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Ambient $PM_{2.5}$ Temporal Variation and Source Apportionment in Mbarara, Uganda

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ABSTRACT

Air pollution is the leading environmental cause of death globally, and most mortality occurs in resource-limited settings such as sub-Saharan Africa. The African continent experiences some of the worst ambient air pollution in the world, yet there are relatively little African data characterizing ambient pollutant levels and source admixtures. In Uganda, ambient $PM_{2.5}$ levels exceed international health standards. However, most studies focus only on urban environments and do not characterize pollutant sources. We measured daily ambient $PM_{2.5}$ concentrations and sources in Mbarara, Uganda from May 2018 through February 2019 using Harvard impactors fitted with size-selective inlets. We compared our estimates to publicly available levels in Kampala, and to World Health Organization (WHO) air quality guidelines. We characterized the leading $PM_{2.5}$ sources in Mbarara using x-ray fluorescence and positive matrix factorization. Daily $PM_{2.5}$ concentrations were 26.7 μg m^{-3} and 59.4 μg m^{-3} in Mbarara and Kampala, respectively ($p < 0.001$). $PM_{2.5}$ concentrations exceeded WHO guidelines on 58% of days in Mbarara and 99% of days in Kampala. In Mbarara, $PM_{2.5}$ was higher in the dry as compared to the rainy season (30.8 vs. 21.3, $p < 0.001$), while seasonal variation was not observed in Kampala. $PM_{2.5}$ concentrations did not vary on weekdays versus weekends in either city. In Mbarara, the six main ambient $PM_{2.5}$ sources identified included (in order of abundance): traffic-related, biomass and secondary aerosols, industry and metallurgy, heavy oil and fuel combustion, fine soil, and salt aerosol. Our findings confirm that air quality in southwestern Uganda is unsafe and that mitigation efforts are urgently needed. Ongoing work focused on improving air quality in the region may have the greatest impact if focused on traffic and biomass-related sources.

Keywords: Air pollution, Air quality, Africa, Biomass, Resource-limited setting

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1 INTRODUCTION

Air pollution is the leading environmental cause of death and disability globally. Air pollution has been a public health concern since the 13th century, with reports from Medieval England citing growing dismay with the air quality owing to the wide adoption of coal as a fuel source (Brimblecombe, 1976). Since then, the growing body of data around the harmful consequences

of environmental pollution is undeniable. The most toxic component of air pollution is particulate matter (PM), which is a mixture of solid particles and liquid droplets suspended in the air. PM is released from natural and anthropogenic activities including aerosolization of dust from unpaved roads or open landfills, exhaust fumes from vehicles and industrial sources, and atmospheric secondary particle formation (Karagulian *et al.*, 2015). Particulate matter exposure causes a wide array of adverse health effects (Hoek *et al.*, 2013; Kim *et al.*, 2015), has been associated with increased all-cause mortality (Chen and Hoek, 2020; Orellano *et al.*, 2020), and can both precipitate and exacerbate a variety of chronic health conditions (Dye *et al.*, 2001; Ibald-Mulli *et al.*, 2001; Wichmann and Voyi, 2012; Owili *et al.*, 2017).

Particulate matter ranges in size from a few nanometers to around 100 microns in aerodynamic diameter. Consequential particle fractions for human health are the inhalable fraction (aerodynamic diameter 10 microns or less (PM_{10}) and aerodynamic diameter 2.5 microns or less ($PM_{2.5}$)). Of these, $PM_{2.5}$ is the most harmful to human health. The perilous effects of $PM_{2.5}$ emanate from its size and morphology, which permits particles to penetrate deeply into the distal airways and alveoli, some of which are small enough to diffuse across the alveolar membrane into the systemic circulation, causing both local and systemic toxicity (Pope and Dockery, 2006; Cho *et al.*, 2009; Hoek *et al.*, 2013; Kim *et al.*, 2015). Once generated, fine particulate matter can persist in the atmosphere for as long as months, further increasing health risks among exposed populations. Given the incontrovertible evidence detailing the negative health effects of $PM_{2.5}$ exposure, in 2021 the World Health Organization (WHO) released the first update of their global air quality guidelines in over 15 years to improve worldwide health from short and long term exposure (WHO, 2021). These updated guidelines provide ambitious air quality targets. The 24-hour fine particulate matter exposure threshold has decreased from 25 μg m^{-3} to 15 μg m^{-3}, reflecting the persistence of health effects even at the lowest end of the exposure spectrum.

Results of $PM_{2.5}$ monitoring programs worldwide have shown that concentrations are higher in urban centers compared to rural or suburban areas, tend to be higher in low and middle income countries as compared to high income countries, and vary across seasons (Karagulian *et al.*, 2015; Henneman *et al.*, 2017; Strosnider *et al.*, 2017). Importantly, global source apportionment studies emphasize that the major sources of ambient $PM_{2.5}$ similarly vary in urban as compared to rural regions, and high income as compared to low and middle income countries. Generally, in lower resourced regions of the world, household air pollution from the burning of biomass fuels for home cooking and heating is an important source of ambient $PM_{2.5}$ (Karagulian *et al.*, 2015). However, its relative contribution in comparison to other pollutant sources can vary quite significantly depending upon local practices and infrastructure. For example, two source apportionment studies characterizing ambient $PM_{2.5}$ sources in Delhi, India found complementary but slightly different results. Sharma and colleagues identified crustal/soil/road dust, biomass burning and fossil fuel combustion, and vehicular and industrial emissions as the three leading sources (Sharma and Mandal, 2023), while Rai and colleagues identified waste incineration and solid fuel combustion, coal combustion, and industrial emissions as the leading sources (Rai *et al.*, 2020). Similarly, source apportionment studies in sub-Saharan Africa have provided varying results. In Nairobi, Kenya, leading ambient $PM_{2.5}$ sources were found to be traffic-related factors, mineral dust, and industrial sources (Gaita *et al.*, 2014), while in Addis Ababa, Ethiopia, vehicular sources were the main source of ambient $PM_{2.5}$, followed by biomass burning and soil dust (Tefera *et al.*, 2021). In contrast, ambient $PM_{2.5}$ levels in Dakar, Senegal were driven by industrial and traffic emissions and mineral dust, with no biomass-related sources (Kebe *et al.*, 2021). Similarly, Owoade and colleagues found that ambient $PM_{2.5}$ levels were driven by soil and savannah burning in Ile-Ife, Nigeria, with no contribution from biomass sources (Owoade *et al.*, 2016), while Muyemeki and colleagues found that coal and biomass combustion were the dominant source of ambient $PM_{2.5}$ in the Vaal Triangle, South Africa (Muyemeki *et al.*, 2021). Much of this variation is likely due to differences in local infrastructure, behaviors, and weather patterns. However, all characterizations of ambient $PM_{2.5}$ sources in sub-Saharan Africa to date have focused on urban locations, so how the balance of pollutant sources drives ambient $PM_{2.5}$ exposure in suburban and/or rural locations – where most of the African population resides – is not well understood.

In Uganda, time-limited measures of ambient $PM_{2.5}$ levels suggest that exposure may be many times higher than international standards considered safe for health and vary considerably across

regions (Schwander *et al.*, 2014; Kirenga *et al.*, 2015; Awokola *et al.*, 2020; Coker *et al.*, 2021; Clarke *et al.*, 2022). However, most studies of ambient air quality in Uganda focus on the urban environment of Kampala or surrounding areas, rely on measurements collected during abbreviated sampling periods, and do not characterize pollutant sources. Recently, Okure *et al.* (2022) published the most comprehensive description of ambient $PM_{2.5}$ levels across Uganda to date, leveraging their urban network of low-cost, nephelometer-based air quality sensors, which provides crucial contextualization of the spatial variation in urban air pollution. However, rural and semi-rural regions were not represented, and the methodology did not allow for the identification of pollutant sources. More recently, Opolot *et al.* (2023) collected roadside dust samples at eight Eastern Uganda sites in December 2019 in order to identify potentially ecotoxic pollutant sources through source apportionment techniques. While the authors identified vehicular sources and traffic flow as the major dust sources at the sampled sites, samples were collected from settled dust on roadsides during a single month and the source apportionment relied on a notably limited number of measured elements, so any comparisons to pollutant sources driving ambient $PM_{2.5}$ exposure in the remainder of Uganda are challenging.

To address this gap in knowledge, we measured daily ambient $PM_{2.5}$ concentrations continuously for 9 months in Mbarara, Uganda – a semi-rural region in southwestern Uganda – from May 2018 through February 2019. We compared our estimates to publicly available ambient $PM_{2.5}$ concentrations measured at the U.S. Embassy in Kampala during the study period, and to World Health Organization international air quality guidelines, and we characterized regional $PM_{2.5}$ sources using the U.S. Environmental Protection Agency's (U.S. EPA) publicly available positive matrix factorization (PMF) model.

2 METHODS

2.1 Study Location and Sampling Site

Mbarara municipality is an agro-processing, manufacturing, and infrastructural hub located approximately 280 kilometers southwest of Kampala (the capital) at an altitude of 1,480 meters. The estimated population is around 200,000 individuals (UBOS, 2016). In recent years, Mbarara has experienced rapid population growth, which has led to increasing traffic burden comprised predominantly of reconditioned vehicles imported from Asia. Across the country, the network of roads – both paved and unpaved – are poorly maintained. Open air waste burning as a means of waste management and biomass burning for domestic and institutional energy are common (UBOS/ICF, 2018). Through this rapid urbanization, minimal zoning regulations have allowed for residential, commercial, and industrial construction to be closely intertwined (e.g., industrial complexes are built abutting residential communities) (Mukwaya *et al.*, 2010). In terms of climate, Uganda lies within the tropical region, where rainfall is the major determinant of climate. Most regions of the country experience two rainy seasons (March–May (MAM) and September–November (SON)) and two dry seasons (December–February (DJF) and June–August (JJA)). However, some of the Northern parts of the country experience a single long wet season from March to November. Although there are clear wet and dry seasons, rainfall occurs throughout the year, albeit rarely during the dry seasons, and temperature varies within a narrow range. Average seasonal rainfall ranges from 99.5 millimeters in the dry season to 414.7 millimeters in the rainy season, and average seasonal temperature ranges from 22.5 to 24.0 degrees Celsius (World Bank Group, 1991–2020). High levels of humidity are experienced during the rainy seasons, while the North-South high velocity winds that predominate in the JJA dry season can occasionally drive Saharan dust towards Uganda. Throughout the remainder of the year, wind speeds are relatively low with little variation.

2.2 Sampling Methods

We measured daily ambient $PM_{2.5}$ concentrations from 25 May 2018 through 12 February 2019 at grounds within the Mbarara University of Science and Technology (MUST) compound. The site is located at an altitude of 1,430 meters (0.614024'S, 30.657370'E), 214.4 meters from the Mbarara-Kabale road, 63.7 meters from the MUST University canteen, 22.1 meters from a rarely used unpaved road and 16.2 meters from a communal refuse burning site. We collected $PM_{2.5}$

samples gravimetrically using a vacuum pump that drew ambient air at 10 liters per minute through a Harvard impactor fitted with a size-selective inlet to remove particles with an aerodynamic diameter greater than 2.5 μm (Turner *et al.*, 2000). The inlet consisted of two polyurethane foam (PUF) impactor stages in series to account for the higher ambient particulate matter concentrations in the region. $PM_{2.5}$ was collected downstream of the size-selective inlet on a pre-weighed 37 mm polytetrafluoroethylene (PTFE) filter. Filter samples were collected every day for 24 hours. We recorded start times and end times and measured the flow rate before and after each sampling period using a calibrated rotameter. For quality assurance, we collected weekly field blank filters, which were loaded and unloaded from the Harvard impactor but not used for sampling.

2.3 Gravimetric Analysis

Filters were weighed before and after sampling sessions using an electronic microbalance (Mettler MT-5, Mettler Toledo, Columbus, OH, USA) in the Environmental Chemistry Laboratory at the Harvard T.H. Chan School of Public Health (HSPH). Prior to weighing, filters were equilibrated for 48 hours in an environmentally controlled balance room with temperature 20 ± 3°C and relative humidity of 40 ± 5%, per U.S. EPA guidelines. The electrical supply in Uganda can be unreliable, with frequent outages and occasional power surges that can affect the pump flow rate during the sampling period. Samples with damaged filters or from days on which the target sampling duration or flow rate were more than 30% different from target were excluded from analyses.

2.4 Black Carbon Analysis

We used the SootScan OT-21 transmissometer (Magee Scientific, Berkeley, CA) to quantify black carbon (BC; IR wavelength 880 nm) concentrations on each filter (Presler-Jur *et al.*, 2017; Deslauriers *et al.*, 2023). This non-destructive approach is a well-known method that quantifies ambient BC concentrations using optical measurements. However, we also conducted an additional quality control process using retrospective measurements from the Harvard central monitoring site located on the roof of the Frances A. Countway Library in Boston, Massachusetts (Deslauriers *et al.*, 2023). This central site measures hourly BC concentrations using an aethalometer (AE-33, Magee Scientific, Berkeley, CA) and simultaneously collects daily $PM_{2.5}$ on Teflon filters. We retrospectively measured the Teflon filters using the OT-21 and averaged the hourly aethalometer-based BC measurements to correspond to the filter sampling periods. The OT-21 transmissometer measurements and central site aethalometer measurements were highly comparable, with a coefficient of determination (R^2) of 0.87 for BC values. Furthermore, the lower detection limit representing 1 attenuation unit was equivalent to 0.027 μg m^{-3} on the filters collected over 24 hours.

2.5 Chemical Analysis

We then analyzed a subset of the filters for the presence of 48 elements ranging in atomic number from 11 (Na) to 82 (Pb). As described previously (Kang *et al.*, 2014), the elemental analysis at HSPH was conducted using an Epsilon 5 EDXRF spectrometer (PANalytical, The Netherlands) which utilizes secondary excitation from 10 secondary selectable targets. The spectrometer employs a 600-W dual (scandium/tungsten, Sc/W) anode X-ray tube, a 100-kV generator, and a solid state germanium (Ge) detector. A total of 49 MicroMatter XRF calibration standard polycarbonate films (Micromatter Co., Vancouver, Canada) were used for calibration of 48 elements ranging in atomic number from 11 (Na) to 82 (Pb). We also used the U.S. National Institute of Standards and Technology (NIST) standard reference material (SRM) 2783, which simulates ambient $PM_{2.5}$ on filter media. Analyzing the standard films as unknowns after using them for calibration showed that the EDXRF analysis had about 2% and about 4% errors for accuracy and precision, respectively. Accuracy tests using NIST SRM 2783 demonstrated that most elements had RSDs below 15%. For additional quality control of the analytic procedure, we selected 50 ambient filters and analyzed them from two other laboratories. The comparative results are also available from the same reference. Of these elements, 19 elements were used for further analysis.

2.6 Additional Data Collected and Data Processing

To place our data in regional context, we obtained publicly available $PM_{2.5}$ concentrations during

the same study period from the U.S. Embassy's ambient air pollution monitoring site in Kampala (AirNow, 2022). Hourly ambient $PM_{2.5}$ concentrations were measured using a Beta Attenuation Monitor (BAM 1020-9800 REV U, Met One Instruments, Inc; Grants Pass, OR, USA), which measures $PM_{2.5}$ mass using beta ray attenuation. Equipment installation, calibration, and maintenance were in accordance with manufacturer specifications, and $PM_{2.5}$ samples were measured at a flow rate of 16.7 liters per minute. We converted the hourly ambient $PM_{2.5}$ measurements into 24-hour averages for comparison to our gravimetric $PM_{2.5}$ data from Mbarara.

We summarized average ambient 24-hour $PM_{2.5}$ concentrations in Mbarara across the study period and compared concentrations by season, day of the week, and the presence of nearby waste burning activities. We compared these data to ambient $PM_{2.5}$ concentrations from the U.S. Embassy's monitor in Kampala. We compared concentration averages between cities, and compared 24-hour ambient $PM_{2.5}$ concentrations in each city to the 2006 WHO ambient air quality guidelines, the guidelines in place at the time of data collection, which specified that daily ambient $PM_{2.5}$ concentrations not exceed 25 $\mu g\ m^{-3}$ (WHO, 2006). We then calculated the air quality index (AQI) for all measured days in both Mbarara and Kampala (U.S. EPA, 2018). The AQI categorizes raw $PM_{2.5}$ data into five levels of air quality from "good" to "hazardous" and is instructive for exposure mitigation behaviors among potentially vulnerable populations. We report median and interquartile range (IQR) for non-normally distributed data and compare data using Wilcoxon rank sum, chi squared, Fisher's exact, and ANOVA, as appropriate. Analyses were conducted using R version 4.2.2 (R Project for Statistical Computing, Vienna, Austria).

2.7 Source Apportionment

We characterized ambient $PM_{2.5}$ sources in Mbarara using Positive Matrix Factorization (PMF). PMF is a receptor model that uses an advanced multivariate factor analysis technique based on weighted least square fits, which uses realistic error estimates to weight data values by imposing non-negativity constraints in the factor computational process. The main advantage of PMF is that it can provide source profiles and contributions with no prior knowledge of PM emission profiles. By using ambient species concentration measurements, PMF identifies sources and apportions the observed species concentrations from samples to sources by looking at the changes in species correlation with time while finding the optimum solution that explains all observed constituents. Here, the U.S. EPA PMF 5.0 model was used (Norris *et al.*, 2014). In the input matrix, each species sample has its own uncertainty and missing values (Polissar *et al.*, 1998; Paatero and Hopke, 2003). Species below their detection limit were replaced by their averaged values and were accompanied by an uncertainty of 4 times the species-specific average value (Paatero *et al.*, 2014). An additional 10% uncertainty in the model runs was also added to account for the uncertainty in the sampling methods. A signal to noise condition was also applied in the input data (Belis *et al.*, 2014). Individual species that retained a significant signal were separated from those dominated by noise. When signal to noise (S/N) ratio was < 0.2, species were judged as bad and removed from the analysis. Species with $0.2 < S/N < 2$ were characterized as weak and their uncertainty was tripled. Species with S/N ratio greater than 2 ($S/N > 2$) were defined as strong and remained unchanged. For further details on the mathematical background of PMF analyses, please see the Data Supplement.

2.8 Ethical Approval

This study was exempted from ethical review by the Harvard T.H. Chan School of Public Health considering the absence of human or animal subjects. Administrative approval was obtained from the Mbarara University of Science and Technology to mount the $PM_{2.5}$ monitor on the university grounds.

3 RESULTS AND DISCUSSION

3.1 Data Description

We measured daily $PM_{2.5}$ concentrations in Mbarara on 215 days during the sampling period. The median daily volume of air sampled was 14.0 m^3 (IQR 13.6, 14.2). Of the 215 days sampled,

18 samples (8%) were removed for sampling duration of less than 12 hours, 1 sample (< 1%) was removed for sampling duration of longer than 24 hours, and 9 samples (4%) were removed due to a flow difference from the start to the end of the sampling period of > 15%, for a total of 186 sampled days (86%) included in the final analysis. Most sampling days (67%, n = 124) occurred during the dry season, 75% (n = 140) occurred on weekdays, and 8% (n = 14) were collected on days that waste at the university communal refuse site was observed to be burning. Publicly available daily ambient $PM_{2.5}$ concentrations in Kampala were available for 237 days during the sampling period.

3.2 Ambient $PM_{2.5}$ Concentrations and AQI in Mbarara and Kampala

The median 24-hour $PM_{2.5}$ concentration in Mbarara was 26.7 μg m^{-3} (IQR 21.8, 34.7), ranging from 7.4 to 173.1 μg m^{-3}. In comparison, the median 24-hour $PM_{2.5}$ concentration in Kampala was more than twice as high at 59.4 μg m^{-3} (IQR 50.0, 69.7; $p < 0.001$), and ranged from 23.8 to 106.1 μg m^{-3} (Table 1). Daily $PM_{2.5}$ concentrations exceeded 2006 WHO guidelines on over half of all sampled days (58%, n = 109) in Mbarara, while $PM_{2.5}$ concentrations in Kampala exceeded 2006 WHO guidelines on nearly all sampled days (99%, n = 235). The daily AQI was better in Mbarara as compared to Kampala ($p < 0.001$; Table 1, Fig. S1), though AQI in Mbarara was rarely in the healthy range overall. Air quality was classified as "moderate" for most of the days sampled in Mbarara (81%, n = 150), while the air quality on nearly all of the days sampled in Kampala was classified as either "unhealthy" or "unhealthy for sensitive groups" (96.5%, n = 249). There were no days with "good" air quality in Kampala, and only 11 days (6%) with "good" air quality in Mbarara. These results indicate that, although $PM_{2.5}$ levels in Mbarara are generally lower than $PM_{2.5}$ levels in Kampala, both cities experience dangerous levels of air pollution.

3.3 Seasonal Ambient $PM_{2.5}$ Variations in Mbarara and Kampala

In Mbarara, ambient $PM_{2.5}$ was higher in the dry as compared to the rainy season (30.8 [IQR 25.2, 37.7] vs. 21.3 [IQR 17.1, 24.2] μg m^{-3}, respectively, $p < 0.001$; Table 2, Fig. 1). Similarly, exceedance of the daily 2006 WHO guideline was more common during the dry than the rainy season (76% [n = 95] vs. 23% [n = 14], $p < 0.001$). In Kampala, there was no seasonal variation in daily $PM_{2.5}$ concentrations (60.1 μg m^{-3} [dry season] vs. 55.9 μg m^{-3} [rainy season], $p = 0.12$; Table 2, Fig. 2). There was also no seasonal difference in number of days where $PM_{2.5}$ concentrations exceeded the WHO guidelines (99% [n = 160] in dry season vs. 100% [n = 75] in rainy season, $p > 0.99$). Although the AQI categories were statistically different by season in both Mbarara and Kampala ($p < 0.001$ and 0.016, respectively; Table 2, Fig. S1), there was no unifying pattern by which categorizations varied in either city.

Table 1. Daily $PM_{2.5}$ levels, Air Quality Index, and comparisons to WHO Guidelines in Mbarara and Kampala[a].

Characteristic	Mbarara (n = 186)	Kampala (n = 237)	*p*-value[b]
$PM_{2.5}$			< 0.001
Median (IQR)	26.7 (21.8, 34.7)	59.4 (50.0, 69.7)	
Range	7.4, 173.1	23.8, 106.1	
AQI Category			< 0.001
Good	11 (5.9%)	0 (0%)	
Moderate	150 (81%)	8 (3.5%)	
Unhealthy for Sensitive Groups	23 (12%)	171 (74%)	
Unhealthy	1 (0.5%)	52 (23%)	
Very Unhealthy	1 (0.5%)	0 (0%)	
Above 2006 WHO Guideline	109 (59%)	235 (99%)	< 0.001

[a] n (%), unless otherwise indicated.
[b] Wilcoxon rank sum test, Fisher's exact test, or Pearson's Chi-squared test, as appropriate.
$PM_{2.5}$ = particulate matter less than 2.5 microns in diameter; IQR = interquartile range; AQI = Air quality index; WHO = World Health Organization.

Table 2. Seasonal variation in daily $PM_{2.5}$ levels, Air Quality Index, and comparisons to WHO Guidelines in Mbarara and Kampala[a].

Characteristic	Mbarara			Kampala		
	Dry Season (n = 124)	Rainy Season (n = 62)	*p*-value[b]	Dry Season (n = 162)	Rainy Season (n = 75)	*p*-value[b]
$PM_{2.5}$			< 0.001			0.12
Median (IQR)	30.8 (25.2, 37.7)	21.3 (17.1, 24.2)		60.1 (50.0, 71.2)	55.9 (50.0, 64.5)	
Range	11.1, 69.2	7.4, 173.1		23.8, 106.1	37.3, 94.8	
AQI Category			< 0.001			0.016
Good	3 (2.4%)	8 (13%)		0 (0%)	0 (0%)	
Moderate	99 (80%)	51 (82%)		8 (5.0%)	0 (0%)	
Unhealthy for Sensitive Groups	21 (17%)	2 (3.2%)		110 (69%)	61 (85%)	
Unhealthy	1 (0.8%)	0 (0%)		41 (26%)	11 (15%)	
Very Unhealthy	0 (0%)	1 (1.6%)		0 (0%)	0 (0%)	
Above 2006 WHO Guideline	95 (77%)	14 (23%)	< 0.001	160 (99%)	75 (100%)	> 0.99

[a] n (%), unless otherwise indicated.
[b] Wilcoxon rank sum test, Fisher's exact test, or Pearson's Chi-squared test, as appropriate.

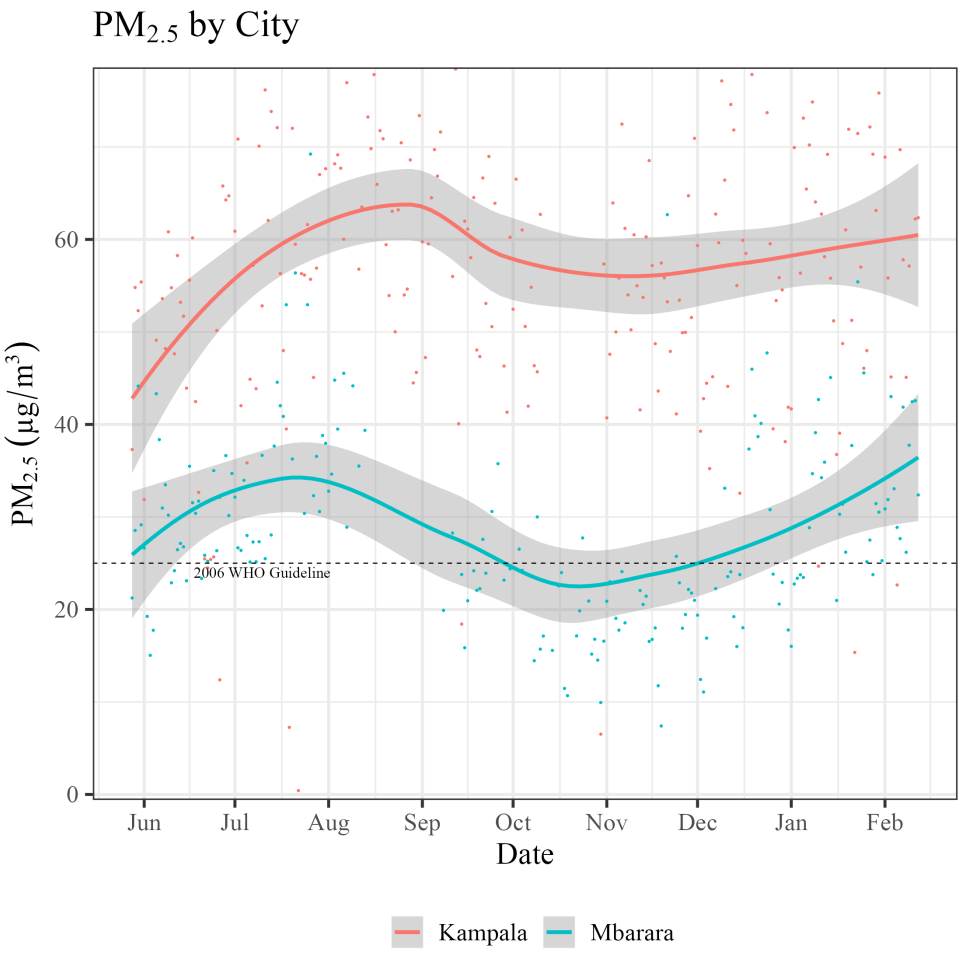

Fig. 1. Daily $PM_{2.5}$ concentrations in Mbarara and Kampala from May 2018 through February 2019. 24-hour $PM_{2.5}$ concentrations measured at the Mbarara University of Science and Technology (blue line) and the U.S. Embassy in Kampala (red line) from May 2018 through February 2019. Individual daily concentrations are represented by the blue and red dots with the corresponding line of best fit superimposed. Daily concentrations demonstrate expected seasonal variation, and nearly always exceed international health standards. $PM_{2.5}$ = particulate matter less than 2.5 microns in diameter. WHO = World Health Organization.

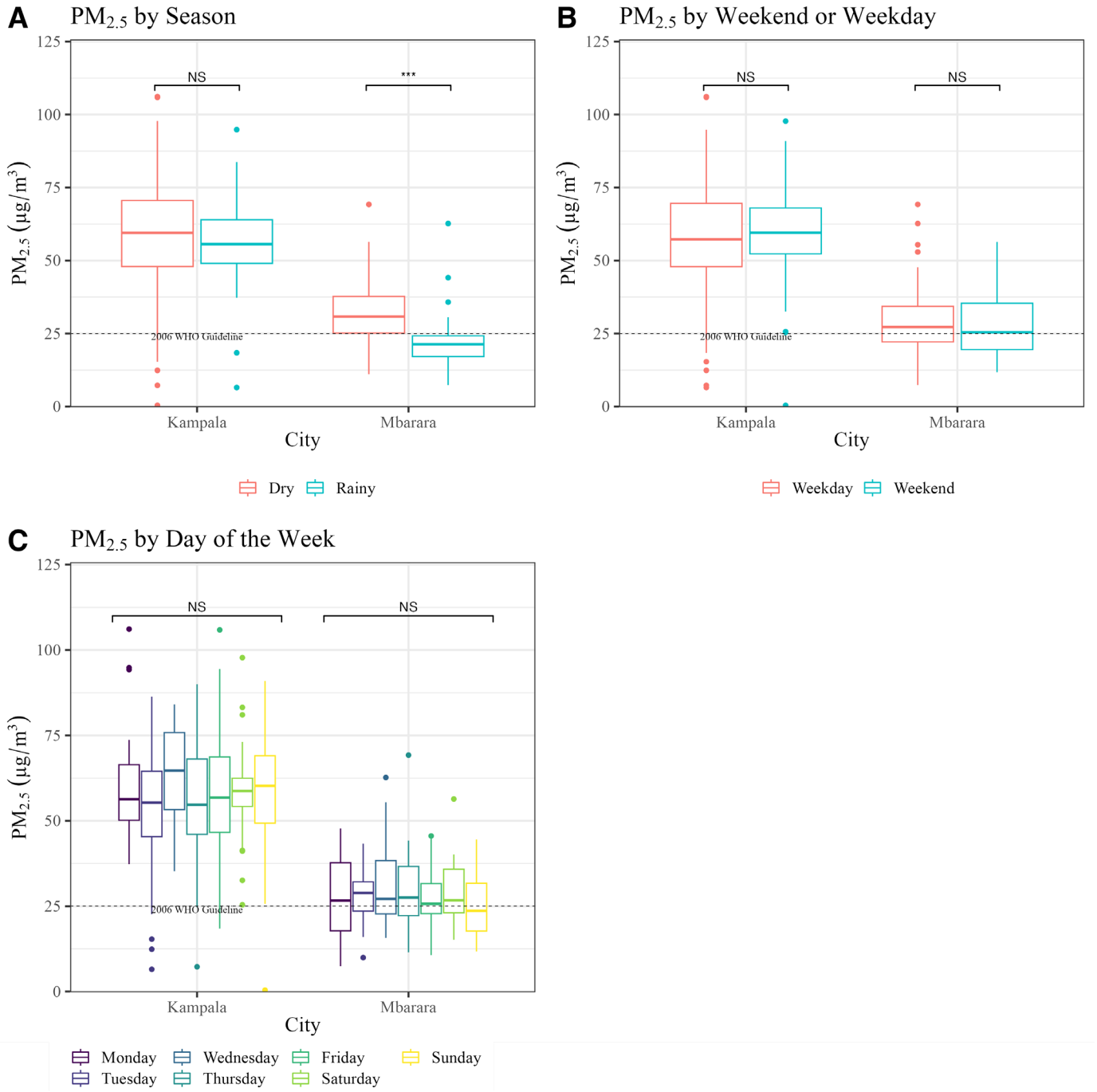

Fig. 2. Variation in ambient $PM_{2.5}$ concentrations in Mbarara and Kampala by covariates of interest. 24-hour $PM_{2.5}$ concentrations measured at the Mbarara University of Science and Technology and the U.S. Embassy in Kampala from May 2018 through February 2019. Daily $PM_{2.5}$ concentrations were higher in the dry season as compared to the rainy season in Mbarara, while daily $PM_{2.5}$ concentrations did not differ by season or by day-of-week in Kampala. *** $p < 0.05$, $PM_{2.5}$ = particulate matter less than 2.5 microns in diameter, NS = Not significant ($p \geq 0.05$), WHO = World Health Organization.

Our results show that there is seasonal variation across dry and rainy months in $PM_{2.5}$ concentration in Mbarara. Seasonal differences are a consequence of differences in the impact of meteorological conditions (e.g., rainfall quantity, temperature, atmospheric boundary layer height (ABLH), and wind speed and direction) on processes of particle generation, dispersion, growth, and deposition. Seasonality influences particle generation processes due to variation in atmospheric conditions, human behavior, or both. In Mbarara, there is little seasonal difference in human activities such

as biomass burning for heating, vehicular use, and industrial operations because temperature variation across seasons is only about 3°C on average. ABLH, which is the height of the lowest layer of the troposphere that constrains the volume for dispersion, diffusion and mixing, also does not vary significantly in this region and is therefore unlikely to have significant influence on particle mixing and dispersion (Onyango *et al.*, 2020). Thus, rainfall is likely to be the main driver of seasonal $PM_{2.5}$ differences in the region through its cleaning effect on suspended particulate matter. Although seasonal variation in $PM_{2.5}$ concentrations in Kampala did not meet statistical significance, Fig. 1 does confirm a sinusoidal pattern to $PM_{2.5}$ concentrations that mirrors that observed in Mbarara, suggesting that regional meteorologic conditions also influence $PM_{2.5}$ concentrations in Kampala.

3.4 Day of the Week Variations in Mbarara and Kampala

In Mbarara, there were no differences in $PM_{2.5}$ concentrations on weekdays compared to weekends (27.2 [22.1, 34.3] vs. 25.4 [19.5, 35.4], $p = 0.46$, Table 3, Fig. 2), nor on any given day of the week compared to the others ($p = 0.74$, Table S1, Fig. 2).

Exceedance of the daily 2006 WHO guideline was also no different on weekdays compared to weekends (60% [n = 84] vs. 54% [n = 25], $p = 0.50$). Similar to Mbarara, in Kampala there were also no differences in $PM_{2.5}$ concentrations on weekdays compared to weekends (58.4 [49.7, 69.8] vs. 59.6 [53.1, 69.0], $p = 0.95$; Table 3, Fig. 2), nor on any given day of the week compared to the others ($p = 0.54$; Table S1, Fig. 2). The number of days during which daily $PM_{2.5}$ concentrations exceeded WHO guidelines was not different on weekdays when compared to weekends (99% [n = 170] vs. 100% [n = 65], $p = 0.53$). AQI categorizations did not differ by day of the week or on weekdays compared to weekends in either Mbarara or Kampala (Table 3, Table S1, Fig. S1).

The differences in the mean concentration of $PM_{2.5}$ on weekday and weekend were not statistically significant. Studies in the U.S. suggest that differences in weekday vs. weekend pollutant concentrations are due to variations in the traffic load in the sampling area (Blanchard and Tanenbaum, 2003; Motallebi *et al.*, 2003; Khoder and Hassan, 2008). Our findings, consistent with those of Okure and colleagues, suggest that the major drivers of $PM_{2.5}$ concentration in Mbarara are unaffected by the day of week (Okure *et al.*, 2022). These findings suggest that either traffic patterns do not vary significantly between weekdays and weekends in Mbarara, particularly as the region has become increasingly urbanized, or that non-traffic sources of $PM_{2.5}$ like biomass burning, resuspended dust, pollen, or other naturally aerosolized particles are driving regional exposure patterns (McDuffie *et al.*, 2021).

Table 3. Day-of-week variation in daily $PM_{2.5}$ levels, Air Quality Index, and comparisons to WHO Guidelines in Mbarara and Kampala[a]

Characteristic	Mbarara			Kampala		
	Weekday[b] (n = 140)	Weekend[b] (n = 46)	*p*-value[c]	Weekday[b] (n = 172)	Weekend[b] (n = 65)	*p*-value[c]
$PM_{2.5}$			0.46			0.95
Median (IQR)	27.2 (22.1, 34.3)	25.4 (19.5, 35.4)		58.4 (49.7, 69.8)	59.6 (53.1, 69.0)	
Range	7.4, 173.1	11.8, 56.4		23.8, 106.1	25.4, 97.8	
AQI Category			0.70			0.71
Good	7 (5.0%)	4 (8.7%)		0 (0%)	0 (0%)	
Moderate	112 (80%)	38 (83%)		5 (3.0%)	3 (4.6%)	
Unhealthy for Sensitive Groups	19 (14%)	4 (8.7%)		122 (73%)	49 (75%)	
Unhealthy	1 (0.7%)	0 (0%)		39 (23%)	13 (20%)	
Very Unhealthy	1 (0.7%)	0 (0%)		0 (0%)	0 (0%)	
Above 2006 WHO Guideline	84 (60%)	25 (54%)	0.50	170 (99%)	65 (100%)	> 0.99

[a] n (%), unless otherwise indicated.
[b] Weekday defined as Monday through Friday, Weekend defined as Saturday and Sunday.
[c] Wilcoxon rank sum test, Fisher's exact test, or Pearson's Chi-squared test, as appropriate.

3.5 Plausible $PM_{2.5}$ Sources in Mbarara

The six main sources of ambient $PM_{2.5}$ from the PMF model are traffic related, biomass burning and secondary aerosols, heavy oils and fuel combustion, industry and metallurgy, fine soil, and salt aerosol. The mean concentration of each elemental species is shown in Table S2. The species profiles and percentages of each source to the total ambient $PM_{2.5}$ mass measured in Mbarara are shown in Figs. 3 and 4.

3.5.1 Traffic-related sources

Traffic related sources contributed 36% of the variation in $PM_{2.5}$ composition. This source was marked with high loading on BC and S, which indicates a substantial contribution of exhaust emissions (Pant and Harrison, 2013) and high loadings on elements such as Al, Si, Ti, and small amounts of Pb, Sr, and Zn, which suggests significant contribution of non-exhaust emissions (Pant and Harrison, 2013). In general, non-exhaust sources include dust resuspended by surface abrasion (often identified by elements of mineral dust such as Al, Si, Mg, K, and Ca), brake abrasion (often identified by Cu, Zn, Sn and Sb), and tire abrasion (often identified by Zn and organic elements) (Grigoratos and Martini, 2015). Based upon our elemental composition, the lower loading on Zn

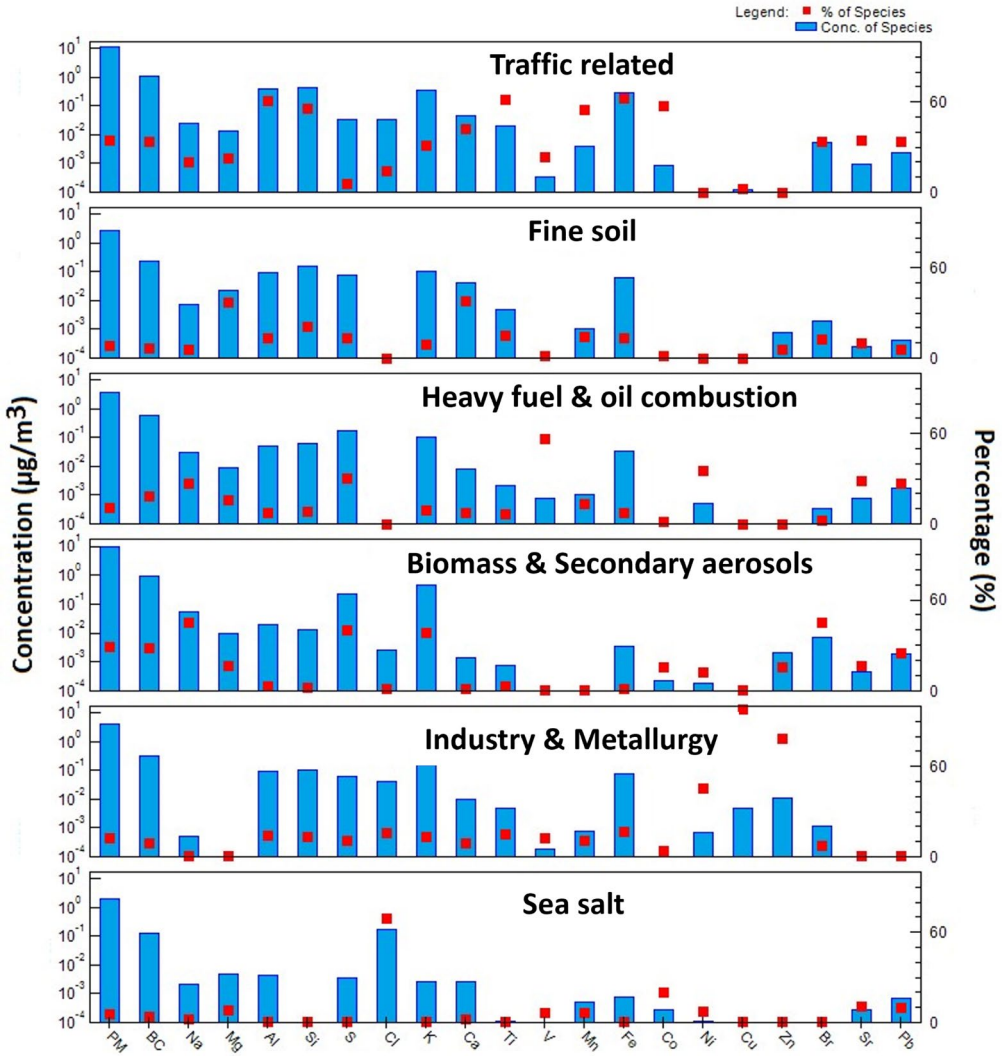

Fig. 3. Leading source profiles of ambient $PM_{2.5}$ samples from Mbarara, Uganda. Elemental composition of $PM_{2.5}$ filters from the Mbarara sampling site was characterized using energy dispersive x-ray fluorescence, and leading source profiles were identified using positive matrix factorization.

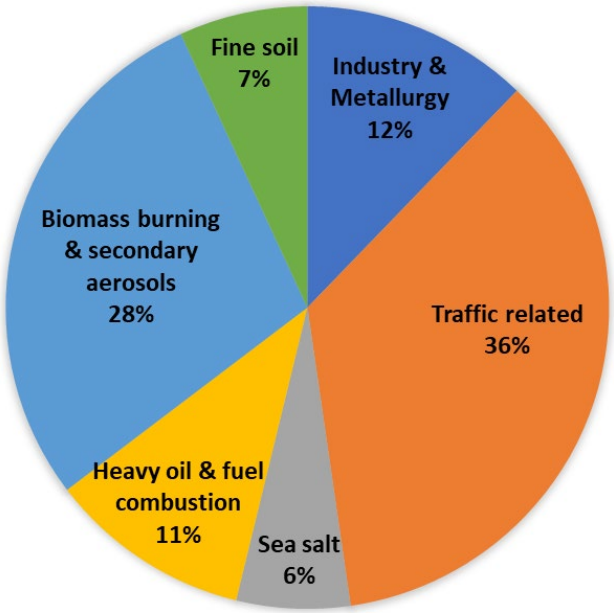

Fig. 4. Leading sources of ambient $PM_{2.5}$ in Mbarara, Uganda. Leading sources of ambient $PM_{2.5}$ in Mbarara, Uganda based on results from elemental composition analysis and positive maxtrix factorization. Traffic-related sources and biomass/secondary aerosol sources are the leading drivers of ambient $PM_{2.5}$ in the region.

and Cu as compared to the other elements suggests that tire abrasion and brake abrasion contribute less so than the resuspension of road dust (Chueinta *et al.*, 2000; Pant and Harrison, 2013). In summary, our observation suggests that the major contributors to traffic-related pollution in Mbarara are exhaust fumes and resuspended road dust, which is similar to what has been reported in the region (Gaita *et al.*, 2014; Tefera *et al.*, 2021) and other resource limited settings such as India (Pant and Harrison, 2013). This result is expected given the growing volume of vehicular transport in Mbarara, most of which are used vehicles imported from Asia, poorly maintained, and are driven on a network of unpaved and poorly maintained roads.

3.5.2 Biomass burning and secondary aerosols

Biomass burning and secondary aerosols – particles formed in the atmosphere from gas phase pollutants (oxides of nitrogen, sulfur, and ammonia) and nucleation mode particles (very small particles with aerodynamic diameters in the range of nanometers) – contributed 28% of the variation in ambient $PM_{2.5}$ composition in Mbarara. We observed high levels of K, S, and Na, which suggests a mixture of biomass burning and secondary aerosols. In general, the key chemical marker of biomass combustion is K (Pant and Harrison, 2012; Obaidullah *et al.*, 2012; Zong *et al.*, 2016; Jain *et al.*, 2020), while chemical signatures of secondary particle formation include compounds of S and Na (Kuprov *et al.*, 2014; Jia *et al.*, 2017; Jain *et al.*, 2020). According to the Government of Uganda Ministry of Water and Environment's technical report on wood fuels, biomass fuels contributed 88% of the total energy consumed in Uganda in 2019 for both domestic and institutional energy (Uganda Ministry of Water and Environment, 2019). This energy consumption pattern, together with the location of our sampling site nearby a mixture of residential and commercial areas, confirms the importance of biomass to ambient $PM_{2.5}$ concentrations in Mbarara. Additionally, Uganda is within the equatorial region of Africa, where sunlight is an important catalyst for photochemical processes that result in secondary particle formation.

3.5.3 Industry and metallurgy

Industrial and metallurgy contributed 12% of the variation in ambient $PM_{2.5}$ composition in Mbarara. This component is characterized by high levels of Ni, Fe, and Zn, which point to the influence of industrial emissions and metal recycling (Begum *et al.*, 2004; Song *et al.*, 2006; Tauler

et al., 2009; Sylvestre *et al.*, 2017). In recent years, Mbarara has experienced an explosion of industrial installations including the metal recycling factory in Kakoba, numerous milk processing plants, breweries and other small-scale factories. The contribution of industrial sources is expected to increase as Mbarara is planning to build a large industrial park. The absence of data on wind speed and direction prevents us from providing more specific estimates of the contribution of each of these factories and industries to $PM_{2.5}$ concentrations at our sampling site.

3.5.4 Heavy oils and fuel combustion

Heavy oils and fuel combustion contributed 11% of the variation in ambient $PM_{2.5}$ composition in Mbarara. Loadings on trace elements such as S, Sr, and V (Maykut *et al.*, 2003; Viana *et al.*, 2008; Shridhar *et al.*, 2010) suggests that heavy diesel engines, common for cargo trucks and as an alternative source to the national grid for electrical power at institutions, are a major contributor to this component (Andrade *et al.*, 2012; Pant and Harrison, 2012). Indeed, in close proximity to our sampling site were several standby diesel generators used by the university and other institutions.

3.5.5 Fine soil

Fine soil (e.g., road dust and soil) contributed 7% of the variation in ambient $PM_{2.5}$ composition in Mbarara. Chemical markers of this source include crustal elements such as Mg, Ca, and Si (Perrino *et al.*, 2011; Sharma *et al.*, 2016). Likely contributors to this source are dust suspension from local activities such as sweeping, traffic on unpaved roads, and long range fine dust such as Saharan dust. However, the contribution of soil resuspension to $PM_{2.5}$ in Mbarara may be underestimated in the current model because Al and Si are also prominent in the traffic-related source, suggesting that soil resuspension is also present in that source. Additionally, mechanically generated dust is generally more present in PM_{10} rather than $PM_{2.5}$ (Khan *et al.*, 2021). Thus, further investigation of the major contributors to $PM_{2.5}$ crustal sources in Mbarara, including a comparison between $PM_{2.5}$ and PM_{10} may be necessary for a more comprehensive understanding of this source.

3.5.6 Sea salt

This chloride-rich source contributed 6% of the variation in ambient $PM_{2.5}$ composition in Mbarara. The presence of Cl has been reported to point to the contribution of sea spray (Pio and Lopes, 1998; Viana *et al.*, 2008; Oh *et al.*, 2011), and Uganda is reasonably close to the Indian Ocean. However, an additional source of salt in the region is Lake Katwe, located about 145 km from Mbarara, which is a major regional site for salt mining. While it is plausible that both lake salt and sea spray contribute to $PM_{2.5}$ in Mbarara, this source has relatively little Na present. Alternatively, the presence of Cl may suggest that this source represents plastics-containing trash burning (Hodzic *et al.*, 2012; Li *et al.*, 2012; Saikawa *et al.*, 2020; Islam *et al.*, 2022). Plastics are a major source of waste generated in household and commercial settings in Uganda, particularly as ongoing urbanization results in increased use of plastics, and plastics are frequently disposed of via burning (Nuwagaba and Namateefu, 2013; Mukama *et al.*, 2016).

Taken together, our work characterizing daily ambient $PM_{2.5}$ concentrations, temporal variation, and sources in Mbarara, Uganda significantly expands the published literature in several important ways. Firstly, our source apportionment findings, in which traffic-related pollutants and biomass and/or secondary aerosols drive most ambient $PM_{2.5}$ exposure in Mbarara, highlight that traffic-related pollutants are a major pollutant source even outside of the urban centers, a novel finding given that most source apportionment work has taken place in urban centers and biomass is often spoken of as the likely leading pollutant source in non-urban settings. Although biomass is the primary fuel source in many households and institutions across the country, unregulated vehicular emissions and poor quality roads are widespread. Our findings also highlight that leading pollutant sources are not always uniform across a given region, emphasizing the need for local studies to inform policies focused on exposure reduction. For example, although our source apportionment results identified similar sources to those identified by investigators in Kenya, Nigeria, and Ethiopia, the predominant sources in each region varied. Similar to our work, the leading ambient $PM_{2.5}$ sources in Addis Ababa were also found to be vehicular emissions and biomass fuel (Tefera *et al.*, 2021), while the leading sources in Nairobi were found to be traffic-related pollutants

and mineral dust (Gaita *et al.*, 2014) and the leading sources in Lagos included crustal dust and vehicle exhaust (Sulaymon *et al.*, 2020). Thus, our findings are integral to informing region-specific, targeted public health interventions aimed at eliminating the major drivers of ambient air pollution in non-urban contexts.

Our work is also the first study to quantify ambient $PM_{2.5}$ concentration and temporal variation in Mbarara, and thus provides important perspective on spatiotemporal variation in western Uganda, a region that is incompletely characterized in the published literature. This is important because, as work by Awokola and colleagues has demonstrated in their recent work characterizing spatiotemporal ambient $PM_{2.5}$ variation cross fifteen locations in eight sub-Saharan African countries (Awokola *et al.*, 2022), relying on data from nearby regions to estimate ambient $PM_{2.5}$ patterns is not a 'one size fits all' approach in that both absolute pollutant concentrations as well as seasonal patterns can vary considerably in ways that are challenging to predict without ground level measurements. To date, the literature on ambient air quality in Uganda focuses generally on large urban centers and almost entirely on the general Kampala region. Schwander and colleagues were among the first to publish ambient $PM_{2.5}$ levels in Uganda (Schwander *et al.*, 2014). They gravimetrically measured 24-hour ambient $PM_{2.5}$ concentrations on two separate days in Mpererwe District, Kampala in January 2013, which ranged from 103.7 to 104.9 $\mu g\ m^{-3}$, and they identified crustal species and carbonaceous aerosols as the leading pollutant sources, though formal source apportionment methodology was not presented. Shortly thereafter, Kirenga *et al.* (2015) measured ambient $PM_{2.5}$ levels using real-time aerosol monitors at 15 sites in Kampala and three sites in Jinja across four weeks in July 2014. Mean ambient $PM_{2.5}$ levels across all sampling sites was 132.1 $\mu g\ m^{-3}$ and there was significant spatial heterogeneity ranging from 53 to 240 $\mu g\ m^{-3}$. They describe variations based on land use categorization (e.g., industrial vs. residential paved vs. resident non-paved), but no formal source analyses were presented. Neither of the above-described studies were of a duration to provide seasonal comparisons. More recently, Kampala was one of 15 sites within a study of ambient $PM_{2.5}$ levels across eight sub-Saharan African countries, where authors measured daily ambient $PM_{2.5}$ levels from February 2020 to January 2021 (Awokola *et al.*, 2022). Daily $PM_{2.5}$ concentrations were not reported, limiting direct comparisons to our results, but annual $PM_{2.5}$ in Kampala was eight times higher than international health standards, and exhibited minimal seasonal variation. Leveraging one year of measurements from a network of 23 real-time electronic nephelometers across Kampala, Coker *et al.* (2021) demonstrated that monthly ambient $PM_{2.5}$ levels vary by location and monthly rainfall average, emphasizing both the role of geographic heterogeneity within a single city as well as the influence of precipitation on ambient $PM_{2.5}$ concentrations, further highlighting the importance of our characterization of ambient $PM_{2.5}$ patterns in Mbarara. Most recently, Okure and colleagues published the most comprehensive assessment of ground-level ambient $PM_{2.5}$ concentrations across Uganda to date, in which they used low-cost electronic nephelometers deployed at 25 sites to measure ambient air quality over a 6 month sampling period (Okure *et al.*, 2022). They demonstrated seasonal ambient $PM_{2.5}$ variation and an inverse relationship between average rainfall and ambient $PM_{2.5}$ concentrations, but they did not collect data in Mbarara, limiting direct comparisons to our work. Notably, however, their measured average $PM_{2.5}$ concentrations at other sites in Western Uganda are generally higher than our daily estimates in Mbarara, which further emphasizes the importance of defining the geographic heterogeneity of $PM_{2.5}$ concentrations rather than applying estimates across regions. Similar variations in ambient $PM_{2.5}$ levels across urban and suburban/rural locations and across dry and rainy seasons have been demonstrated in several other East African cities (Mkoma *et al.*, 2010; Gaita *et al.*, 2016; Kiai *et al.*, 2021; Glenn *et al.*, 2022).

3.6 Study Limitations and Future Directions

The main strength of this analysis is that it is the first to quantify ground-level ambient $PM_{2.5}$ concentrations and plausible sources in Mbarara using standard gravimetric methodology and source apportionment techniques. This study also has limitations. Firstly, although our sampling duration is longer than most of the literature on air quality from Uganda, we only collected samples on 186 days within one year, so we cannot account for potential aberrancies in air pollution levels during that timeframe. Secondly, there could be differences in measurement techniques between our site in Mbarara and the publicly available $PM_{2.5}$ data from the U.S. Embassy in Kampala. For

example, beta attenuation monitors have been shown to overestimate ambient $PM_{2.5}$ concentrations in high dust environments due to variation in attenuation to mass ratios and bounce-off from overloaded size-selective inlets that result in higher measurements (Alahmad *et al.*, 2021). However, dust events are uncommon in Uganda, so it likely remains valid as a comparator. We did not collect meteorological data, so we cannot draw more granular conclusions about pollutant origins. Source apportionment data were only available on a subset of the sampling days, all of which were in the dry season, further emphasizing the preliminary nature of our findings. Lastly, methodological variation in source apportionment studies has been shown to lead to divergent conclusions as to pollutant sources within a given region (Pant and Harrison, 2012), potentially due to the absence of local emission source profiles, which suggests that future studies characterizing ambient $PM_{2.5}$ sources in Uganda may come to different conclusions. To that end, additional studies of longer duration across several Ugandan sites that additionally collect meteorological data are currently underway, which will be necessary to explore the rigor of our findings.

4 CONCLUSIONS

In conclusion, daily $PM_{2.5}$ levels in Mbarara frequently exceed international health standards, are driven mainly by traffic and biomass sources, and exhibit seasonal variation. Our findings highlight that exposure mitigation efforts are urgently needed to protect health. In order to translate these scientific findings into community action focused on reducing $PM_{2.5}$ exposure, future work is needed to explore the public's perception of air pollution, its health effects, and how individuals prioritize air pollution-related risks against other priorities. This will be key in effectively engaging the public in reducing air pollution-related morbidity.

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SUPPLEMENTARY MATERIAL

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