# Predictors of indoor particulate matter and carbon monoxide concentrations in households of an informal urban settlement in Fort Portal city, Uganda

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**Research Article**

**Keywords:** PM2.5, CO, predictors, informal settlement, Air quality, Uganda, Pollution

**Posted Date:** April 4th, 2022

**DOI:** https://doi.org/10.21203/rs.3.rs-1509952/v1

# Abstract

**Background:** Poor indoor air quality (IAQ) is a leading cause of respiratory and cardiopulmonary illnesses. Particulate matter ($PM_{2.5}$) and carbon monoxide (CO) are critical indicators of IAQ, yet there is limited evidence of their concentrations in informal urban settlements in low-income countries.

**Objective:** This study assessed household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in an informal settlement in Fort Portal City, Uganda.

**Methodology:** We conducted a cross-sectional study in 374 households. Concentrations of $PM_{2.5}$ and CO were measured using a Multi-purpose Laser Particle detector and the Carbon Monoxide IAQ Meter, respectively. Data on household characteristics were collected using a structured questionnaire and an observational checklist. Data were analyzed using STATA version 14.0. Linear regression was used to establish the relationship between $PM_{2.5,}$ CO concentrations, and household characteristics.

**Results:** The majority, 88.8% (332/374) of the households, used charcoal for cooking. More than half, 51.9% (194/374), cooked outdoors. Cooking areas had significantly higher $PM_{2.5}$ and CO concentrations compared to the living area ($t=18.14$, $p \leq 0.05$) and ($t=5.77$ $p \leq 0.05$), respectively. Cooking from outdoors was associated with a 0.112 increase in the $PM_{2.5}$ concentrations in the cooking area (0.112 [95% CI: -0.069, 1.614; p= 0.033]). Cooking with moderately polluting fuel was associated with a 0.718 increase in CO concentrations (0.718 [95% CI: 0.084, 1.352; p= 0.027]) in the living area.

**Discussion:** The concentration of $PM_{2.5}$ and CO during the cooking time for both the cooking area and the living area were above the World Health Organization Air Quality Guideline of 25μg/$m^3$ and 7ppm for 24 hours, respectively. Interventions to improve indoor air quality in informal settlements should address changes in cooking fuel types and enhance air quality.


# Background

Globally, indoor air pollution (IAP) was responsible for 3.8 million death in 2018 (1), contributing to 7.7% of the global mortality (2) and 91.5 million disability-adjusted life years (DALYs) (3) in 2019. It represented the third leading risk factor (6.4% of global DALYs) among children under five years and the second leading risk factor in disease burden for women globally (4). The public health threat of IAP is highest in low- and middle-income countries, where it contributes to approximately 10% of mortality (2), resulting in a 1000-fold difference from high-income countries (5). In 2019, household air pollution (HAP) resulted in 697,000 deaths in Africa (6). IAP has been significantly associated with respiratory tract infections, especially in children, in Uganda (7, 8).

Household air pollution is generated by incomplete combustion of fuels leading to the emission of air pollutants, including Nitrogen dioxide ($NO_2$), fine particulate matter (PM), and carbon monoxide (CO) (9, 10). It is closely linked to the rapid urbanization and unmitigated household use of solid fuels. The widespread use of solid fuel combustion for cooking and heating energy needs among an estimated 3 billion people in low- and middle-income countries (LMICs) is partly responsible for the increasing levels of household air pollution. Reliance on solid fuels for household energy in LMICs is mainly due to limited access (availability and affordability) to cleaner sources of energy such as electricity or liquefied petroleum gas (LPG) (11). The number of people using solid fuels for household energy is expected to increase globally through 2030. Sub-Saharan Africa is projected to have the highest increase in household solid fuel use for cooking.

Available data indicate that 90% of households in Uganda use solid biomass fuel, which elevates the risk of household air pollution (12). Inhalation of air pollutants such as PM contributes to cardiopulmonary illnesses. At the same time, very high CO exposure is associated with hypoxia that affects organs with increased oxygen consumption, including the developing fetus (13-15). Furthermore, exposure to $PM_{2.5}$ and CO is associated with acute lower respiratory infections (ALRI), estimated to cause 5,700 childhood deaths in Ugandans annually (8, 16). The risk is exacerbated in crowded urban environments such as informal settlements since urban environments are responsible for producing 78% of carbon emissions (17). Informal settlements are characterized by overcrowded, dilapidated, and unregulated housing structures that generally have poor ventilation, inadequate water, sanitation, and hygiene access, limited services and infrastructure, inadequate government response to needs and services (18, 19), lack of planned and allocated cooking areas, other unmitigated sources of air pollution such as open burning of solid wastes (20) and, poor ambient air quality (21). This leads to the "triple threat" of communicable, non-communicable diseases (NCDs) and injuries in these informal urban settlements. Informal settlements in Uganda are at risk of increased rural-urban migration due to anticipated urbanization of the cities (22), leading to population growth and increased demand and usage of cooking fuel energy.

To combat air pollution in Uganda, the Ministry of Energy and Mineral Development instituted a Value added tax (VAT) waiver (23) of 17% on low-pressure gas (LPG). It embarked on national grid expansion and reinforcement for electricity (24) to encourage its usage of LPG and electricity for cooking as they are cleaner energies. Additionally, the Ministry of Lands, Housing, and Urban Development oversee the physical planning of areas in Uganda. It regulates and approves building plans for each district to reduce informal settlements and unregulated structures. Despite these measures, IAP is still prevalent (25). Many studies have been done on IAP in Uganda (26-29) and the associated health effects in rural and formal settings (30-37). Most studies have looked at environmental risk factors such as exposure levels (38) and health effects of HAP (8, 39, 40){Rumchev, 2007 #5}; however, few have focused on IAP in households in informal urban settlements. Furthermore, predictors of the levels of concentrations of $PM_{2.5}$ and CO in the cooking and living area of informal dwellings during the cooking time have not been adequately explored. Yet, the established IAQ guidelines cater for a 24hr average (11) which includes both cooking and non-cooking time, from which IAQ has been found to differ significantly (26). Therefore, this study aimed to assess household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in Kisenyi-Mugunu, an informal settlement in the newly created city of Fort Portal city, Uganda.

## Methods

# Study setting and population

The study was conducted in Kisenyi-Mugunu, an informal settlement in the Western division of Fort Portal City. Fort Portal is the city of Kabarole district, located in Western Uganda. Kabarole district has a total population of 469,236. Of this population, 17.1% are children aged 0–4 years. In this district, only 18.3% of the population has access to electricity, with 63.1% using kerosene lamps for lighting (41). The majority of the residents have low-socioeconomic status and rely primarily on charcoal and firewood for cooking fuel. The housing structures in this area are generally informal and unregulated, with poor ventilation. There is also poor storage of charcoal which may lead to wetting when it rains, thus deteriorating the fuel's quality and cooking efficiency leading to increased smoke production when burnt (42). The study population included residents of Kisenyi-Mugunu, and the study units were households in Kisenyi-Mugunu, Fort portal.

# Study design, sample size, and sampling

A cross-sectional study design was used. Data were collected in September 2020. The required sample size was calculated using the Kish Leslie formula for cross-sectional studies (43). A p-value of 50% was used due to limited evidence on IAQ in households in informal settlements and a 95% level of confidence with a margin of error of 0.05. Substituting into this formula translated to a minimum sample of 385 households. However, 11 households were dropped due to missing air quality measurements leaving us with 374 participants.

With the help of the village chairperson, households in Kisenyi-Mugunu that had children under five years of age were identified, and a list of these residents was provided to researchers. Study households were then randomly selected using computer-generated random numbers. Since this research is part of a more extensive study investigating the health effects of IAP on child respiratory health, inclusion criteria included having a child under five years and the caretaker of the child consenting to participate in the study. Exclusion criteria included having a very sick child. Respondents included caretakers of under-fives.

# Data collection

After the consenting process, household interviews were conducted using pretested structured questionnaires. Additionally, observation checklists were used to establish the conditions related to cooking inside and around the home and the cooking practices of the household. The data collection tools were developed and validated by experts in air quality at the Makerere University School of Public Health. Real-time photometric measurement of $PM_{2.5}$ was done using a Multi-purpose Laser Particle detector LKC-1000S+ (Temtop, USA), while real-time measurements of CO were done using EXTECH Carbon Monoxide Meter Model CO15. Calibration of the instruments was done before the training and field measurements. In each household, IAQ measurements for both the cooking area and the living space were conducted during the cooking hours between 8:00 am and 6:00 pm. This was after the cooking fuel had been lit and active cooking was taking place. The air samples were taken at 1m above the floor (the approximate breathing zone height of a child under five years) and 1m from the cooking area (the approximate distance of a child under five years away from the cooking area). The monitors were placed with the air receivers/inlets at least 1.5m away from the windows and the doors because of reduced airflow near surfaces (44). A one-minute average for the measurement of indoor air was adapted according to Saad et al., 2017 (45). One research assistant took the air quality reading, and the data were later entered into Kobo collect form for the corresponding household. This study was performed in the wet season when ambient air pollution is expected to lower (21).

# Study variables

The dependent variables were the concentrations of $PM_{2.5}$ and CO. The independent variables include the primary type of fuel used for cooking, type of kitchen ventilation, cooking area's location, location of the fuel storage area, duration of cooking, usage of damp/wet fuel, and type of cookstove and its state of repair. The primary type of cooking fuels included 1) straw/shrubs/grass, 2) wood, 3) charcoal, 4) kerosene, 5) electricity, and 6) LPG/cylinder gas was used. For inferential statistics, the primary type of cooking fuel was re-categorized into three classes; 1) less polluting fuels (electricity, LPG, and kerosene), 2) moderately polluting fuels (charcoal), and 3) highly polluting fuels (wood, straw, shrubs, and grass). Adequate ventilation was defined as having two or more ventilation openings placed to ensure parallel or cross-ventilation (46). Therefore, cooking and living areas with two or more openings were considered adequate ventilation.

# Quality control, data management, and statistical analysis

A 2-day training of research to be undertaken by the study investigators was conducted to enhance data quality. The pretest fieldwork was conducted in Bwaise II Kawempe division Kampala. This was purposively selected for the pretest because it had similar characteristics (being informal and densely populated) to the study area. Research assistants were asked for feedback about the clarity of the questions and effectiveness of instructions, and necessary revisions were made. Data were collected using the KoboCollect mobile application preloaded on smartphones and tablets. Participant responses were entered in an offline Kobo collect form for each household. Data were submitted to a secure online server (www.kobo.humanitarianresponse.info) daily. The investigators conducted daily data quality checks. Only the study investigators had the security key to ensure data security. Data were downloaded into Microsoft Excel 2010 and exported to Stata 14.0 (StataCorp Texas, USA) for statistical analysis. Some participants' responses were dropped due to missing air quality measurements leaving 374 participants. Data were analyzed using both descriptive and inferential statistics. Frequencies and cross-tabulations were generated (where appropriate). For the inferential statistics, linear regression was used to derive associations (e.g., β-beta coefficients) between $PM_{2.5}$ and CO concentrations and household characteristics unpaired t-test was used to estimate the statistical significance of differences between $PM_{2.5}$ and CO in the cooking and living area. The concentration of the $PM_{2.5}$ and CO were log-transformed before running regressions for a more near symmetrical distribution. A variable with a *p*-value less than 0.05 was considered significant.

# Ethical considerations

Ethical approval for the study was obtained from Makerere University School of Public Health Higher Degrees Research and Ethics Committee (Reg No. 783). The study was also registered with Uganda National Council for Science and Technology (Registration number HS695ES). Administrative clearance was sought from the Kabarole district local government, which presides over the study area. Information sheets and consent forms were available in the local language (Rutooro) or English with details on the purpose of the project, procedures to be followed, and the risks and benefits of participation. Informed written consent to participate in the study was sought from all study participants.

## Results

A total of 374 respondents were interviewed representing a response rate of 97.1%. The mean age of the respondents was 30.22 (SD ± 0.51), 95% CI [29.21–31.23]. More than half (55.62%, 208/374) had attained post-primary education (Table 1). The households comprised an average of 4 people. The majority of the cooking, 90.11% (337/374), was done by the head of the household's spouse.

Table 1
Sociodemographic characteristics of respondents of Kisneyi-Mugunu slum, Fort Portal City, Uganda

| Variable | Category | Frequency N = 374 (%) |
|---|---|---|
| **Age category** | Below 20 | 43 (11.5) |
| | 21–30 | 195 (52.14) |
| | 31–40 | 98 (26.2) |
| | 41–50 | 21 (5.61) |
| | Above 50 | 17 (4.55) |
| **Level of education** | No formal education | 27 (7.22) |
| | Primary | 139 (37.17) |
| | Secondary | 181 (48.40) |
| | Tertiary | 27 (7.22) |
| **Religion** | Anglican | 100 (26.74) |
| | Catholic | 157 (41.98) |
| | Muslim | 73 (19.52) |
| | Pentecostal | 31 (8.29) |
| | Seventh-Day Adventist | 13 (3.48) |
| **Marital status** | Living with partner | 168 (44.92) |
| | Single | 134 (35.83) |
| | Married | 60 (16.04) |
| | Widowed | 7 (1.87) |
| | Divorced | 5 (1.34) |
| **The person who usually does the cooking** | Spouse of the household head | 337 (90.11) |
| | Another relative | 21 (5.61) |
| | Maid/ House helper | 15 (4.01) |
| | Do not cook at all | 1 (0.27) |

More than three-quarters (88.77%, 332/374) of the respondents used charcoal as the primary type of fuel, while less than 1% used LPG or electricity (Table 2). Respondents, on average, spent USD$0.6 (SD ± 0.02) on fuel daily. Above half, 51.87% (194/374) found the daily cost of the fuel acceptable, while 28.61% (107/374) reported the everyday price as not affordable. The households cooked an average of 2 meals a day, and about 4.5 hours were spent cooking per day. More than half (63.37%, 237/374) did not have a separate room used as a kitchen (Table 2). Half, 51.87% (194/374), did their cooking outdoors, while 16.04% (60/374) usually cooked indoors. Cooking in a separate building outside the house was reported by 32.09% (120/374) of households. Over half, 57.23% (190/332) that used charcoal as the primary type of fuel reported cooking outdoors, while 93.94% (31/33) of those that used wood reported cooking from a separate building outside the house.

Table 2
Cooking characteristics among households in Mugunu slum, Fort Portal City, Uganda

| Variable | Category | Frequency N = 374 (%) |
|---|---|---|
| **The primary type of cooking fuel** | Charcoal | 332 (88.77) |
| | Electricity | 1 (0.27) |
| | Kerosene | 3 (0.80) |
| | LPG/cylinder gas | 2 (0.53) |
| | Straw/shrubs/grass | 3 (0.80) |
| | Wood | 33 (8.82) |
| **Affordability of fuel** | Affordable | 194 (51.87) |
| | Not affordable | 107 (28.61) |
| | Very Affordable | 73 (19.52) |
| **Separate room as a kitchen** | Yes | 137 (36.63) |
| | No | 237 (63.37) |
| **Location of cooking area** | Inside the house | 60 (16.04) |
| | Outdoors | 194 (51.87) |
| | Separate building | 120 (32.09) |
| **Location of kitchen windows** | Not close to the main entrance door | 278 (74.33) |
| | Close to the main entrance door | 96 (25.67) |
| **Fuel storage area** | Inside the house | 164 (43.85) |
| | Outdoors | 73 (19.52) |
| | Separate building | 137 (36.63) |
| **Adequacy of cooking area ventilation** | Not adequate | 149 (39.84) |
| | Adequate | 225 (60.16) |
| **Traditional cookstove** | Yes | 311 (83.16) |
| | No | 63 (16.84) |
| **State of repair of the traditional stove (n = 311)** | Good | 260 (83.60) |
| | Not good | 51 (16.40) |
| **Improved cookstove** | Yes | 92 (24.60) |
| | No | 282 (75.40) |
| **State of repair of Improved cook stove (n = 92)** | Good | 83 (90.22) |
| | Not good | 9 (9.78) |
| **Fuel biomass storage area protected from water ((n = 368)** | Yes | 236 (64.13) |
| | No | 132 (35.87) |
| **Fuel biomass damp (n = 368)** | No | 211 (57.34) |
| | Yes | 157 (42.66) |

The majority (74.33%, 278/374) of the households did not have a window close to the main door. However, adequate ventilation of the cooking area was observed for 60.16% (225/374) of the households (Table 2). For those who cooked outdoors, the average cooking distance from the house's main entrance was 3.14 ± 0.17 0m. The cooking time in the study was generally between 8:00 Am and 6:00 PM. Traditional portable and lightweight charcoal cookstoves made of metal with a ceramic liner and one fire per pot which are batch-fed, were used by the majority of households, 83.16% (311/374), and of these, 83.6% (265/311) were in a good work condition. Fuel was stored indoors by almost half (43.85%, 164/374) of the respondents, and 36.63% (137/374) stored the fuel in a separate building outside the house. However, only 64.13% (236/368) reported that the biomass fuel was protected from rainwater, while 157/368 (42.66%) were found using damp biomass fuel (Table 2).

During the cooking time, the mean $PM_{2.5}$ concentrations for the cooking and living area were 175.93 ± 12.49 μg/$m^3$ and 124.29 ± 7.95 μg/$m^3$, respectively (Table 3).

Table 3

*Mean distribution concentration of PM2.5 and CO for the cooking and living area in households in Mugunu slum, Fort Portal City, Uganda*

| | **$PM_{2.5}$ (μg/$m^3$)** | | **CO (ppm)** | |
|---|---|---|---|---|
| | **Cooking area** | **Living area** | **Cooking area** | **Living area** |
| **Mean** | 175.93 | 124.29 | 41.22 | 15.53 |
| **Std. Err.** | 12.49 | 7.95 | 3.31 | 1.70 |
| **[95% CI]** | 151.37 - 200.49 | 108.66–139.92 | 34.71–47.74 | 12.18–18.87 |

These concentrations are higher than the WHO air quality guideline of 25μg/$m^3$ for 24hr. The mean CO concentration during the cooking time was 41.22 ppm and 15.23 ppm for the cooking and living areas, respectively. This was also above the 24hr WHO air quality guideline of 7ppm; however, it was below the 87ppm WHO 15 Minute Average. From an unpaired t-test, it was found that there was a statistically significant difference between $PM_{2.5}$ and CO concentration in the cooking and living area ($t = 18.14$, $p \leq 0.05$) and ($t = 5.77$ $p \leq 0.05$). Cooking in a separate building outside the house resulted in the highest pollution with $PM_{2.5}$ and CO of 176.13 μg/$m^3$ and 46.86ppm, respectively (Table 4). Cooking outdoors also presented high levels of $PM_{2.5}$ (162.58 μg/$m^3$) and CO (44.37 ppm). Cooking with all fuel types showed high concentrations of PM2.5 and CO in this particular informal settlement's cooking and living areas (Table 4). In the neighboring village of Rwengoma, ambient air quality monitors (21) reported an average $PM_{2.5}$ of 69.62 μg/$m^3$ in the week during which these study air quality measurements were taken.

Table 4

Distribution of $PM_{2.5}$ and CO in the cooking area by the location where cooking was usually done in households in Mugunu slum, Fort Portal City, Uganda

| | **$PM_{2.5}$ (μg/$m^3$)** | **CO (ppm)** |
|---|---|---|
| Location of cooking area | Mean (SD) | Mean (SD) |
| **Indoors (n = 60)** | 162.58 ± 11.79 | 44.37 ± 4.57 |
| **Outdoors (n = 194)** | 166.66 ± 6.72 | 39.27 ± 2.49 |
| **Separate building outside the house (n = 120)** | 176.13 ± 9.45 | 46.86 ± 3.12 |

At multivariate analysis cooking outdoors was associated with a 0.112 increment in $PM_{2.5}$ concentrations in the cooking area ($\beta_{\text{cooking outdoors}} = 0.112$ [95% CI: -0.069, 1.614; $p = 0.033$]) (Table 6). Considering majority of households cooked outdoors in this study, further analysis on cooking outdoors revealed that cooking with less polluting and moderately polluting fuel was associated with a 1.77 ($\beta^2_{\text{cooking outside* less polluting}}$ = -1.77(-3.355, -0.186) and 0.934 ($\beta^2_{\text{cooking outside* moderately polluting}}$ = -0.934 (-1.736, -0.133) decrement in $PM_{2.5}$ respectively (Table 5). Cooking with moderately polluting fuel was associated with a 0.719 increment in CO concentrations ($\beta_{\text{moderately polluting}}$ = 0.718 [95% CI: 0.084, 1.352; p = 0.027]) (Table 6) in the living room.

Table 5
Adjusted regression coefficient for variables associated with the concentration of PM2.5 concentrations in the cooking area and living area in households in Mugunu slum, Fort Portal City, Uganda

| **Variable** | **Cooking area** | | **Living area** | |
|---|---|---|---|---|
| | **Coefficient (95% CI)** | **P-value** | **Coefficient (95% CI)** | **P-value** |
| Adequate ventilation | | | | |
| No | ref | | ref | |
| Yes | -0.027(-0.213, 0.159) | 0.78 | -0.062(-0.224, 0.099) | 0.47 |
| Window close to the door | | | | |
| No | ref | | ref | |
| Yes | 0.176 (-0.022, 0.374) | 0.08 | 0.043 (-0.131, 0.215) | 0.63 |
| Damp fuel | | | | |
| No | ref | | ref | |
| Yes | 0.112(-0.064, 0.289) | 0.21 | 0.048 (-0.105, 0.202) | 0.53 |
| **Cooking outside** | | | | |
| No | ref | | ref | |
| Yes | 0.112(0.069, 1.614) | *0.03 | -0.024 (-0.201, 0.152) | 0.76 |
| Type of fuel category | | | | |
| Less polluting | 0.272(-0.800, 1.345) | 0.62 | 0.022( -0.600, 0.645) | 0.95 |
| Moderately polluting | -0.377(-1.115, 0.362) | 0.32 | 0.031( -0.217, 0.27 | 0.81 |
| Highly polluting | ref | | ref | |
| **Cooking outside * Type of fuel category** | | | | |
| Less polluting | -1.770(-3.355, -0.186) | *0.03 | - | - |
| Moderately polluting | -0.934 (-1.736, -0.133) | *0.02 | - | - |
| Highly polluting | ref | | - | - |

Table 6
Adjusted regression coefficient for variables associated with the concentration of Carbon monoxide in the cooking area and living area in households in Mugunu slum, Fort Portal City, Uganda

| **Variable** | **Cooking area** | | **Living area** | |
|---|---|---|---|---|
| | **Coefficient (95% CI)** | **P-value** | **Coefficient (95% CI)** | **P-value** |
| Adequate ventilation | | | | |
| No | ref | | ref | |
| Yes | -0.124( -0.479,0 .231) | 0.49 | -0.258(-0.619, 0.102) | 0.16 |
| Window close to the door | | | | |
| No | ref | | ref | |
| Yes | 0.283( -0.086, 0.652) | 0.13 | − .019( -0.401, 0.363) | 0.92 |
| Damp fuel | | | | |
| No | ref | | ref | |
| Yes | -0.086( -0.421, 0.249) | 0.61 | -0.0669(-0.402, 0.269) | 0.69 |
| Cooking outside | | | | |
| No | ref | | ref | |
| Yes | 0.493( -1.454, 2.441) | 0.62 | -0.207(-0.596, 0.182) | 0.30 |
| Type of fuel category | | | | |
| Less polluting | 1.697( -0.589, 3.982) | 0.15 | 1.314(-0.034, 2.663) | 0.06 |
| Moderately polluting | 0.427( -1.474, 2.328) | 0.66 | 0.718( 0.084, 1.352) | *0.03 |
| Highly polluting | ref | | ref | |
| Cooking outside * Type of fuel category | | | | |
| Less polluting | -1.608( -5.127, 1.912) | 0.37 | - | - |
| Moderately polluting | -0.129( -2.116, 1.858) | 0.90 | - | - |
| Highly polluting | ref | | - | - |
| p-value less than 0.05 | | | | |
| *Considering a 95% CI, a p-value ≤ 0.05 was considered to be statistically significant in this study.* | | | | |

## Discussion

This study aimed to assess household characteristics that predict the concentrations of $PM_{2.5}$ and CO within households in an informal urban settlement in the newly created city of Fort Portal city, Uganda. The primary type of cooking fuel used by the households was charcoal. The concentration of $PM_{2.5}$ and CO during the cooking time for both the cooking area and the living area were above the WHO Air Quality limits of 25µg/m$^3$ and 7ppm for 24hr, even for those households that used cleaner energy of LPG and electricity. Cooking from outside was associated with higher $PM_{2.5}$ concentrations in the cooking area. However, cooking from outside using LPG and charcoal showed a reduction of $PM_{2.5}$ concentrations compared to highly polluting fuels of wood, straw/ shrubs, and grass. Cooking with charcoal was associated with increased CO concentration in the living space.

In this study, charcoal was the primary fuel used for cooking. Charcoal is a readily available and accessible fuel as this district is surrounded by forests, which serve as a source of wood for charcoal burning. Similar studies conducted in informal settings have found a smaller proportion of households using charcoal or wood at the household level (47–49); however, it was comparable to findings from a nearby city of Mbarara, Uganda, and Avenor in Accra, Ghana where charcoal was reported to be the most commonly used cooking fuel (38, 50). The burning of charcoal biomass has environmental and health effects. The demand for charcoal encourages deforestation that destroys habitats of vital ecosystems leading to a reduction in ecosystem services, including tourism and climate change. Combustion of charcoal releases particulate matter, volatile organic compounds, including $PM_{2.5}$ and CO, in the cooking and living area that may exceed the WHO Air Quality limits of 25μg/$m^3$ for $PM_{2.5}$ and 7ppm for CO for 24hr, as was observed in this study.

Households that used less polluting fuels of electricity and LPG also had high mean $PM_{2.5}$ concentrations indoors. This study finding indicates that there is possible migration of $PM_{2.5}$ from neighboring sources. These may include pits where open burning of garbage is done and garages. The other sources also include proximal households that use solid biomass for cooking. These sources facilitate the migration of PM2.5 and CO into households using less polluting fuels (51). This study finding contradicts that observed in Korogocho and Viwandani informal settlements of Nairobi (47), where usage of LPG and electricity resulted in a reduction in $PM_{2.5}$. Our findings imply that the switch to less polluting fuels has to happen for a significant proportion of the neighborhood for the protective effect of cleaner energy against $PM_{2.5}$ and CO to be realized.

In this study, moderately polluting fuel use (e.g., charcoal) was associated with higher CO concentration in the living area. When using the traditional cookstove, the incomplete combustion of charcoal may have resulted from the accumulation of CO in the poorly ventilated living spaces. Other studies have shown an association between charcoal combustion and increased indoor CO (52, 53). Exposure to indoor CO can accumulate toxic concentrations with mild and short-term exposure resulting in nausea, headaches, dizziness, impaired psychomotor function, loss of balance, fatigue, and respiratory symptoms (8, 54, 55). More prolonged exposures to CO can lead to loss of consciousness and death (52).

Outdoor cooking was associated with a 0.112 unit increase in $PM_{2.5}$. Most households cooked outside to avoid smoke from entering their houses as they lacked space designated for cooking in their single or double roomed structures. Ambient air currents disperse airborne particles produced when cooking is done outdoors, away from the cooking area. However, ambient $PM_{2.5}$ concentration from outdoor activities such as open burning of garbage, dust from the earth pathways and roads, and dispersal from nearby cooking areas which used biomass fuels may have contributed to the $PM_{2.5}$ in the outdoor cooking areas. The cooking location is one of the practices that influence the average concentrations of smoke in the cooking areas (56, 57). For this study, the ambient air PM2.5 (58) may have negated the positive benefits of cooking outdoors. Ambient air quality monitors (21) in the neighboring Rwengoma village reported an average $PM_{2.5}$ of 69.62 μg/$m^3$ in the week during which these study air quality measurements were taken. However, other studies have observed that outdoor cooking resulted in reduced $PM_{2.5}$ (57). Our study was conducted in an informal setting. In contrast, Rosat et al. (2014) (57) was conducted in a rural village that may have been sparsely populated compared to the informal settlements that are densely populated with more anthropogenic activities resulting in lower $PM_{2.5}$ in ambient air quality for rural areas.

Cooking with less polluting and moderately polluting fuel was associated with a unit decrease of 1.77 and 0.934 in $PM_{2.5,}$ respectively. Despite the increased concentration of $PM_{2.5}$ associated with cooking outdoors in this informal urban settlement, using a less polluting cooking fuel of electricity, LPG, or kerosene or moderately polluting cooking fuel of charcoal resulted in decreased concentrations of $PM_{2.5}$ compared to solid biomass fuels of wood and straw/shrubs/grass. The use of less polluting fuels may have resulted in a higher decrease in $PM_{2.5}$ than moderately polluting fuels because when using traditional cookstoves, incomplete combustion of solid biomass fuels occurs due to difficulty in mixing the fuel and air during burning, unlike for LPG (gas) and kerosene (liquid) leading to release of a significant proportion of products of incomplete combustion PM2.5 (10, 58). The decrease in $PM_{2.5}$ concentration with the type of cooking fuel is similar to a study conducted in rural Malawi that assessed the effect of cooking location and type of cooking fuel on the level of $PM_{2.5}$ (59). The use of less polluting fuels during outdoor cooking in informal settings may reduce $PM_{2.5}$ in the cooking area, further emphasizing the need to promote cleaner cooking energy.

This study determined the cooking time $PM_{2.5}$ and CO concentrations of the cooking areas and living areas for many households in this informal urban settlement. The cooking period presents the most imminent danger because this is the time the fuel sources are actively burning with the highest expected concentration of incomplete combustion byproducts of $PM_{2.5}$ and CO. Some limitations of this study are the cross-sectional nature of the research and the limited air quality measuring devices available to use for the large sample size. Thus, a one-minute measurement was adapted according to Saad et al. (45).

# Conclusions

The mean $PM_{2.5}$ and CO concentrations in cooking and living areas exceeded the WHO Air quality limits. Cooking outdoors did not have a protective effect against $PM_{2.5,}$ and cooking with charcoal increased the CO in the living area of this informal settlement. Interventions to improve indoor air quality in informal settlements need to promote a switch to cleaner cooking energy for all households in the neighborhood to reduce indoor $PM_{2.5}$ and CO concentrations to be realized.

# Abbreviations

ALRI Acute lower respiratory infections

CO Carbon monoxide

DAYs Disability-adjusted life years

HAP Household air pollution

IAP Indoor air pollution

LMICs Low- and middle-income countries

LPG Liquefied petroleum gas

NCDs Non-communicable diseases

$NO_2$ Nitrogen dioxide

PM Particulate matter

VAT Value added tax

WHO World Health Organization

# Declarations

### *Ethical approval and consent to participate*

This study received ethical approval from Makerere University School of Public Health Higher Degrees Research and Ethics Committee and registered with Uganda National Council for Science and Technology (registration number HS695ES.) Administrative clearance was sought from the Kabarole district Local government. Written informed consent was sought from the study participants.

### *Consent for publication*

Not applicable

*Availability of data and materials*

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

*Competing interests*

The authors report no conflict of interest, financial or otherwise.

*Funding*

Makerere University School of Public Health funded this study under the Small Grants Programme, Grant Number: MakSPH-GRCB/19-20/01/02. The content is solely the responsibility of the authors and does not necessarily represent the official views of Makerere University.

*Authors' contributions*

WKK was the principal investigator of this study. She oversaw concept development, proposal development, Ethical approval, and conducting the study; supervised data collection, analyzed the data, and developed the manuscript.

RKM He guided in the proposal development and manuscript preparations.

EA guided in the proposal development and manuscript preparations.

STW guided in the proposal development, analysis, and manuscript preparation.

VN guided in the concept development.

TS guided in the proposal development, supervision of data collection, and manuscript preparation.

AN guided in the manuscript development.

ESC gave expert guidance during manuscript development and assisted in acquiring the ambient air quality data.

JCS gave expert guidance during concept development, proposal development, and manuscript development.

JBI gave expert guidance during concept development, proposal development, and manuscript development.

*Acknowledgments*

We would like to acknowledge the District health officer of Kabarole, Dr. Mathias Tumwebaze, who supported us and guided using the study area, the research assistants, and the study participants from Kisenyi-Mugunu especially their chairperson, Deogratious Ssebuwuffu guided in the data analysis process and also the AirQo team which provide us the data of ambient air quality from their monitors of Rwengoma village.

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