

Health Risk Associated with Near-Road Ambient Air Concentration of Particulate Matter in Mukono Municipal Council, Uganda

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Abstract

More than 98% of urban centres exceeding 100,000 people in Low and Middle-Income Countries (LMICs), do not meet the WHO air quality limits. Data on air pollution from LMICs is scarce. We measured the mean concentrations of near-road PM_{2.5} in the period of Aug.-Dec. 2020, described the Mukono Municipality's near-road populations' exposure to PM_{2.5}, and assessed the associated health risk. PurpleAir PA-II laser particle counters, measured near-road ambient air PM_{2.5} concentration in Mukono Municipality during the period of 09/1/20 to 12/04/20. Excel Toolpak was used for data analysis and the health risk assessed with the WHO AirQ+ tool. The mean ambient near-road PM_{2.5} in Mukono Municipality were 30.97, 33.84 and 47.74 ug/m³ for background, near-unpaved and near-paved roads, respectively. Mukono Municipality's population was exposed to ambient PM_{2.5} concentrations higher than the WHO annual limit of 10 ug/m³. This level of air pollution is associated with preventable annual premature deaths of up to 133.11 per 100,000 population. Vehicles were assumed to be the predominant source of near-road ambient air PM_{2.5} pollution. The Municipality's population was exposed to near-road ambient air PM_{2.5} exceeding the WHO annual limit by as much as *4.7 for the paved roads, *3.3 for the unpaved roads and *3 for the background. This leads to increased risk of preventable premature deaths in the Municipality. Mukono Municipality could monitor PM_{2.5}; guide developers to place buildings more than 100 meters away from roadsides and should promote policies for newer vehicles on Ugandan roads.

Keywords: Ambient Air quality, Health risk, Mukono Municipality, Near-Road, PM 2.5.

Introduction

The United Nations categorizes clean air as a human right [1, 2]. Air pollution is defined by the World Health Organisation [3] as “contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere”. Air Pollution can be ambient (outdoor) or household (indoor) but one can contribute to the other. According to the World Health Organisation, air pollution is the number one environmental health challenge with 7 million premature deaths associated with it and over 90% of the global population living in areas with air pollutants exceeding the WHO limits [4]. To guide member countries on air quality improvement, the United Nations set targets for air quality in SDGs 3.9, SDG 7 and SDG 11.6 and WHO set air pollution limits [5, 6]. According to WHO [7], pollutants with

strongest evidence of negative health effects are particulate matter (PM), Ozone (O₃), Nitrogen dioxide (NO₂) and Sulphur dioxide (SO₂). Particulate matter PM 2.5 is independently and consistently associated with the most serious health risks, even when the ambient concentration is below the WHO limits [8, 9]. The World Health Organisation [10] asserts that air pollution is associated with excess Ischemic Heart Disease, Stroke, Chronic Obstructive Pulmonary Disease, Lung Cancer and Acute Respiratory Infections in children. The World Health Organisation estimates that outdoor air pollution leads to 4.2 million pre-mature deaths annually, and of these, 91% occur in Middle and Low-Income Countries (LMIC) like Uganda. A recent study by Lelieveld and others [11] found that air pollution leads to more premature deaths than previously known, by a factor of two. Air pollution tends to be worse in urban areas and according to WHO, more than 98% of urban areas with populations

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exceeding 100,000 population in LMIC, do not meet the WHO limits [12, 13]. Data on air pollution, especially from LMIC, is limited [12, 14]. Particulate matter, which has no known threshold below which there is no health risk, is used as a proxy indicator for air quality since it is the most health damaging air pollutant [15, 16]. Literature shows that at population level, a 6% increase in all-cause mortality is associated with each $10 \mu\text{g}/\text{m}^3$ rise in ambient air particulate matter of size $2.5 \mu\text{m}$ [PM_{2.5}] [5, 15, 16]. The few publications from Uganda show that air in Kampala City and in the surrounding urban centers is polluted with particulate matter concentrations exceeding the WHO guidelines [17, 18, 19, 20]. Roadsides of busy highways are some of the most polluted sites in urban areas due to the presence of dense human and motor traffic [21, 21, 22, 23]. According to the World Health Organisation, PM_{2.5} originates primarily from combustion sources such as fossil fuel driven automobiles and biomass burning [5]. Limits of $10 \mu\text{g}/\text{m}^3$ for annual mean and $25 \mu\text{g}/\text{m}^3$ for 24-hour mean of PM_{2.5} were set by WHO [5] to guide efforts to improve air quality in the varying contexts. There is scarce data on Ugandan urban near-road air quality and the health risks associated with it is unknown. Using low cost real time laser sensors of the type PurpleAir PA-II, this study measured the mean ambient air concentrations of near-road PM_{2.5} in Mukono Municipality during the period August 12th to December 4th 2020, described the Municipality's near-road populations' exposure to PM_{2.5} and assessed the associated health risk.

Methodology

The Setting

Mukono Municipality with coordinates of 0.3549° N , 32.7520° E and an area of approximately 210 sq km, is 21 kilometers from Kampala along the Kampala-Jinja highway which serves the countries of Kenya, Uganda, Rwanda, Burundi, South Sudan and Eastern Democratic Republic of Congo. Mukono district has a mean temperature of about 25 degrees celcius; humidity of about 75% and wind speed ranging between 4 and 12 kilometers per hour. The area has 5 to >200mm of rain every month with peak rains in April/May and October/November [24]. The Kampala-Jinja

Highway is paved with bitumen, but most roads are gravel. Topography of the Municipality is generally homogeneous with single storey or low-rise buildings located close to either side of the roads (Figure 2). There is limited vegetation along the roads in the Municipality. Most buildings serve a dual purpose of business and accommodation and therefore, there is a high density of people working and residing alongside the roads in Mukono municipality.

Materials

Seven laser particle counters of the type PurpleAir (PA-II), were used to collect data for the period Aug-Dec 2020. The PA-II sensors' data correlate highly ($r > 0.9$) with the Standard United States Environmental Protection Agency (EPA) methods [25]. The sensors' range of $-20 \sim +60^\circ \text{ C}$ and $0 \sim 99\%$ fits with the Mukono environment with high humidity most of the year and temperature of $24 \sim 33^\circ \text{ C}$ [26]. The PA-II effective range of $0 \sim 500 \mu\text{g}/\text{m}^3$ and maximum range of $\geq 1000 \mu\text{g}/\text{m}^3$ is appropriate in environments where previous studies in nearby towns found concentrations of particulate matter above $100 \mu\text{g}/\text{m}^3$ [17, 18, 27]. In consideration of the Mukono Municipality land area and population, the EPA urban scale of representativeness and the European Joint Research (JRC) centre recommendations, seven sensors were considered adequate to collect representative data [28, 29]. Each sensor was fixed at a purposefully selected near-the-road location in Mukono Municipality at a height of about 3 to 5 meters above the ground, connected to stable power and Wi-Fi, away from any obstructions and between 10 and 80 meters from the edge of the road [28].

Data Collection and Analysis

The PA-II laser particle counters report PM_{2.5} mass concentration to the purple air map in $\mu\text{g}/\text{m}^3$ on a downloadable excel sheet. The data was downloaded and analysed with Excel data analysis toolpak. The health risk was calculated using the World Health Organisation's AirQ+ - v.2.0 tool for health risk assessment of air pollution [15]. The 24 hour PM_{2.5} means were compared with the WHO guidelines since Uganda does not have published national ambient air quality standards [30]. The WHO tool calculates health risk for a defined population like that of Mukono

Municipality [5, 15]. The adverse health outcome of interest in this study was preventable premature deaths due to long-term exposure to air pollution. The World Health Organisation [5] annual mean air quality limits for PM_{2.5}, the ambient air PM_{2.5} mean measured by PA-II sensor during the data collection period of Aug-Dec. 2020, the Uganda crude death rate of 655.4/100,000 and an estimated population of 162,744 were used in the health risk assessment [5, 31]. The Environmental Health Risk Assessment Model (enHEALTH) [32] informed the methodology. The main issue being the potential gain in terms of premature deaths prevented if the quality of air in Mukono Municipality was maintained within the WHO [5] limits. The main hazard considered in this study was the near-road ambient air PM_{2.5} concentration. The main exposure pathways were considered being inhalation and contact with eyes and the skin.

Ethical Considerations

The protocol was submitted to the Uganda Christian University Research Ethics Committee for review and thereafter to the Uganda National Council for Science Technology, which granted permission number HS651ES to conduct this study. At each of the selected sampling sites, permission was obtained from the buildings' owners to permit mounting of the sensors.

Definitions

Particulate Matter

Particulate matter is a mixture of solid and/or liquid particles which may be organic or inorganic in nature. Particulate matter can be \leq PM₁₀, which is equal to or less than ten microns; equal to or less than 2.5 microns (PM_{2.5}) and the ultrafine PM₁, which is equal to or less than one micron. Particulate matter size of focus in this study was PM_{2.5} because, according to the World Health Organisation, long-term exposure to PM_{2.5} is consistently associated with adverse health issues [8, 9].

Near Road

Distances ranging between 0 and 100 meters from the edge of a selected road. Within this distance, there is a little decay of particulate matter (PM) concentrations related to road activity [36].

Background Air Quality Data

This is a concentration of PM_{2.5} due to natural or unidentified sources.

In this study, population in areas more than 100 meters from the roadsides were assumed to be exposed to background air quality measured by the UCU Hamu Sensor.

Health Risk

The proportion of harmful consequences associated with exposure to PM_{2.5}.

Results

Mean Near-Road PM 2.5 Ambient Air Concentration in Mukono Municipal Council in the Period August 12th, 2020 to December 4th, 2020

Figure 1 shows the trend of PM_{2.5} ambient near-road air concentrations recorded by seven laser sensors during the period 12th August to 4th December 2020 versus the annual WHO limit of ambient air PM_{2.5} concentration which is 10 $\mu\text{g}/\text{m}^3$ [5]. The sensors' readings were all above the WHO [5] limit except for UCU Hamu Mukasa Library and Namityango Senior Secondary School (SSS) sensors on one day of 16th November 2020. Also, the trendlines for Namityango SSS and for UCU Tech Park were generally lower than records from other sensors. The sensors with lower trend lines were on a busy but unpaved road used as an alternative route through Mukono Municipality during heavy traffic.

The 24-hour mean near-road ambient air PM_{2.5} concentrations for five sensors were found to be above the WHO (2005) limit of 10 $\mu\text{g}/\text{m}^3$ for the entire period of data collection. For the sensor at UCU Hamu which worked as the control and the sensor at Namityango SSS which was alongside an unpaved road, the 24-hour mean near-road ambient air PM_{2.5} concentrations were below the WHO [5] limit of 10 $\mu\text{g}/\text{m}^3$ for one day during the whole period of data collection. When a hypothetical Mukono Municipality limit of 31 $\mu\text{g}/\text{m}^3$ was assumed, the exceedences were still high, ranging from 35% at the background sensor to 99% at Church of Uganda Hospital's sensor (Figure 2).

The sensors at the Church of Uganda Hospital, St. Paul Wantone and at Seeta Highway recorded the highest mean

concentrations of ambient near the road PM_{2.5} concentrations and they also had higher standard deviations [Table 1]. The mean near-road ambient PM_{2.5} concentrations were lower for the unpaved roads compared to the paved roads. A t-test was performed to compare the 24-hour means for near-road ambient PM_{2.5} concentrations alongside the paved versus those

of the unpaved roads and the difference was found to be statistically significant with a p-value of 0.001. The 24 hour mean near-road ambient PM_{2.5} concentration for the UCU Hamu sensor which provided background data was above the WHO limit of 10 $\mu\text{g}/\text{m}^3$ for 99% of the days during data collection.

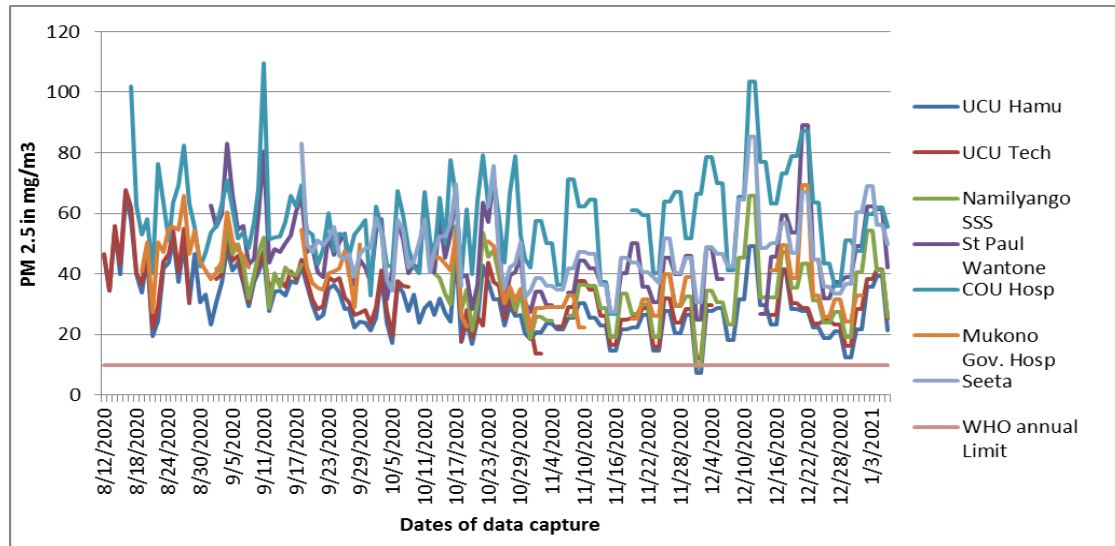


Figure 1. The Trends of Mean Concentration of PM_{2.5} Recorded by Seven Sensors across the Period 12th August to 4th December 2020 in Mukono Municipality, Uganda

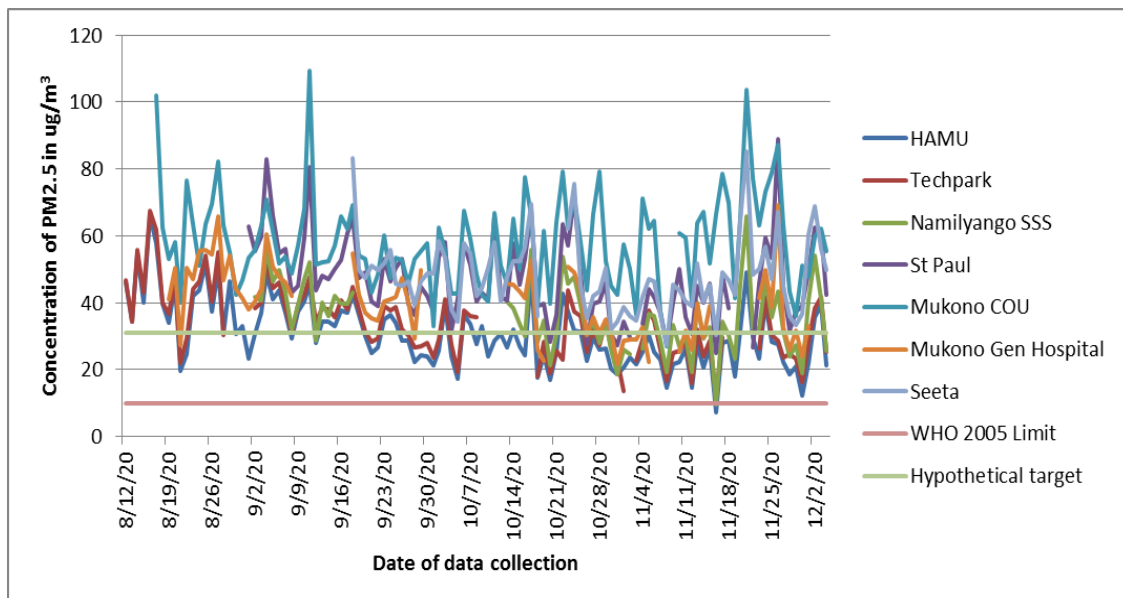


Figure 2. Means exceeding a hypothetical Mukono Municipality target of 31 $\mu\text{g}/\text{m}^3$

Table 1. Descriptive Statistics of Mean, Minimum, Maximum , Standard Deviation, Percentage of days Exceeding WHO Limit of 10 ug/m³ and Percentage of Days Exceeding a Hypothetical Mukono Municipality limit of 31 ug/m³ for Seven Sensors

	Sensors	Statistic					
		Mean	Minimum	Maximum	SD	Percentage of days exceeding WHO limit of 10 ug/m ³	Percentage of days exceeding a hypothetical Mukono Municipality limit of 31 ug/m ³
	UCU Hamu(Background)	30.97	7.25	66.25	10.12	99	35
Unpaved	UCU Tech	32.17	12.13	67.62	10.21	100	55
	Namilyango SSS	35.51	9.62	65.82	10.4	99	76
	Mean PM 2.5 at unpaved road	33.84					
Paved road	St Paul Wantone	46.15	25.01	85.01	12.85	100	91
	COU Hospital	58.31	26.83	109.45	14.24	100	99
	Mukono Gov. Hosp	38.81	21.75	69.18	10.85	100	84
	Seeta Highway	47.67	27.29	85.22	11.56	100	98
	Mean PM 2.5 at paved road	47.74					

Mukono Municipality's Near-Road Populations' Exposure to PM_{2.5}

A large proportion of the houses which serve as both commercial and residential spaces are located adjacent to the roads in Mukono Municipality as depicted in figure 3. This study focused on ambient air pollution but it was assumed that roadside air also infiltrated into working and residential spaces. The Mukono Municipality populations living/residing more than 100 meters away from roadsides, which was assumed to be the background areas, were exposed to ambient mean PM 2.5 concentration

of 30.97ug/m³. The population residing within 100 meters of busy unpaved roads were exposed to ambient mean PM_{2.5} concentration of 33.84ug/m³. The Mukono Municipality population, located within 100 meters of the paved Kampala-Jinja road highway, was exposed to ambient mean PM 2.5 concentration of 47.74ug/m³. For the whole of Mukono Municipality population, regardless of location of the residences or workplaces, exceedences of the WHO (2005) limit for ambient air mean PM_{2.5} concentration in this study was ≥99%.

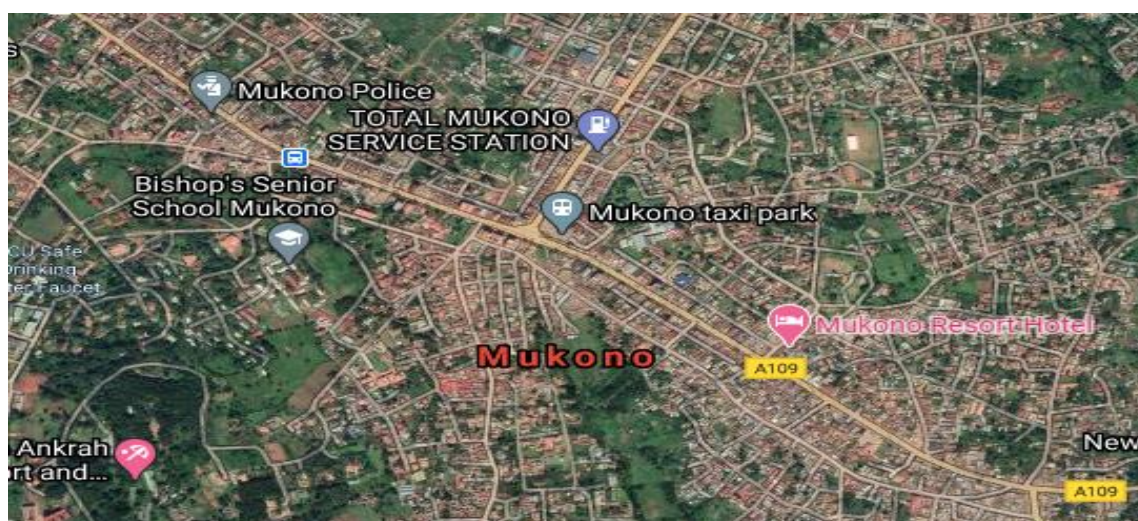


Figure 3. Showing Location of Buildings Adjacent to Roadsides in Mukono Municipality

A hypothetical Mukono Municipality target of 31 $\mu\text{g}/\text{m}^3$, which was measured by the UCU Hamu sensor, was assumed. The sensor collecting background data (UCU Hamu) exceeded the targeted for about 50% of the days of data collection. The sensors on unpaved roads (UCU Techpark and Namilyango SSS),

exceeded the hypothetical target for about 70% of the days of data collection. The sensors on the paved Kampala-Jinja Highway (Mukono COU, Mukono Govt Hospt, Seeta and St PaulWantone), exceeded the hypothetical target for approximately 94% of the days of data collection.

Table 2. Health Risk Associated with Background Ambient Air Concentration of PM 2.5 in Mukono Municipality

	Central	Lower	Upper
Estimated Attributable Proportion	11.34%	7.54%	14.74%
Estimated number of attributable cases	121	80	157
Estimated number of Attributable Cases per 100,000 population at risk	74.29	49.45	96.61

Exposure of the Mukono Municipality population to the ambient background PM2.5 concentration of 30.97 $\mu\text{g}/\text{m}^3$ in the long term would lead to more than 121 premature deaths caused by long-term exposure to PM2.5. These

deaths could be avoided if concentration of PM2.5 would not exceed 10 $\mu\text{g}/\text{m}^3$, which is the threshold recommendation by the WHO Air Quality Guidelines [5].

Table 3. Health Risk Associated with Near-Road Ambient Air Concentration of PM 2.5 along the Unpaved Roads

	Central	Lower	Upper
Estimated Attributable Proportion	13.36%	8.93%	17.31%
Estimated number of attributable cases	142	95	185
Estimated number of Attributable Cases per 100,000 population at risk	87.56	87.56	113.46

Exposure of the Mukono Municipality population to the ambient near un-paved PM2.5 concentration of 33.84 $\mu\text{g}/\text{m}^3$ in the long term would lead to more than 142 premature deaths caused by long-term exposure to PM2.5. These

deaths could be avoided if concentration of PM2.5 would not exceed 10 $\mu\text{g}/\text{m}^3$, which is the threshold recommendation by the WHO Air Quality Guidelines [5].

Table 4. Health Risk Associated with Near-Road Ambient Air Concentration of PM 2.5 along the Paved Kampala Jinja Highway

	Central	Lower	Upper
Estimated Attributable Proportion	20.31%	13.76%	25.99%
Estimated number of attributable cases	217	147	277
Estimated number of Attributable Cases per 100,000 population at risk	133.11	90.17	170.31

Exposure of the Mukono Municipality population to the ambient near paved road PM2.5 concentration of 47.74 $\mu\text{g}/\text{m}^3$ in the long term would lead to more than 217 premature deaths caused by long term exposure to PM2.5. These deaths could be avoided if concentration of PM2.5 would not exceed 10 $\mu\text{g}/\text{m}^3$, which is the threshold recommendation by the WHO Air Quality Guidelines [5].

Discussion

Mean Near-Road PM 2.5 Ambient Air Concentration in Mukono Municipal Council in the Period August 12th, 2020 to December 4th, 2020

The trends of PM2.5 concentrations in ambient air along near unpaved and near paved roads in Mukono Municipality which was

recorded by seven Purpleair sensors during the period August 12th 2020 to December 4th 2020 show air pollution level above the WHO [5] annual limit. This is true even for the sensor which measured ambient background PM_{2.5} concentration at UCU Hamu. The ambient air concentrations exceeded the WHO [5] annual limit by as much as *4.7 for the paved roads, *3.3 for the unpaved roads and *3 for the background. The PM_{2.5} ambient air concentration in Mukono Municipal Council was found to be much higher along the busy Kampala-Jinja paved road when compared to the unpaved road ($p < 0.001$). This was different from the expected and also different from some documented literature [17]. However, the difference may be partly explained by the much heavier traffic on Kampala-Jinja highway when compared to the unpaved roads. The Kampala-Jinja highway is paved in most places, wider and is preferred by most motorists, especially those driving the large Cargo trucks. Additionally, the Kampala-Jinja highway has dust coming from the multiple potholes which are in the Mukono area. The PM_{2.5} in ambient air in urban areas is known to be related to fossil powered vehicles' traffic and indeed the busier traffic locations including Seeta, St Paul Wantone and COU Mukono which recorded the highest PM_{2.5} concentrations [5, 34]. The heavier traffic which produces a lot of exhaust fumes and non-exhaust dust particles may explain the higher levels of pollution on the paved Kampala-Jinja road versus unpaved roads in the municipality [35]. The sensors at the COU and at the Mukono Government hospitals suggest that the patients and health workers, and especially the inpatients who sometimes stay for many days, may be exposed to high levels of air pollution which may worsen their health complications [36]. A positive correlation between outdoor and indoor PM_{2.5} has been documented by other researchers and therefore high levels of PM_{2.5} does suggest high levels of the same indoors of hospitals, especially where there is no air conditioning as the case is in most Ugandan hospitals [37]. Although there was no accurate record of what proportion of the population in Mukono Municipality live or work within 100 meters of the roads, the google map in figure 3 shows that most houses are located close to the roads and especially close to Kampala-Jinja

highway (A109). The 24 hour means of 33.84 ug/m³ for the unpaved roads, 47.74 ug/m³ for the paved roads and 30.97 ug/m³ for the background are all above the WHO [5] 24-hour mean limit of 25 ug/m³ and much higher than the WHO [5] annual limit of 10 ug/m³ for PM_{2.5}. The mean near-road ambient air concentrations found in this study were similar to the ambient air mean concentrations provided by Airqo station at Mukono Municipality, Ggulu station, which gave a mean of 49.32 (35.6-55.4) in the period of October-November 2020 [20]. The larger standard deviations readings along the paved Kampala-Jinja highway show more variation of ambient PM_{2.5} concentration probably related to variations in traffic volume, and it also implies that the concentrations frequently rise up to higher levels of health concern. The percentage of days exceeding WHO limit of 10 ug/m³ for all sensors were high at $\geq 99\%$ which means that exposure to concentrations of PM_{2.5} above the WHO [5] limit is long term and therefore, the Mukono Municipality near-the-road population is vulnerable to the associated health risks of respiratory and heart disease as well as excessive premature mortality [36]. Even if Mukono Municipality targeted a limit of 31 ug/m³, there would still be many days exceeding this limit. This level of air pollution with PM_{2.5}, according to the APA Air Quality Index, is graded as fair to poor and is associated with increased health risks particularly to the populations with pre-existing lung and heart problems. There is no known threshold below which ambient air particulate matter concentration is safe and so any concentrations above the WHO limits is unhealthy [5, 15, 16].

Mukono Municipality's Near-Road Populations' Exposure to PM_{2.5}

Buildings in Mukono Municipality are located very close to the edge of the road (Figure 2) and this exposes the occupants who work or reside there to high concentrations of PM_{2.5} which infiltrates indoors as it disperses [38, 33]. Some of the buildings are just a few meters off the edge of the road and therefore, close proximity to the road, combined with wind speeds of 4-12 km/hr (up to 3 on the Beaufort scale) in Mukono Municipality, results into high concentrations of PM_{2.5} near the

roads and thus exposing the population to the associated health risks for long periods of time [38, 24, 39]. The traffic along Kampala-Jinja road is usually very slow because of potholes and congestion, as well as frequent stop-and-go movements. There is a large number of heavy-duty cargo trucks on the Kampala-Jinja highway. These trucks are rarely diverted to the

smaller unpaved roads. Diesel powered heavy-duty trucks are known to be more polluting with PM_{2.5} and other pollutants than smaller petrol powered cars [38]. These traffic and road characteristics, combined with low wind speed in Mukono, make exposure to PM_{2.5} air pollution worse [38].



Figure 4. Traffic on Kampala-Jinja Highway near COU Hosp. Showing Lines of Vehicles, Potholes in the Road and a Haze due to Dust and Exhaust Fumes

The population located away from the roads, in the background areas, are also exposed to high levels of PM_{2.5} with 99% of the data collection days exceeding the WHO [5] limits. This implies that the whole population in Mukono Municipality, including that living away from the roadsides, is exposed to PM_{2.5} pollution and the associated health risks. However, the risk to ambient PM_{2.5} exposure is higher for the population living in close proximity of ≤ 100 meters from the edge of the paved Kampala-Jinja highway which registered the highest ambient mean PM_{2.5} concentration of 47.74 $\mu\text{g}/\text{m}^3$ for the data collection period of August 12th to December 4th 2020.

Health Risk Associated with Ambient Near-Road PM_{2.5} in Mukono Municipality

The outcome of interest for this near-road ambient air quality study in Mukono Municipality, was the preventable premature deaths if the quality of air met the WHO [5] annual limits or if management of the Municipality set and worked towards a PM_{2.5} target of 31 $\mu\text{g}/\text{m}^3$ which was found in the background ambient air. The avoidable attributable cases were highest at

133.11/100,000 population at risk if the whole municipality was exposed to the ambient PM_{2.5} air quality along the paved roads (Table 4). Along the unpaved roads with ambient PM_{2.5} mean concentration of 33.84 $\mu\text{g}/\text{m}^3$, the avoidable attributable cases were 87.56/100,000 population if the Municipality's population was exposed to this level of air quality (Table 3). On the other hand, if the Municipality's population was exposed to the background air quality, then the avoidable attributable cases would be 74.29/100,000 population (Table 2). A concentration-response relationship is known to exist between the ambient PM_{2.5} concentration and morbidity and mortality and the findings in this study are consistent with this literature [5, 40]. If the Mukono Municipality leadership were to set a target of 31 $\mu\text{g}/\text{m}^3$ for ambient air quality, the WHO AirQ+ (2019) tool shows that the avoidable attributable cases would be fewer at 62.78/100,000 for the paved and 10.92/100,000 for the unpaved roads. This implies that the preventable premature deaths are fewer if the target is set at a higher level, but quickly moving from high levels of air quality pollution to the WHO limit, may not always be possible given what it takes,

especially considering resource and organizational capacity constraints [5].

Conclusion

The mean ambient near-road PM_{2.5} in Mukono Municipality across the period Aug-Dec 2020 were 30.97 µg/m³, 33.84 µg/m³ and 47.74 µg/m³ for background, near-unpaved and near-paved roads respectively. These concentrations exceed the WHO [5] limit of 10 µg/m³ for annual ambient air mean. The nature of the roads, the type and characteristics of traffic and the proximity of the business and residential buildings as well as institutions like hospitals to the roads, are the factors which increase exposure of the Municipality's population to high levels of PM_{2.5}. The whole Mukono municipality population is exposed to these high ambient PM_{2.5} concentrations since even the background mean of 30.97 µg/m³ is much higher than the WHO [5] annual limit of 10 µg/m³. This level of near-the-road, air pollution is associated with up to 133.11/100,000 preventable deaths if the air quality was kept within the WHO [5] limit.

Recommendations

The Mukono Municipal Council's leadership should be aware of the high levels of air pollution in the municipality and the health risk associated with it. With the current availability of low-cost laser air quality sensors like Purpleair II, which correlate highly ($r > 0.9$) with the Standard United States Environmental

Protection Agency (EPA) methods, the Municipality can monitor the PM_{2.5} in real time so that their decisions are evidence based. The Municipality's planners should guide developers to put residential houses and institutions like hospitals and schools more than 100 meters away from busy roadways [41]. The Municipality's leadership can collaborate with National Environmental Management Authority (NEMA) and the Ministry of Works and Transport to develop policies which promote the use of newer vehicles whose exhaust gases are cleaner for common pollutants, including particulate matter [42].

Limitations

There were only seven sensors in an area of 210 square kilometers, and data was collected over a period of three months only. There were data collection gaps due to power and or internet disruptions. A longer period of data collection with more sensors would enable comparison of data across seasons.

Suggestions for Further Research

Indoor air pollution due to infiltration of ambient air PM_{2.5} into buildings is likely to be a public health problem, particularly for buildings adjacent to busy motorways. A study to assess Mukono Municipality's indoor air quality would give policy makers more information about the magnitude of the problem.

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