in addressing air pollution in many countries along their development pathway [22].

We observed a declining trend in $PM_{2.5}$ over the study period. The reasons for this are unknown, but may be attributed to a decline in traffic over this time period, partially attributed to behavioral changes that occurred during the COVID–19 pandemic and increased fuel prices which reduced vehicular traffic [23–25]. Other cities have seen a variety of weather parameters contribute to declines in PM2.5 over time, including changes in rainfall density, humidity, temperature, wind speed, and thermal inversion episodes [4, 7]. Further analytical studies and continued monitoring are needed to explain the observed decline and inform source apportionment assessments of air pollution in Kampala City.

Despite the observed decreasing trend over the time period, $PM_{2.5}$ concentrations remained above 'safe' levels throughout the study period. Two divisions that were particularly affected, Kawempe and Central divisions, have many informal settlements and food businesses that use biomass fuel for cooking and small-scale industries. Kawempe and Central divisions contain the largest informal settlements compared with Nakawa, Makindye, and Rubaga divisions, as well as a mixture of commerce and industry, transport terminals, and poor residential settlements [26–30]. It is possible that these may be contributing to the higher levels of $PM_{2.5}$ in these areas. In addition, Kampala is a hilly city with highly localized weather and air patterns, and some areas may be particularly prone to poor air quality compared to others [18]. In hilly areas, moderate wind speed increases the dispersion of pollutants, whereas in low-lying areas with reduced wind speed, air pollutants become trapped thus increasing levels of air pollution. A deeper understanding of how the topography affects air quality in the city could help to explain some of the differences observed across the divisions.

The two $PM_{2.5}$ concentration daily peaks occurred in the mid-late morning and later evening in Kampala City. This is similar to findings from a previous study in Kampala City [31] as well as findings from a study including 3,110 sites across the world [32] and one across 11 cities in Sub-Saharan Africa [33]. The morning and evening peak $PM_{2.5}$ concentrations observed in these studies have been attributed to both normal thermal inversion and automobile traffic pollution; indeed, data show that traffic emissions are among the biggest contributors to air pollution in urban settings [34]. A systematic review and meta-analysis showed that one-quarter of urban ambient $PM_{2.5}$ comes from vehicular traffic, 20% by domestic biomass burning, 15% by industrial activities, 22% from unspecified sources of human origin, and 18% from natural dust and salt [34]. In Kampala, a significant improvement in air quality was also observed during the COVID-19 lockdown periods in Uganda, during which comprehensive restrictions were imposed on vehicular traffic, compared to the same months in the adjacent non-lockdown years [35]. The second peak in the evening is also impacted by the decrease in the planetary boundary layer, which increases the dispersion of $PM_{2.5}$ concentrations to the ground level [19].

Study limitations

Three out of twenty-four air quality monitors were non-functional for 4 months (March—June, 2022), resulting in missing $PM_{2.5}$ concentration data during the affected period. This could have led to underestimation or overestimation of the air quality levels during the affected months and overall assessment period. Furthermore, we did not assess the impact of climatological conditions, for example wind speed, rainfall, temperatures, and precipitation, on $PM_{2.5}$ concentration in Kampala City because we did not have all the required data to explore this relationship.

Conclusion

We found unhealthy air quality evidenced by $PM_{2.5}$ concentration exceeding the WHO targeted safe level throughout the day, even during times of less traffic and economic activities in Kampala City. There was a modest improvement in $PM_{2.5}$ air quality from January 2020 to June 2022. Specific divisions consistently faced higher levels of $PM_{2.5}$ than others. Deeper study of the reasons for the decline and the presence of $PM_{2.5}$ hotspots could facilitate the prioritization of interventions to improve quality in Kampala City. Based on the evidence in this paper, the Kampala Capital City Clean Air Action Plan was developed with interventions including promoting individual responsibility for air quality and assigning roles to different stakeholders towards improving air quality in the city. Initiatives to improve air quality cannot be confined to only Kampala Capital City Authority; there is a need for multi-sectoral collaboration to achieve the mandate of the Kampala Capital City Clean Air Action Plan.

List of abbreviations

EPA: Environmental Protection Agency; KCCA: Kampala Capital City Authority; PM: Particulate Matter; $PM_{2.5:}$ Fine Particulate Matter; r: Kendall's tau correlation coefficient; S': Seasonal Mann-Kendall statistic; WHO: World Health Organization

Declarations

Ethical approval

Kampala Capital City Authority requested for descriptive analysis of $PM_{2.5}$ concentrations generated by Clarity© Node Solar–Powered monitors. The Office of the Associate Director for Science, Centres of Disease Control and Prevention/Uganda, also determined that this activity was not human subject research, and its primary intent was public health practice or a disease control activity (specifically, epidemic or endemic disease control activity). Administrative clearance to extract $PM_{2.5}$ concentration data from the Clarity© Dashboard was obtained from KCCA. All methods were performed in accordance with the approval and administrative clearance. This activity was reviewed by CDC and was conducted consistent with applicable federal law and CDC policy. [§]

[§]See e.g., 45 C.F.R. part 46, 21 C.F.R. part 56; 42 U.S.C. §241(d); 5 U.S.C. §552a; 44 U.S.C. §3501 et seq.

Availability of data and materials

The datasets upon which our findings are based belong to KCCA. For confidentiality reasons, the datasets are not publicly available. However, the datasets can be availed upon reasonable request from the corresponding author and with permission from the KCCA.

Conflict of interest

The authors declare no conflict of interest.

Consent for publication

Not applicable

Funding and disclaimer

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Authors' contributions

MN and AN analyzed the spatio–temporal trends of $PM_{2.5}$ concentrations under technical guidance and supervision of SZ, RM, DK, LB, ARA, JH and DOA. MN, AN, SZ and DOA analyzed and interpreted the data. MN drafted the manuscript. MN, AN, RM, CB, LB, JH and DOA, critically reviewed the manuscript for intellectual content. All co–authors read and approved the final manuscript. MN is the guarantor of the paper.

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